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# PERFORMANCE OF DEEP AND FLEXURAL BEAMS STRENGTHENED WITH BONDED STEEL PLATES BY UTILIZING DIFFERENT GLUES

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**ABSTRACT**

This paper presents the test result of experimental study on flexural behavior of strengthened reinforced concrete beams by epoxy bonding steel plates to its soft. Twelve beams were tested to investigate the effectiveness of two types of epoxy glue of widely differing stiffness and the shear over span ratio. The beams were in two series, one in which strut action with shear failure dominant and the other flexure stress were governing. The results are discussed in the context of their implications for strengthening operations where the engineer is seeking to improve the deformation and cracking behavior under service loading or alternatively to increase the ultimate strength. It is shown that in deep beams where shear is the dominant factor, the use of bonded plates demonstrates no improvement in strength. It is also shown that for beams where failure is in flexure, glues of widely differing stiffness, in their hardened state, can perform satisfactorily under both service and ultimate loading. However, in general stiffer glues produced better results for service conditions and less stiff glues were better at ultimate load.

**Keywords:** strengthen beams, epoxy glue, deep beam, flexural behaviour.

## 1. INTRODUCTION

Strengthening existing concrete structures in order to improve their performance under service loads or to increase their ultimate strength is one of the important aspect for engineers. If the structures are still in use, the strengthening operations needs to be carried out quickly, with a minimum of disruption to normal operations and small increases in head-room. In these respects, the glued plate technique has a great deal to offer.

Steel plates are bonded to the concrete surface using epoxy glue. These then act compositely with original member increasing the stiffness, energy absorption and strength. In the last forty years the technique was adopted in many countries to improve the flexural behavior of the beams [1-8]. Despite the peeling of end plates prior to failure in some beams, the technique exhibits a good improvement in strength and ductility.

Regarding the premature plate peeling failure and to achieving sufficient ductility in beams strengthened researchers [9-12] provides anchor bolts or U-shaped plates at the ends of the glued plate. The experiments indicated that the beam ductility increases, and the anchorage of the plate to the beam through bolts or U-shaped plates proves to be an efficient method for preventing the premature plate peeling failure.

Additionally, the steel plate and concrete beam composite technique have been developed for the shear strengthening and repairs [13-16]. Attaching steel plates to the external surfaces of concrete beams can provide a practical solution to the upgrading of existing structures. When plates are fixed to the sides (web) of a beam a large increase in the shear capacity can be recognized. The experimental results from two methods of plate attachment, namely adhesive bonding and bolting, are examined. The influence of various parameters, such as the plate material properties, amount of internal stirrups, lateral confinement of the compression zone, and amount of flexural reinforcement on the effectiveness of external plate bonding, has been critically assessed. The results show that, with properly designed, externally bonded plates in the form of end anchorages, U-shaped strips/stirrups, and confinement plates for the compression zone, it is possible to transform the brittle shear failure of a beam without any shear reinforcement into a ductile flexural failure.

Externally bonded carbon fiber reinforced polymer (CFRP) composite laminates have been successfully applied to reinforced concrete (RC) beams and other structural elements for the purpose of increase load carrying capacity of such elements [17].

Glass-fiber reinforced polyuria (GFRPU) is a composite of polyurea and fibers and is applied as reinforcement through a simple spraying method [18]. The applicability of GFRPU was investigated through the experiments, and the test results indicate that the GFRPU strengthening method is feasible for enhancing the load-carrying capacity and flexural ductility.

It is significant to state that owing to the relatively lower prices and ductile stress-strain properties of steel, bonding steel plates to the tension and sides faces of the R.C beams is imperative alternative to other available strengthening techniques.

## 2. RESEARCH SIGNIFICANCE

The experimental research described in this paper was carried out to illustrate the following:

a) The differences in performance between beams strengthened by plates bonded with two different epoxy glues having widely differ elastic moduli.

b) The effectiveness of the glued plate technique in deep beam where strut action with shear are the predominate factors.

c) The efficiency of the technique in beams with flexural mode failures.

## 3. EXPERIMENTAL PROGRAM

Two series of reinforced concrete beams were tested to investigate the effectiveness of glues with widely differing properties. The following data from some of these beams are presented to illustrate the performance of members strengthened by plates bonded to their tensile faces only.

### 3.1 Beam specimens

The beams of series RBI were deep, with shear span to effective depth ratios (av/d) of 1.63. These beams were chosen to investigate the performance of members in which strut action with shear was the dominant factor. Beams of series RB2 were longer, with av/d ratios of 5.0, and were designed to investigate the behavior of members failing in flexure. All the beams had the same cross section, 150 x 150mm and had the same internal tension reinforcement of 2(8mm) diameter bars of high tensile strength (steel ratio=0.0053). Shear reinforcement was provided in the shear spans of all beams to prevent conventional reinforced concrete shear failure.

One beam from each series was left unplated to act as controls. Two beams of series RBI had glue only applied to their tensile faces to check on cracking of the glue relative to that of the concrete. All the other beams were strengthened, using plates of 120 x1.6mm or 120 x 3.0mm crosssection and glue thicknesses of 1.5mm and 3.0mm.

Glueing operations were all carried out when the concrete was 14 days old and the tests were performed 14 days later.

The procedure for the glueing operation was he plates were abraded with steel grit of 60/80micron mean size. Both faces of the plates were shotblasted to prevent warping of the plates. The concrete surface was abraded with an electrical disc grinder to remove laitance and expose the aggregates. They were then wire brushed and vacuum cleaned to remove all loose particles. The adhesive was applied after mixing its component, to both concrete and plate surfaces. The joint thickness was controlled by a number of small hardened adhesive spaces. The plate was then applied and held in position by a uniformly distributed pressure obtained by a thick plywood plate clamped to the tested beam. The pressure was maintained for 24 hours and the beams were left for a further 14 days before being tested at 28 days.

Full details of all beams are given in Figure-1 and Table-1.

**Table-1.** Details of beams.

| Beam No. | Glue Type | Glue Thickness (mm) | Plate Section Area ($mm^2$) | Concrete Cube Strength ($N/mm^2$) |
|---|---|---|---|---|
| RB1 | - | - | - | 47.2 |
| RB1-A1 | A | 1.5 | - | 47.2 |
| RB1-B1 | B | 1.5 | - | 47.2 |
| RB1-A2 | A | 1.5 | 192 | 35.0 |
| RB1-B2 | B | 1.5 | 192 | 42.3 |
| RB1-A3 | A | 3 | 192 | 35.0 |
| RB1-B3 | B | 3 | 192 | 42.3 |
| RB1-A4 | A | 1.5 | 360 | 35.0 |
| RB1-B4 | B | 1.5 | 360 | 42.3 |
| RB2 | - | - | - | 36.7 |
| RB2-A2 | A | 1.5 | 192 | 36.8 |
| RB2-B2 | B | 1.5 | 192 | 36.7 |

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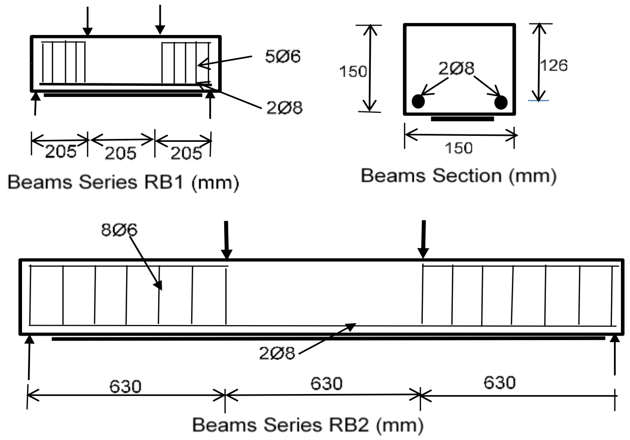

Figure-1: Beams Details Drawings

### 3.2 Materials

#### 3.2.1 Epoxy glues

They are generally two part systems; a resin and a hardener, which when mixed have consistencies ranging from a liquid to a stiff paste, the viscosities depending to some extent on the amount of inert filler used. In practice plates are often applied to the soffits of members and therefore a formulation which gives a soft paste like consistency is recommended [2]. When hardened, glues of this consistency can still vary considerably in their properties. For the tests described here therefore, two glues of differing stiffness in the hardened state were used, A and B were examined and the results are presented in Table-2.

**Table-2.** Properties of epoxy glues.

| Glue Type | Compressive Strength (Mpa) | Elastic Modulus (kN/mm$^2$) | Poisson's Ratio |
|---|---|---|---|
| A | 93.6 | 9.9 | 0.3 |
| B | 42.3 | 0.92 | 0.38 |

The thickness of the glue layer should generally bekept as thin as practicable down to about 1.5 mm, since in flexure there is no structural advantage with thicker layers. In the tests discussed in this paper, a glue thickness of 1.5mm was used for the beams of series RB2, but thicknesses of 1.5mmand 3.0mm were used for the beams of seriesRB1.

#### 3.2.2 Steel plates

In practical applications and in research, most of the plates used have been mild steel. The main advantages of mild steel overhigh yield steel seems to be that the strain required to develop the strength of the plate is less, thus giving greater crack and deflection control under service loads and less possibility of failure at the glue line at higher loads.

For the tests reported here, mild steel plates were used. Average properties for the 1.6mm and 3.0mmthick plates were examined and the results are presented in Table-3.

**Table-3.** Steel plates properties.

| Plate Thickness mm | Elastic Modulus kN/mm$^2$ | Yield Stress N/mm$^2$ | Yield Strain x10$^{-6}$ | Ultimate Stress N/mm$^2$ |
|---|---|---|---|---|
| 1.6 | 182 | 261 | 1650 | 357 |
| 3 | 200 | 225 | 1556 | 378 |

#### 3.2.3 Bar reinforcement

High yield, deformed bars were used for the internal bars. Average properties for these bars were as follows:

Elastic modulus - 200 kN/mm$^2$
0.2% proof stress - 508 N/mm$^2$
Strain at proof stress- 3900 x 10$^{-6}$
Ultimate stress - 607 N/mm$^2$

#### 3.2.4 Concrete

The concrete materials were crushed gravel, dried river sand and ordinary Portland cement. Characteristic cube strengths at 28 days ranged from 35.0 to 47.2 N/mm2. Concrete strength for individual beams is given in Table-1. The cylindrical compressive strength of concrete ($f_c^/$) is chosen to be 0.85 of the cubing strength.

#### 3.2.5 Test procedure

All the beams were tested using steel rig of 50 ton Avery machine, in four-point bending, giving constant bending moment over the middle third of the span. Loading was applied in equal increments up to failure and after each increment readings were taken of load, mid-span deflections and strains and crack widths over the constant moment regions. Cracks widths were measured at the level of the internal reinforcement.

## 4. TEST RESULTS AND DISCUSSIONS

### 4.1 Mods of failure and ultimate strengths

The experimental and theoretical results are given in Table-4. The theoretical calculations were carried out following the ACI-Code [18] strength method.

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**Table-4.** Tests results.

| Beam No. | Failure Load(kN) | Theoretical Loads (kN) | | First Crack Load(kN) | Service Crack Width(mm) | Mode of Failure |
|---|---|---|---|---|---|---|
| | | Failure | Service | | | |
| RB1 | 95.0 | 71.0 | 40.0 | 18.0 | 0.060 | Flexure |
| RB1-A1 | 91.0 | 71.0 | 40.0 | 28.0 | 0.060 | Flexure |
| RB1-B1 | 91.5 | 71.0 | 40.0 | 23.0 | 0.050 | Flexure |
| RB1-A2 | 84.0 | 122.6 | 69.0 | 50.0 | 0.020 | Plate Sep. |
| RB1-B2 | 88.0 | 125.0 | 70.3 | 37.0 | 0.024 | Plate Sep. |
| RB1-A3 | 85.3 | 123.4 | 69.4 | 45.5 | 0.015 | Plate Sep. |
| RB1-B3 | 91.3 | 125.8 | 70.7 | 39.0 | 0.045 | Plate Sep. |
| RB1-A4 | 90.0 | 159.4 | 89.6 | 56.0 | 0.030 | Plate Sep. |
| RB1-B4 | 90.0 | 163.6 | 92.1 | 38.0 | 0.060 | Plate Sep. |
| RB2 | 24.4 | 22.6 | 12.7 | 6.0 | 0.103 | Flexure |
| RB2-A2 | 42.3 | 40.1 | 22.6 | 17.5 | 0.016 | Flexure |
| RB2-B2 | 43.2 | 40.1 | 22.6 | 11.0 | 0.025 | Flexure |

The application of the glue to the basic section resulted in a slight reduction in strength which may be explained by the delayed cracking of the glue. The glue cracked after the concrete and thus tensile forces in the glue would be suddenly transferred to the cracked basic section and may have caused some slight damage. Ina plated beam, failing in flexure, the transfer of tensile forces from the glue would be less sudden and have no serious effect.

The six plated beams RB1-A2 to RB1-B4 all failed at loads less than the basic section. Failure for all the beams was by plate separation at one end and then tearing off of the concrete cover to the internal bars, see Figure-2, thus reducing the bond for these bars. This type of failure is common in cases where there is high shear, or thick plates are used.

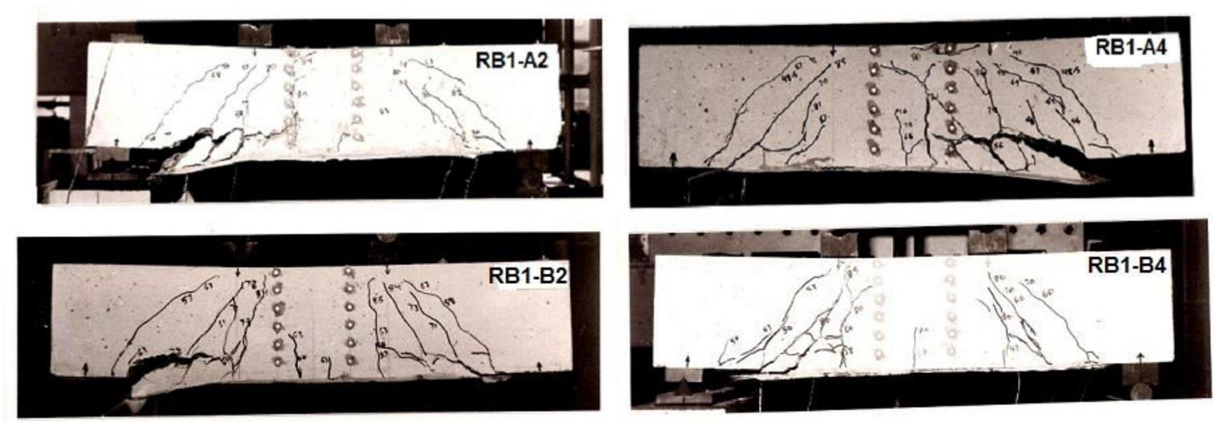


**Figure-2.** Mode of failure for beams RB1.

The mechanism in the region of the end of the plate, which initiates this failure, is complex and depends on the combined effects of interface bond stresses and peeling forces.

The slightly improved performances of beams with Glue B relative to those with Glue a are due to the lower modulus of the glue used. High stress concentrations are induced at the ends of the plates due to rapid buildup of plate force. With lower modulus glue however the 'transmission length' for the plate is longer, thus resulting in a lower peak stress.

The longer beams RB2, RB2-A2 and RB2-B2 all failed in flexure, as shown in Figure-3.

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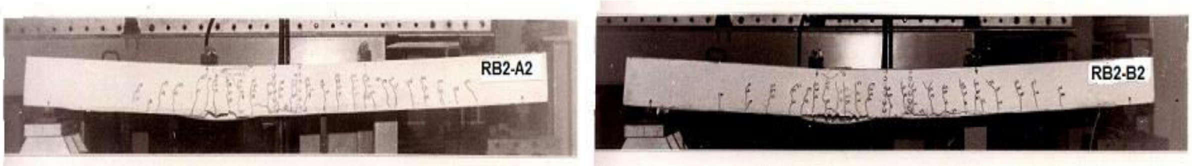


**Figure-3.** Mode of failure for beams B2.

In beam RB2 the internal bars fractured where as the plated beams failed by yielding of the plates and the bars and then crushing of the concrete in the compression zone. From Table-4 it is seen that both plated beams reached their theoretical ultimate strengths. Thus both glues appear to be equally effective in achieving full composite action between the plates and the basic section. As in the case of the beams of series RB1Glue B gave slightly better ultimate strength.

**4.2 Deflection**

Deflections for the beams of series RB1 are shown in Figure-4. It is seen that the plated beams are generally stiffer than the basic section with glue A being slightly better. Up to a load of about 60 kN, increased plate thicknesses had very little effect on stiffness. Above this load, slightly increased stiffness's were produced with thicker plates.

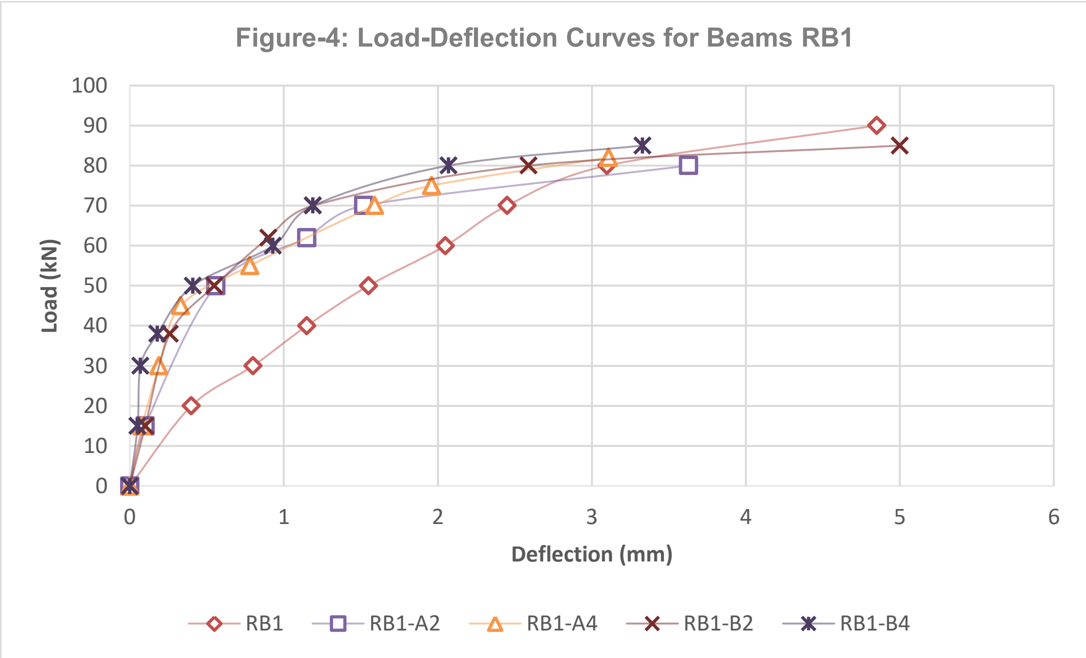


**Figure-4.** Load deflection curves for beams RB1.

Above 60 kN load, Glue B gave stiffer responses, probably due to the earlier plate separation with the stiffer glue. Premature failure of the plated beams resulted in reduced ductility relative to the basic section.

The Load-deflection curves for the beams of seriesRB2 are shown in Figure-5.

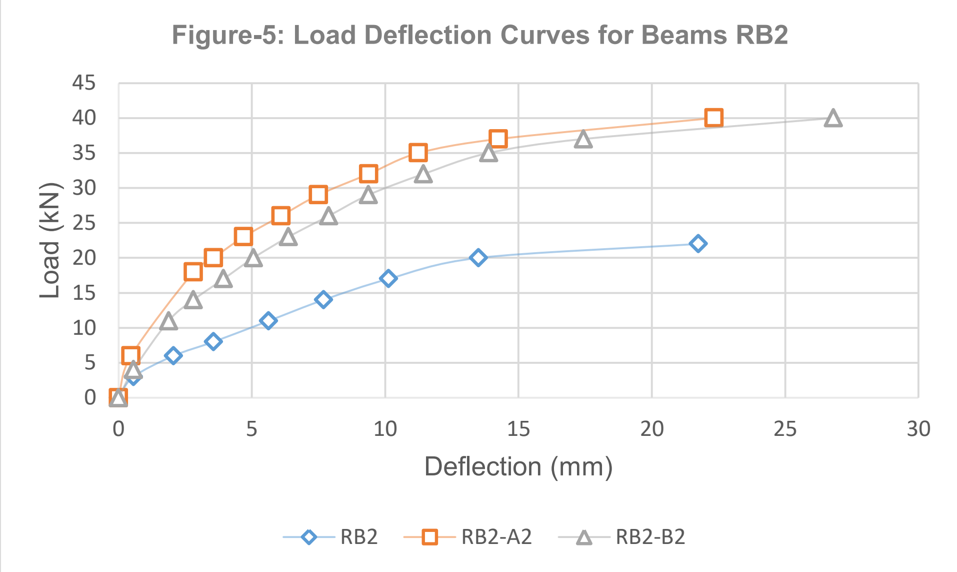


**Figure-5.** Load deflection curves for beams RB2.

It is seen that the plated beams are considerably stiffer, Glue Abeing the more effective. The curves assume composite action between the plate and basic section and concrete and glue in tension are cracked. Comparing the two sets of curves, beam RB2-A2was stiffer than expected. Thus if deflection is the main problem to be rectified, a system using a high modulus glue will have the most effect.

### 4.3. Cracking

A summary of the cracking results for all the beams is given in Table-4. The application of plates delayed the appearance of the first flexural cracks in the concrete (except RB1-B4), but all beams were cracked under full service load. The average crack width under full service load was considerably reduced in the plated beams (except RB1-B4) despite the load level being generally more than twice that for them basic section. There are a number of reasons for this; the plated beam is stiffer (approx. by three), plating promotes cracks at closer centers (approx. half the spacing) and the plate is applied at the position where cracks begin thus giving greater restraint. Both glues performed satisfactorily, but the stiffer glue was much more effective.

### 4.4. Steel bars strains

A measure of the effectiveness of the bond provided by the glue can be obtained from a consideration of the development of strain in the plates. Figure-6 shows the load strain curves for the plates and bars of the beams in series RB2.

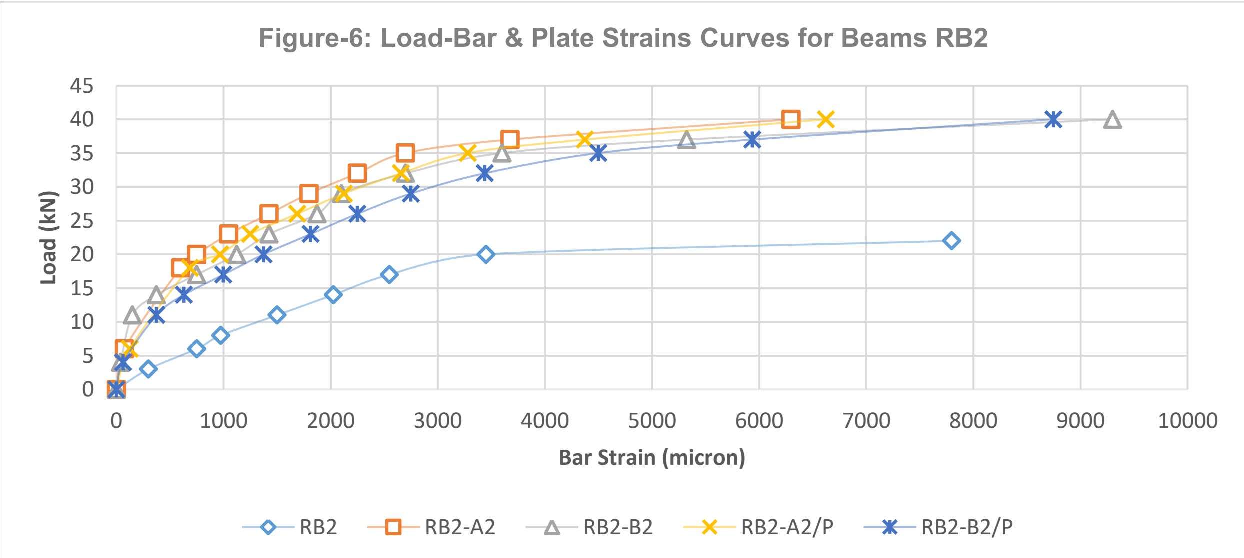


**Figure-6.** Load bar and plate strains curves for beams RB2.

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Up to a load of about 30 kN, full composite action appears to be achieved since the plate strains are constantly greater than those of the corresponding internal bars, reflecting the greater distance of the plates from the neutral axis. Above 30 kN the plate strains increase less rapidly than those of the internal bars suggesting that there was a slight reduction in the interface bond efficiency as the ultimate load was approached. However, the yield strain for the plates was 1650 micro-strain and strains in excess of 7000 micro-strain were reached putting the plates in the strain hardening region. Thus the slight reduction in bond efficiency at the higher load levels had no effect on the ultimate strengths achieved. Both glues performed satisfactorily, Glue A being generally the more effective.

The results for bars strains of beams series RB1 are presented in Figure-7.

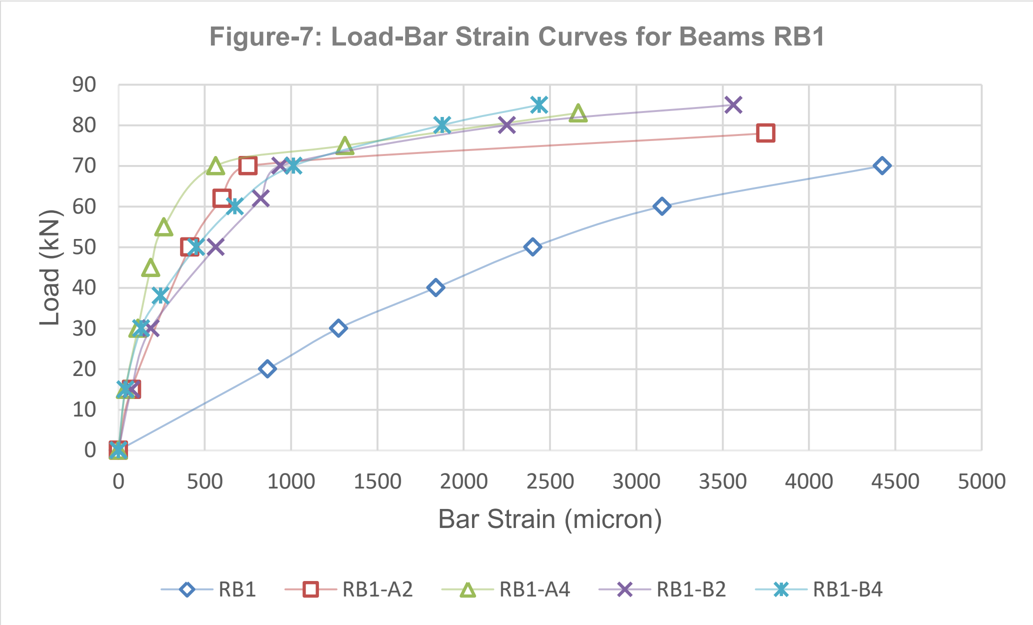


**Figure-7.** Load bar strain curves for beams RB1.

Thicker plates had correspondingly lower strains. Yield strain for the plates was not achieved in any of the beams. Strains in excess of twice the proof strain were achieved in the bars of beams RB1, RB1-A1, B1 and A2. In the other beams of series RB1 failure occurred when the bar strains were in the region of the proof strain.

## 5. CONCLUSIONS

From the results and discussions presented the following general conclusions can be made:

a) Glues with widely different stiffness's can give satisfactory performance at service and ultimate load. However, as a general rule when strengthening to satisfy service conditions stiffer glues are more effective and when strengthening for ultimate load conditions softer glues are better.

b) Mild steel plates have proved satisfactory both experimentally and in practice.

c) Deep beans in which shear is a dominant factor maybe reduced in strength if plates are used on their tension faces.

d) Flexural strength can be increased considerably by the application of tension plates. Composite action between the plates and the basic section can be achieved and the ultimate strength can be assessed by using normal reinforced concrete theory.

e) Tension plating reduces deflections and crack widths.

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