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FLEXURAL STRENGTHENING OF REINFORCED CONCRETE BEAMS USING EXTERNAL UNBONDED STEEL BARS

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ABSTRACT

The use of externally unbonded steel rods for strengthening beams in flexure was proposed as a new technique recently. This technique has advantages in speed and simplicity of installation over other established strengthening techniques. It was shown that the technique could provide useful enhancements in load capacity in all but heavily reinforced cross-sections. The present work aims to further investigation of this developed technique. Factors such as the number of deflectors used and the ratio of external to internal reinforcement areas were considered. Results showed that an increase in the ultimate strength and an increase in the stiffness were obtained using the EUR method while maintaining the traditional ductility behavior of RC beams. This gain in strength and stiffness increased as the ratio of external to internal reinforcement areas or the umber of deflectors increased. However, a well protecting method should be provided to give the external reinforcement the aimed durability requirements.

إن استعمال أسياخ الحديد الخارجية المنفصلة في تقوية الكمرات في الانحناء قد تم استحداثه كأسلوب جديد للتقوية في السنوات الأخيرة، وتتميز هذه الطريقة بالسرعة والبساطة في التطبيق عند مقارنتها بالطرق الأخرى للتقوية، وقد تبين أن هذه الطريقة توفر زيادة قيمة في كفاءة التحميل ماعدا في حالة القطاعات الكثيفة التسليح، الهدف من هذا البحث هو دراسة هذا الأسلوب الجديد للتقوية بمزيد من التفصيل ودراسة تأثير عوامل مثل عدد العناصر المؤدية لانحناء الأسياخ ونسبة التسليح الخارجي للداخلي الأداء، وقد أظهرت النتائج أن استخدام هذه الطريقة في التقوية أدى إلى زيادة في المقاومة القصوى والصلابة للكمرات المقواه مع الحفاظ على ممطوليتها، كما أن هذه الزيادة في المقاومة والصلابة ازدادت بزيادة نسبة التسليح الخارجي للداخلي أو عدد العناصر المؤدية لانحناء الأسياخ. وتتطلب هذه الطريقة بطبيعة الحال توفير الحماية اللازمة للأسياخ الخارجية لضمان استمرارية أدائها على المدى الطويل.

Keywords: Reinforced concrete; beams; strengthening; external unbonded bars.

1. INTRODUCTION

The requirement to strengthen an existing concrete structure may arise for a variety of reasons. Changes in use or in Codes of Practice, deficiencies in design and construction, or structural deterioration may all result in a need to strengthen. A variety of techniques have been developed, including plate bonding, external prestressing, overslabbing, or increasing the quantity of bonded reinforcement [1]. Cairns and Rafeeqi [1,2] proposed a retrofitting technique, namely external unbonded reinforcement (EUR), for strengthening of existing structures in service and demonstrated the viability of the technique for flexural strengthening of simply supported beams.

Fig. 1 shows the strengthening arrangement under investigation. Unbonded reinforcement is retrofitted to both sides of a member at a depth similar to that of main flexural reinforcement. The added bars are threaded and anchored by nuts bearing against transverse yokes at the ends of the beam. The bars are only lightly tensioned to overcome sag and are not prestressed. External bars are of a similar steel grade to ordinary high yield reinforcement. 'Deflectors' were fitted along the span to maintain external bars at constant effective depth [1]. To determine whether these deflectors could be dispensed with for further simplifying installation was also studied [2].

They [1,2] presented the advantages of such technique: Unbonded reinforcement offers significant advantages in speed and simplicity of installation over alternative methods of strengthening. Installation of external reinforcement to simply supported beams would be a simple operation with yokes around ends of the beam anchoring threaded rods on both sides. Minimal disruption to use would be experienced during installation.

External unbonded reinforcement retains many of the merits of external unbonded prestressed tendons but eliminates time consuming stressing operations. Clearance requirements around anchorages are reduced as access is not required for prestressing jacks, and less expensive materials are used. The greater cross-sectional area of external reinforcement makes it less susceptible to corrosion, vandalism and sabotage.

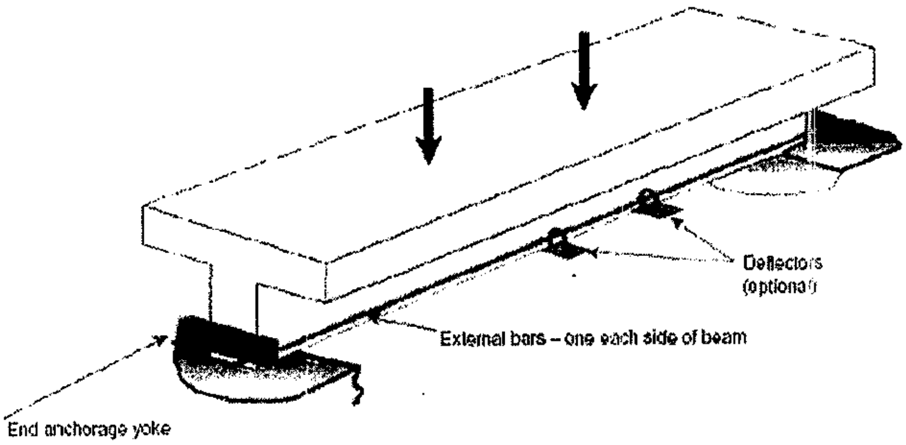

Fig. 1: Schematic illustration of the strengthening technique [1,2]

Unlike externally bonded plates, surface preparation of the concrete for installation of unbonded bars is minimal and installation is not affected by environmental conditions or the condition of the concrete substrate. Longitudinal cracking along flexural reinforcement as a result of corrosion need not require extensive patch repair prior to installation as would be required with plate bonding. Although their investigation was confined to strengthening in flexure, external bars would also enhance strength of beams deficient in shear. For sensitive structures, the method is compatible with principles of conservation which require that interventions be removable at a later date if required. As with both of these established methods, the increase in self weight of the structure is negligible and there is no appreciable reduction in headroom [1,2].

Not surprisingly, the method also has certain weaknesses when compared to alternative techniques for strengthening, and no suggestion is made that it will be appropriate in all circumstances. In particular, it will not be appropriate for strengthening of heavily reinforced cross-sections, and is likely to confer lesser improvements on serviceability performance than on ultimate strength. Results to date do suggest, however, that it could offer clear advantages in appropriate circumstances [1,2].

The normal composite interaction between reinforcement and concrete is lost when reinforcement is not bonded within the concrete section and plane section behavior is therefore no longer valid. Beam behavior changes from flexure to a flexure/tied arch hybrid. The variation in reinforcement strains throughout the span of a simply supported beam carrying two-point loads each P/2 and symmetrically positioned about midspan (Fig. 2(a)) is sketched in Fig. 2(b). The strain in the external bars is uniform throughout the span, while the variation in strain in bonded bars reflects the variation in applied bending moment throughout the span. In order to satisfy compatibility the extension of bonded and of external bars must be equal, that is, the area under the two diagrams must be the same. Midspan strains must therefore be greater in the bonded bars. External reinforcement will therefore be less effective than an equivalent area of bonded reinforcement. The ratio of strain in bonded to that in unbonded bars will depend on a number of factors. For a given strain in bonded bars at midspan, strain in unbonded bars will increase as the shear span reduces in order that deformations of the two sets of reinforcement are compatible. The shape of the bending moment diagram, the overall length of the beam in relation to its span, and the effective depth of external bars in relation to that of bonded reinforcement will influence the relationship for the same reason. The strength enhancement provided by unbonded reinforcement will also depend on the total quantity of reinforcement and the strength of the concrete as well as the proportion of unbonded reinforcement [2].

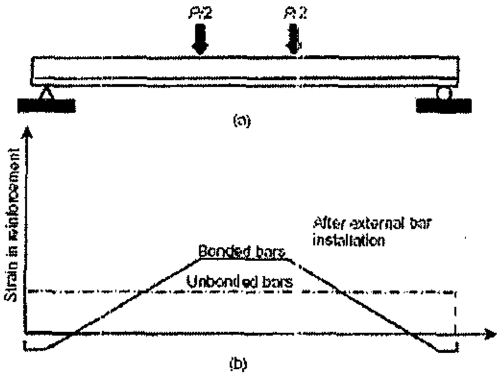

Fig. 2: Variations in strains in reinforcement throughout the span of the beam strengthened with external reinforcement [2]

The experimental program carried out [1,2] showed among other conclusions that external unbonded reinforcement could provide appreciable increases in the ultimate flexural strength of reinforced concrete beams. Lightly reinforced beams could attain greater increases in strength than heavily reinforced beams. Capacity might be increased by up to 100%, depending on the geometric ratio of the bonded bars, but only modest strength enhancements could be achieved with heavily reinforced cross-sections. The strengthened beams showed modest improvements in serviceability behavior; the increase in stiffness was markedly lower than the increase in strength. The gain in stiffness and strength could be improved by the use of deflectors to maintain external bars at constant effective depth. From the limited results presented there, deflectors appeared to be necessary for span/depth ratios in excess of 12.

A numerical model for beams retrofitted with external unbonded reinforcement has been developed by the same authors [3], based on modeling guidance presented in BS 8110 and in the CEB-FIP Model Code 90. Because external reinforcement is not bonded to the beam throughout its span, but is anchored only at the ends, normal plane section behavior assumptions cannot be used. The numerical model was based on section analysis, and incorporated non-linear material behavior and nonlinear geometric effects. The model was first validated against results from an experimental program comprising 35 physical tests on laboratory specimens. The model was then used to supplement the experimental study by exploring parameters which could not receive adequate experimental coverage.

The model predicts enhancements in ultimate strength accurately, but was less successful in the prediction of deflection. The reason for this was believed to lie in inaccuracies in representing unloading from preceding load cycles. The influence of the shape of the bending moment diagram and of span/depth ratio, parameters which were not adequately explored in the experimental investigation, were reported. Deflectors were typically calculated to double strength enhancement at shorter span/depth ratios; the benefits were greater with higher ratios. Their use will be advantageous in the majority of situations [3].

Sallam et. al. [4] studied the parameters controlling the capability of external unbonded bars technique in strengthening RC beams such as number and locations of deflectors, adding small values of prestressing, load configuration, and the effective span of the beam. Three different deflector locations with three values of prestressing were applied on two different beam sizes, which were tested under three-point bending (3PB) and four-point bending (4PB). Furthermore, the effect of the area of tensile reinforcement of the beam to the external reinforcement area was considered. External un-bonded bars increased the load bearing capacity of the control beam without decreasing its ductility. Exerting a small value of tensile stress on the external bars improved markedly the structural behavior of strengthened beams with a negligible additional effort. The prestressing improved the efficiency of the present strengthening technique in the case of 4PB more than that of 3PB. Increasing the number of deflectors improved the performance of external un-bonded bars.

Therefore, the aim of the present work was to further investigate this innovative strengthening technique through studying the structural behavior of strengthened RC beams in flexure using externally bonded steel bars. Factors such as the number of deflectors used and the ratio of the external to internal reinforcement ratio were considered.

2. EXPERIMENTAION

A group of five beams were cast in the laboratory. The first beam was considered as a reference beam and it was 15 x 25 x 250 cm in dimensions with reinforcement details as shown in Fig. 3. The other four beams were made in order to strengthen them by the EUR method. They were similar to the reference beam except that unbonded reinforcement was retrofitted to both sides of each beam at a depth similar to that of main flexural reinforcement as was detailed above in Fig. 1.

The concrete used in the fabrication of all beams consisted of type 1 ordinary Portland Cement as a binding material, ordinary gravel of maximum nominal size equal to 20 mm as a coarse aggregate, natural sand as a fine aggregate and natural drinking water. Its mix promotions were 1 : 2.3 : 3.4 : 0.45 as Portland Cement : sand : gravel : water with a cement factor of 450 kg/m3. The average 28-day compressive strength of this mix was 30 MPa.

The steel reinforcement bars were high grade steel of diameter 12 and 16 mm and mild steel of diameter 8 mm. The yield and ultimate tensile strengths were 528 and 747 MPa for the 12 mm bars, respectively, and those of the 16 mm bars were 473 and 746 MPa, respectively. Corresponding values for the 8 mm bars were 310 and 460 MPa, respectively.

Details of the test set-up are shown in Fig. 3 and the strengthening details of the strengthened beams are given in Table 1, and Fig. 1.

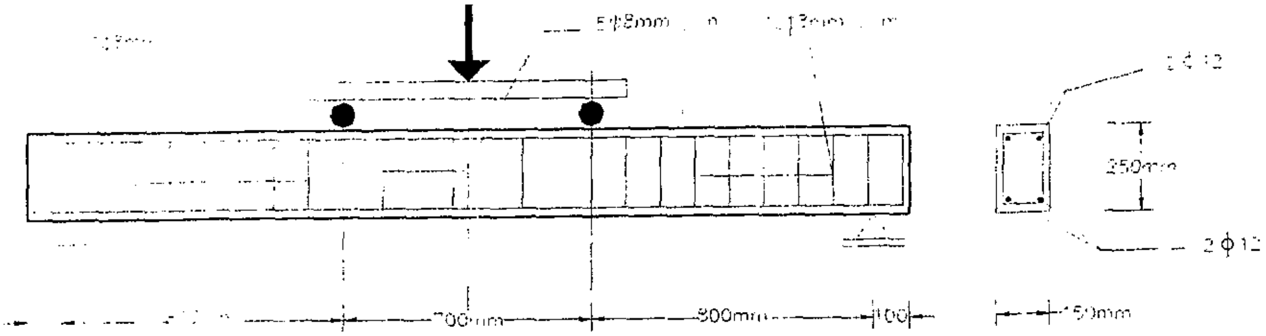

Fig. 3: Details of the reference control beam CB and the test set-up

3. RESULTS AND DISCUSSION

Table 1 and Fig. 4 show the results of this group of beams consisting of beams of the reference beam and four EUR strengthened beams. Beam CB was the reference control beam and its details and test set-up were shown in Fig. 3. This beam showed a traditional behavior of a reinforced concrete beam under loading. As the load was applied, cracks started to appear in the bottom tension side of the midspan. As the load was increased, more cracks appeared and propagated upwards in the midspan. At higher loads, additional cracks appeared in both shear spans and propagated in an inclined way towards the loading point. At a total load (P) of 64 KN failure occurred by crushing of concrete at the top side of the beam in the midspan after yielding of the tension steel as shown in plate 1. Fig. 4 shows the total load-deflection diagram for this beam up to the ultimate load, where the horizontal portion of the curve reflects yielding of the internal tension steel reinforcement.

Beam EUR 2Φ12 1 def was strengthened with two steel bars of diameter 12 mm each by the EUR method and using one deflector at the midspan of the beam (see Table 1 and Fig. 4). A similar crack pattern to that of the control beam CB was almost obtained. Higher stiffness and ultimate load of 82 kN (about 28.1 % higher than that of the control beam CB) were obtained due to strenghthening as can be seen in Table 1 and Fig. 4. However, the mode of failure obtained was characterized by a local at the right end of the beam occurring in concrete against the right yoke and followed successively and instantaneously by crushing in concrete in the midspan at the top side of the beam after yielding of the tension steel reinforcement (see Plate 2 and Plate 3). The increase in failure load of this beam in comparison to beam CB of about 28.1 % was mainly due to the increase in the tension reinforcement by the EUR method by 100 % from one side and the premature local failure at the right end of the beam from the other side.

Table 1 : Strengthening details and results of the tested beams

Beam specimen	Strengthening by the EUR method	% increase in tension reinf. w.r.t. beam CB	No. of deflectors	Ultimate load (KN)	% increase in ult. load w.r.t. beam CB	Mode of failure
CB	-	-	-	64	-	Traditional *
EUR 2Φ12 1 def	√	100	1	82	28.1	Local **
EUR 2Φ12 3 def	√	100	3	102	59.4	Local **
EUR 2Φ16 1 def	√	177.8	1	94	46.9	Local **
EUR 2Φ16 3 def	√	177.8	3	102	59.4	Local **

* Yielding of the steel followed by crushing of concrete at the top side of the midspan

** Premature local failure in concrete against yoke at one end of the beam

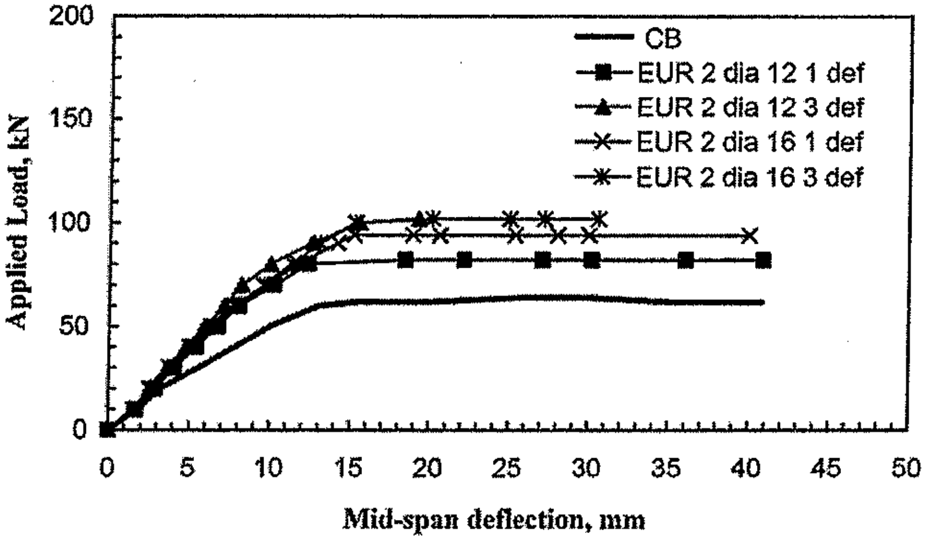

Fig. 4: Applied load-midspan deflection of the tested beams.

Beam EUR 2Φ12 3 def was similar to beam EUR 2Φ12 1 def except that three deflectors instead of one deflector were used at the midspan and at the two loading points (Table 1 and Fig.4). As expected, an almost similar crack pattern and mode of failure were obtained. The load-deflection diagram of this beam in comparison to those of the previous two beams is shown in Fig. 4. It can be seen that a slight increase in the stiffness compared to beam EUR 2Φ12 1 def and a higher ultimate load of 102 kN (about 59.3 % higher than that of the control beam CB and about 24.4 % increase in comparison to beam EUR 2Φ12 1 def) were obtained when failure occurred by local concrete failure at one end of the beam followed by concrete crushing in the midspan at the top side of the beam after yielding of the tension steel. It can also be seen that failure occurred at a lower midspan deflection due to the increase in the tensile force in the EUR bars as the deflectors enforced these bars to deflect with the beam. As a result, failure occurred at an earlier level of deflection. Hence, the increase in the number of deflectors resulted in that the external unboded reinforcement followed a path closer to that of the internal steel reinforcement during loading and thus more ultimate strength and a slight increase in the stiffness were obtained.

Beam EUR 2Φ16 1 def was similar to beam EUR 2Φ12 1 def but having two external bars of diameter 16 mm each instead of 12 mm diameter bars in the other one (Table 1 and Fig. 4). A similar cracking pattern, load-deflection behavior, and mode of failure were obtained except that the beam failed at a higher ultimate load of 94 kN (about 46.9 % higher than that of the control beam CB and about 14.6 % increase in comparison to beam EUR 2Φ12 1 def) when local failure occurred at one end of the beam followed by the crushing of concrete in the midspan after yielding of the tension steel. This increase in the failure load of this beam in comparison to beam EUR 2Φ12 1 def was mainly due to the increase in the EUR area by about 77.8 %. However, the gain in the stiffness was markedly than that of the strength.

Beam EUR 2Φ16 3 def was similar to the previous beam beam EUR 2Φ16 1 def but having three deflectors instead of one deflector (Table 1 and Fig. 4). They were located at the midspan and at the two loading points. Likewise, a similar cracking pattern, load-deflection behavior, and mode of failure were obtained for this beam similar to the previous one. However, a slight increase in the stiffness compared to beam EUR 2Φ16 1 def and a higher ultimate failure load of 102 kN were obtained (about 59.3 % higher than that of the control beam CB and about 8.5 % increase in comparison to beam EUR 2Φ16 1 def) when failure occurred by local concrete failure at one end of the beam followed by concrete crushing in the midspan at the top side of the beam after yielding of the tension steel. It can also be seen that failure occurred at a lower midspan deflection due to the increase in the tensile force in the EUR bars as the deflectors enforced these bars to deflect with the beam. As a result, failure occurred at an earlier level of deflection.

4. CONCLUSIONS

Within the scope of this study the following conclusions can be drawn:

1. The unbonded external reinforcement (EUR) technique presents a good method for external strengthening of RC beams.
2. An increase in the stiffness and ultimate strength were obtained using the EUR method while maintaining the traditional ductility behavior of RC beams.

3. When the area of external strengthening was increased from 100 % to 178 % of the internal reinforcement area, the gain in ultimate strength increased but with a smaller rate from 28 % to 47 % of that of the reference unstrengthened beam before local failure occurred at one end of the beam in both cases,, while the gain in stiffness was markedly lower than that in the strength.
4. Increasing the number of deflectors from one to three did increase the ultimate strength of the beam by 24 % and 9 % when the area of external strengthening was 100 % and 178 % of the internal reinforcement area, respectively, before local failure occurred in both cases. However, only slight improvement in stiffness was recorded.
5. A more efficient performance would be obtained if local failure of concrete against the yoke at the ends of the beam could be avoided.
6. This technique provides speed and simplicity of installation over other established strengthening techniques, but however a well protecting method should be provided to give the external reinforcement the aimed durability requirements.

5. REFERENCES

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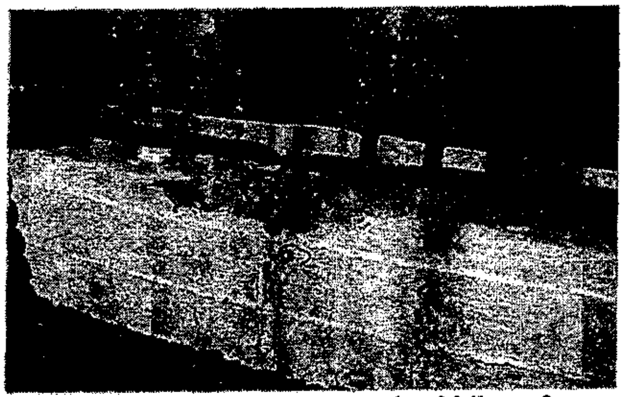

Plate 1: Crack pattern and mode of failure of Beam CB

Plate 2: *Local mode of failure* of beam EUR 2Φ12 1 def at the right end

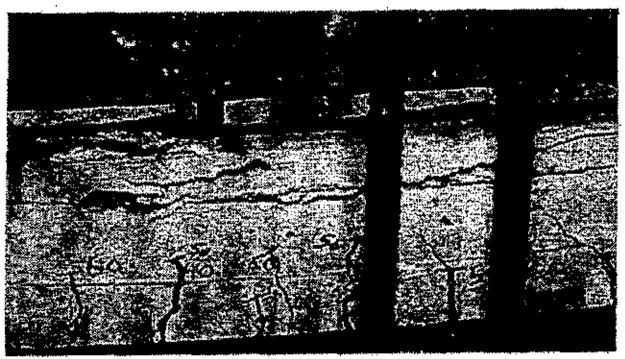

Plate 3: *Crushing mode of* failure of beam EUR 2Φ12 1 def at the midspan after yielding of the tension steel