2nd Int. PhD Symposium in Civil Engineering 1998 Budapest

REPAIR AND STRENGTHENING OF REINFORCED CONCRETE BEAMS USING COMPOSITE MATERIALS

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SUMMARY

External bonding of composite plates to reinforced concrete structures represents an interesting alternative to steel as it can avoid the corrosion of the plate. In our laboratory we have experimented this technique with several FRP (Fibre Reinforced Plastics) materials.

The experimental study divides into two parts: on one hand we have initially preloaded beams and then repaired them with epoxy-bonded glass fibre plates, on the other hand beams were simply strengthened with several composite materials. We have observed the effect of several parameters such as the thickness of the plate on the flexural behaviour of the beams.

Keywords: plate bonding, flexural strengthening, Fibre Reinforced Plastics (FRP), precracking

1. INTRODUCTION

Deterioration of reinforced concrete structures due to corrosion of the rebars or continual upgrading of service loads (increase of the traffic load on bridges for example) has resulted in a large number of structures requiring repairing or strengthening.

Various methods are available to repair or strengthen those structures. External bonding of steel plates to damaged reinforced concrete structures is one of these methods and has been shown to be quite an efficient and a well-known repair or strengthening technique. It has been largely studied in France (L'Hermite, 1967), (Bresson, 1971) and intensive research performed in the beginning of the eighties (Theillout, 1983) results in French rules concerning the design of those structures (SOCOTEC, 1986).

The use of composite materials represents an alternative to steel as it can avoid the corrosion of the plate. FRP materials are also very lightweight, have a high strength to weight ratio and are generally resistant to chemicals. The price of these materials, especially of Carbon Fibre Reinforced Plastics (CFRP), could represents a drawback but the ease in handling the material on construction sites, due to the light weight, helps to reduce labour costs. This technique has been largely investigated especially in Switzerland (Meier, 1995) where existing structures have been retrofitted using epoxy-bonded composite materials.

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We have experimented this technique on RC beams using several composite materials: glass fibre plates and rods, and carbon fibre sheets. A series of beams were precracked and need to be repaired. The beams of the second series were simply strengthened using those materials. This paper deals with the flexural behaviour of those repaired or strengthened beams and especially with the failure modes.

2. EXPERIMENTAL PROGRAM

2.1 Test specimens

Ten rectangular beams were tested in order to evaluate the effect of externally bonded composite-material reinforcement on the flexural capacity of RC beams. All ten beams had span length of 2.80 m (beams were 3 m long) and cross-sectional dimensions of 15 × 30 cm.
These beams had internal reinforcement provided by two 14 mm diameter rebars (yield strength: 500 MPa). Twenty-one 6 mm diameter stirrups were also used.
The average compressive strength of the concrete at the day of the test was 40 MPa.
Descriptions of the ten beams are listed in Tab. 1.

P_1	Control beam
P_2	Precracked beam repaired using a 3 mm Delmat plate
P_3	Precracked beam repaired using a 3 mm Delmat plate
P_4	Precracked beam repaired using a 6 mm Delmat plate
P_5	Reinforced beam using a single layer of 7.4 mm diameter Jitec rods
P_6	Reinforced beam using a 6 mm Delmat plate
P_7	Reinforced beam using a single layer of two Sikadur sheets
P_8	Reinforced beam using a single layer of two Sikadur sheets
P_9	Reinforced beam using two layers of two Sikadur sheets
P_{10}	Reinforced beam using two layers of two Sikadur sheets

Tab. 1: Description of the ten beams.

2.2 Composite Materials

Three different composite materials have been used in this experimental program: Delmat glass fibre plates, Jitec glass fibre rods and Sikadur carbon fibre sheets. Delmat plate is a glass fibre mat (short fibres arranged in all directions). Jitec rods and Sikadur sheets consist in unidirectional respectively glass and carbon fibres.
The effect of the thickness of the Delmat plate (3 and 6 mm) was studied on the flexural behaviour of the beams. As carbon sheets were 1.2 mm thick and 5 cm wide, we have bonded a single layer of two 5 cm wide sheets (beams P_7 and P_8) or two layers of two sheets (beams P_9 and P_{10}) as it is shown on Fig. 1.

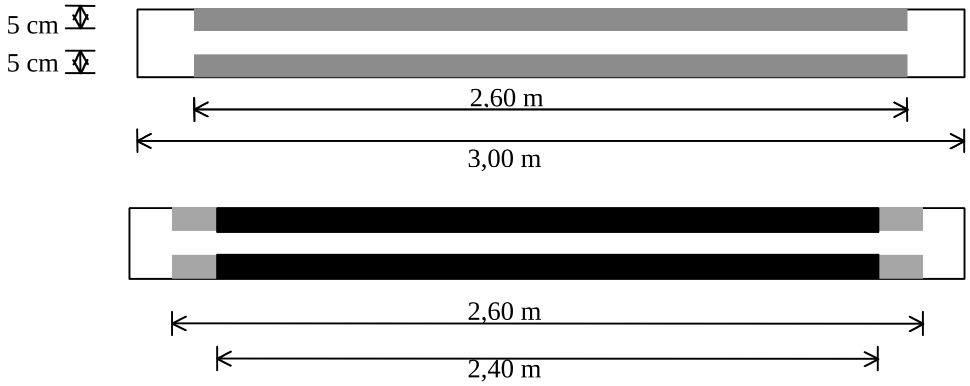

Fig. 1: Bonding of a single layer or of a double layer.

Characteristics of the three composite materials are listed in Tab.2.

	Delmat plate	Jitec rods	Sikadur sheets
Dimensions (L × e × l) [cm]	15 × 0,3 × 200 15 × 0,6 × 200	*17* rods, section 0,43 cm^2, l = 200 cm	*2* × 5 × 0,12 × 260 (*2* × 5 × 0,12 × 260) + (*2* × 5 × 0,12 × 240)
Density	1,81	1,95	1,6
Tensile strength [N/mm^2]	55	1550	2400
Modulus of elasticity [N/mm^2]	11700	44000	150000

Tab. 2: Characteristics of composite materials.

2.3 Bonding of the composite materials

The beams to be externally repaired or strengthened were blasted down to aggregate at the tension face by a grinding wheel. The cracks of the preloaded beams were injected with a resin. Then the surfaces of the blasted concrete and of the composite material were accurately cleaned before bonding. Sikadur 30 was applied on the face of the composite and on the tension face of the concrete beams. We tried to maintain the thickness of the bond uniform (2 mm) throughout the length.

2.4 Testing procedure and instrumentation

A first series of beams (P_2 to P_4) was preloaded to a percentage of the ultimate load of the control beam. This percentage has been defined as a damaging degree and corresponds to an average width of the cracks of 0.5 mm. These three beams have been repaired using a 3 mm or 6 mm Delmat plate. Then they were tested up to failure. With this first series we want to study the effect of the precracking and of the plate thickness on the flexural behaviour of the beams.
The second series (P_5 to P_{10}) consists in strengthening the beams using three different composite materials (plate, rods and sheets) as well as studying the effect of a single or double layer of carbon sheets.
All beams were tested up to failure under four-point bending.

During the test, the vertical deflection at midspan (1) and the applied load were measured. Gages were used to measure tensile strain in the internal steel (one gage (2) at midspan), compressive strain on the concrete (three gages (3), (4), (5) at midspan) and tensile strain in the composite (two gages (6), (7) at midspan on each sheet and two gages (8), (9) on others locations). These instruments are represented on the test set-up below.

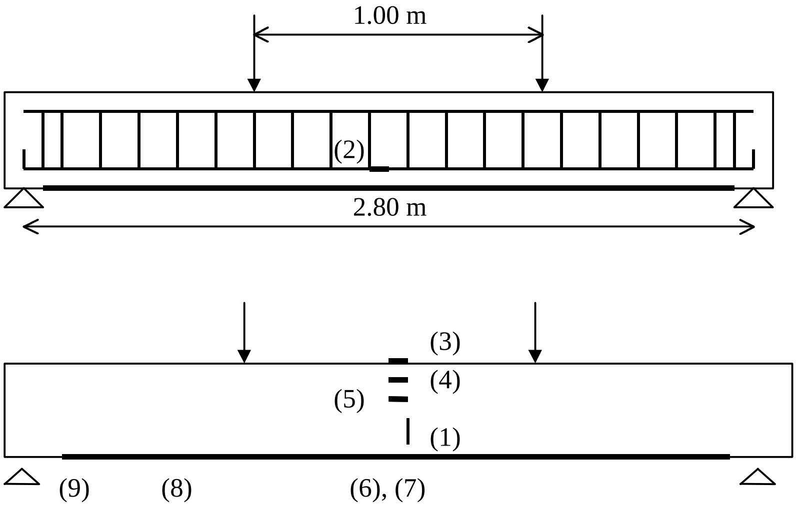

Fig. 2: Test set-up and position of instruments.

3. TEST RESULTS

Results from the ten beams are summarised in Tab. 3 and plots of load-versus-deflection for typical beams are shown in Fig. 3, 4 and 5.

Beam	**Ultimate load [kN]**	**Ultimate strain in the external reinforcement**	**Failure mode**
P_1	90		Concrete crushing
P_2	101	8 ‰	Failure of the plate
P_3	101	8 ‰	Failure of the plate
P_4	115	6 ‰	Local debonding of the 6 mm Delmat plate and shear failure of a concrete layer between the rebars and the external plate
P_5	100	2 ‰	Failure of a concrete layer along the internal reinforcement
P_6	132	10 ‰	Idem
P_7	136	4 ‰	Idem
P_8	143	4 ‰	Idem
P_9	156	2.8 ‰	Idem
P_{10}	159	2.8 ‰	Idem

Tab. 3: Experimental results of the ten beams.

3.1 Beam behaviour

3.1.1 Glass fibre materials

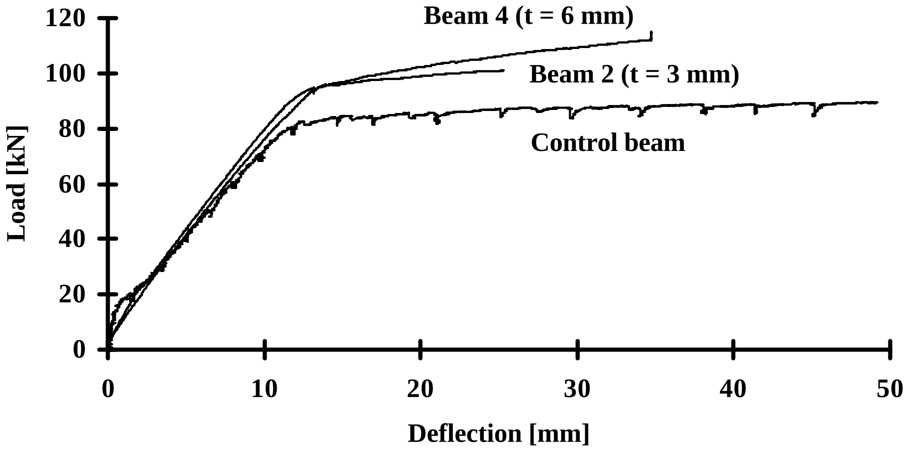

Fig. 3: Load-versus-midspan deflection plot for repaired beams (effect of the thickness of the plate).

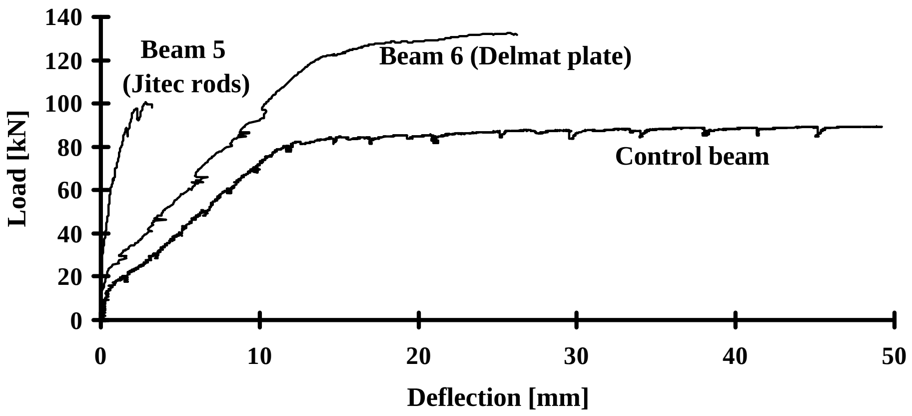

Fig. 4: Load-versus -midspan deflection plot for reinforced beams using glass fibre materials.

When loaded, the control beam developed flexural tensile cracks in the constant moment region at load of 20 kN. At loads near 80 kN, the tensile reinforcing steel yielded. The beam failed in flexure due to crushing of extreme compression fibre at load of 90 kN.

All composite repaired beams P_2, P_3, P_4 or externally reinforced beams P_5 and P_6 showed significant increases in flexural stiffness and ultimate capacity as compared to the control beam.

Beams P_2 and P_3 had increases in ultimate load of 10 % over beam P_1. These precracked beams were seriously damaged as internal steel has yielded in all cases. Before being repaired they exhibited an average midspan deflection of 10 mm and many flexural cracks. Midspan deflections for beams P_2 and P_3 after the second flexural test were respectively 25 and 21 mm long (50 Beam P_4 failed at 115 kN (30 % increase over P_1) and suggests that the increase of the ultimate capacity depends on the plate thickness. At the ultimate stage the preloaded repaired beams show better mechanical characteristics than the control beam.

Beams P_5 and P_6 had increases in ultimate load of respectively 10 % and 45 % over P_1, while midspan deflection, composite strains and cracks width were reduced. High stiffness was reached by using glass fibre rods, which behaved similarly to a plate. Beam P_5 behaved in a linear fashion whereas the others beams exhibited two different behaviours. The repaired or externally reinforced beams showed linear behaviour between the first cracking and a point, which does not always correspond to the yielding of the tensile steel. After this point, those beams seem to behave in a plastic fashion which really surprised us as we know that composite materials exhibit linear elastic behaviour up to failure.

3.1.2.Carbon fibre sheets

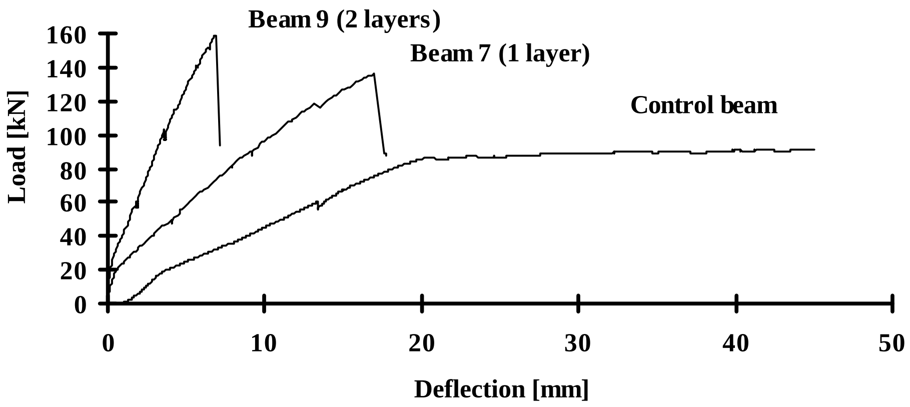

Figure 5: Load-versus-midspan deflection plot for reinforced beams using carbon fibre sheets.

Beams P_7 and P_8 had increases in ultimate load of respectively 51 % and 58 % over P_1, while beams P_9 and P_{10} failed at 156 and 159 kN (73% and 77% over P_1). Midspan deflection, tensile strains in the carbon sheets and cracks width were also reduced and an increase of the stiffness of the beams was noticed. The bonding of a second layer of carbon sheets can lead to an increase of the ultimate load and of the stiffness of the beam. Only 1.2 mm carbon sheets were available and we had to bond a double layer of them to take into account the thickness parameter. We can conclude from the tests that the influence of this parameter on the flexural behaviour of the beams is obvious.

The influence of the external reinforcement on the development of the cracks is really good. The cracking is more diffuse and the opening of the cracks is in the region of 0.1 mm (several millimetres for the control beam).
Nevertheless the decrease of strains and cracking shows some drawbacks as they were a tool for the designer to predict if the failure of the structure was close or not.
Whereas glass fibre strengthened beams exhibited a kind of plastic behaviour, carbon fibre reinforced beams behave elastically up to failure. This lack of ductility is dangerous as it leads to a brittle failure of the beams.

3.2 Failure modes

The failure modes, which have been observed on the beams are different from that of a classical reinforced concrete beam (concrete crushing or failure of the internal steel). Moreover the failure modes of the repaired beams are different from those of the externally reinforced beams.

3.2.1 Failure modes of the repaired beams

Before being repaired the beams exhibited open cracks, midspan deflection and the internal rebars had yielded. During the second flexural test the opening of the existing cracks increased. Beams P_2 and P_3 failed when the 3 mm plate failed in tension due to the opening of a large crack at midspan. This failure occurred in a sudden manner. Those Delmat plates do not have a high tensile strength and the ultimate tensile strain has been reached. For beam P_4 we attended to the combination of two phenomenon : local debonding of the 6 mm Delmat plate and shear failure of a concrete layer between the rebars and the external plate. This failure also occurred in a sudden manner

3.2.2 Failure modes of the externally reinforced beams

All externally reinforced beams using glass or carbon fibre materials have failed in the same manner. We attended to the failure of a concrete layer along the internal reinforcement. The concrete was not initially precracked and the development of the cracks during the reinforcement test is highly influenced by the carbon sheets. The first cracking is delayed and more diffuse. Shear cracks occur at the ends of the plates or of the sheets for values of the load between 70% and 80% of the ultimate load. Then those cracks come near again the midspan by using existing flexural cracks. Finally the sudden propagation of a horizontal crack in the concrete-steel bond region occur. This crack runs along the weakest surface, which is the concrete-steel interface. It leads to the failure of the beam as soon as this crack opens and separates the concrete cover from the rest of the beam.
It is interesting to note that the weakest point of the assemblage concrete-bond-composite material is not the concrete-composite interface but the concrete-internal steel interface.

We have observed the same failure mode for all externally reinforced beams. When having a look at the load-versus-deflection diagram for beam P_5 (6 mm Delmat plate reinforced beam) this brittle failure is not obvious as the beam seem to behave plastically. The failure of a brittle-type is more obvious for the carbon sheets reinforced beams. Fig. 5 shows the sudden decrease of load, which suggests the failure of the beam. We have also observed that strains in the carbon sheets at failure were rather low (between 2.8 ‰ and 4 ‰) whereas the ultimate tensile strain of the material is of 14 ‰. The full flexural capacity of the externally bonded beams was not reached and the high elastic strain of the carbon sheets is not really used.

4. CONCLUSION

Glass fibre or carbon fibre materials bonded beams transformed the ductile flexural failure of the control beam into a brittle failure, which cannot agree with an utilisation in civil engineering works. Therefore we need to optimise this method of reinforcement and in particularly to develop ductile failures (this could be achieved by using an anchorage system).

A global design strategy requires the determination of the interface law, which governs the behaviour of the beams. Indeed the knowledge of the stress-strain laws of the different materials (concrete, steel, bond and composite) is not enough. This interface shear law will be soon obtained by using a numerical-experimental approach. Then a global design of externally bonded beams could be performed with a finite element program. The precracked concrete could then be taken into account.

5. ACKNOWLEDGEMENTS

The experiments of this investigation were carried out with the financial support of the French Agency for the Valorisation of Research (ANVAR). The authors also gratefully acknowledge SIKA France for supplying carbon sheets and adhesive.

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