REPAIR AND STRENGTHENING OF REINFORCED CONCRETE PLATES BY EPOXY-BONDED STEEL PLATES

D.A. Van Gemert (I)

SUMMARY

The paper deals with the repair and strengthening of damaged reinforced concrete elements by means of epoxy bonded steel strips. Experimental results of the stress distribution in the adhesive layer in laboratory test specimens are given. From the experiments, design rules are drafted for the external reinforcements and their anchorage to the concrete.

The retrofitting of a concrete floor plate in an apartment building, severely damaged by a gas explosion, is discussed. As a second case study the repairing of a three span prestressed concrete bridge where, due to corrosion, some of the prestressing cables were broken, is presented.

INTRODUCTION

The repairing, retrofitting and strengthening of reinforced concrete structures, damaged by earthquake, calls for the largest possible number of repairing techniques, from which the most effective one will be chosen in each particular repairing case. The repairing of a concrete structure has always been very difficult, and adequate solutions have often entailed extensive works. The development of a wide variety of artificial resins, especially epoxy based adhesives, has given rise to new and entensive possibilities for repairing concrete constructions. Research on this subject was started by R. L'Hermite and J. Bresson (Ref. 1).

The principle of the method is quite simple :steel strips or steel elements with complex shapes are glued to the concrete surface by means of epoxy adhesive, creating a concrete-glue-steel composite element. In this way it is possible to give a higher strength to the concrete elements against bending moments and transverse forces, as well as to increase the stiffness of the elements, so that deformability decreases. The glue itself must show very high chemical and mechanical properties. Until now only epoxy adhesives are convenient for gluing steel to concrete : they show an excellent bond both to concrete and to steel, their shrinkage at hardening is practically zero, and they are highly chemically inert. The preparation of the steel consists in grit-blasting of the area in contact with the glue to level SA3. The concrete surface is prepared by grit-blasting or by manual grinding, to remove the weak external cement layer and to expose a clean and sound concrete surface for gluing. The glue is applied to the steel plate, which is then gradually pressed against the concrete, until no more adhesive is squeezed out. The thickness of the adhesive layer varies between zero and 2-3 mm. The quality control problem of the appropriate epoxy glues and the conditions of application are discussed in Ref. 2.

A test programme was set up at the Reyntjens Laboratory of the Katholieke Universiteit at Leuven to provide practical information about the stress

(I) Prof. Dr. Ir., Department of Civil Engineering,
Katholieke Universiteit, Louvain, Belgium.

distribution in epoxy bonded steel-concrete joints and to look for safe and economic design rules.

The experiments were designed to simulate the real stress situation in the practical applications. Two main types of tests were carried out : pure shear tests and shear-bending tests. The results reported herein are found with the epoxy adhesive EPICOL U (N.V. Resiplast, Belgium). The conclusions, however, are valid for various other epoxy adhesives, available on the Belgian market and tested in our laboratory.

PURE SHEAR

A special test piece is developed for this purpose. The test piece is an unreinforced concrete prism with the dimensions 150 mm x 150 mm x 300 mm, Fig. 1. Two pairs of steel plates are glued on the opposite sides of the prism. One pair has a width of 100 mm, and all the measurements are made on these plates. Before testing, two longitudinal cuts are sawed alongside the plates to get a well-determined surface under loading. The two other plates are 150 mm in width, and serve as fixing elements. The test piece is loaded in a specially designed frame by an upward and downward force, Fig. 2.

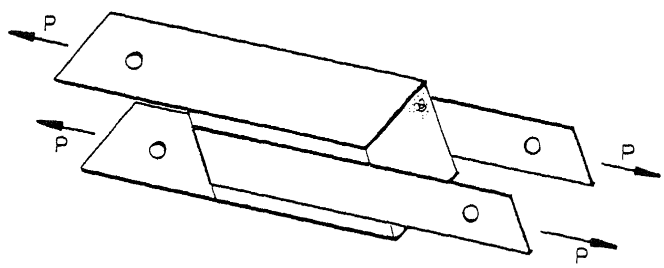


Fig. 1 : Test piece for pure shear test

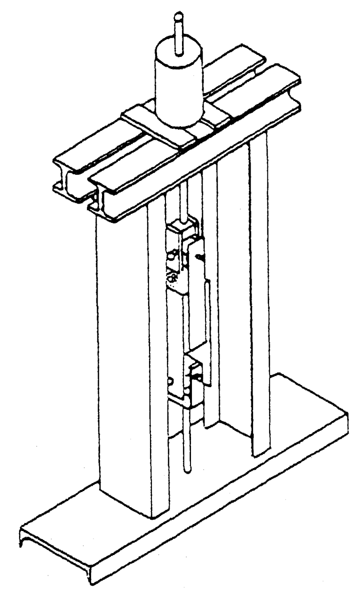


Fig. 2 : Testing apparatus

The distribution of the forces in the plates and of the shearing stresses in the adhesive layer are obtained from strain-gauge measurements over the length of the plates. The strain-gauges are placed on the outside and innerside of the plate, which is later glued to the concrete. This is necessary because the deformation of the concrete block causes secondary strains which may disturb the normal force strains. Typical results of the measured stress distribution are given in Fig. 3 and 4 for a test piece showing an ultimate load P of 87 kN per plate. In the region of low tensile forces (Fig. 3, curve 1) there is an exponential drop of the resultant force in the plate and of the shearing stresses in the adhesive. In the first zone shearing stresses reach a maximum of about 2,5 N/mm2, while at a greater distance and at higher loads they can reach 5,5 to 6 N/mm2.

At higher loads (curves 2 and 3 in Fig. 3) the stresses in the initial zone of the anchorage are not growing equally with the applied force, but they are reduced by cracking of the concrete. In the initial zone of the joint the shearing stress increases linearly with the applied force P until it reaches a value of about 1,5 N/mm2, Fig. 5. This value corresponds to the concrete tensile strength at the surface, measured by the pull-off method, Fig. 6. The tensile strength at the surface is much

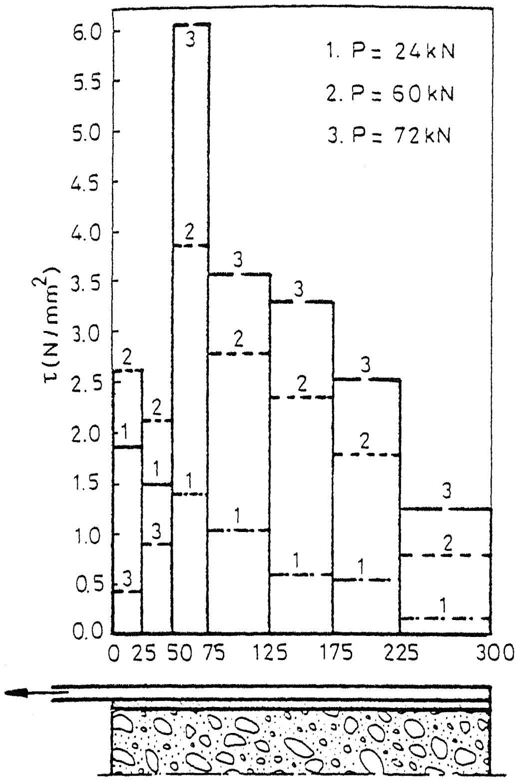


Fig. 3 : Average shearing stresses at a first loading

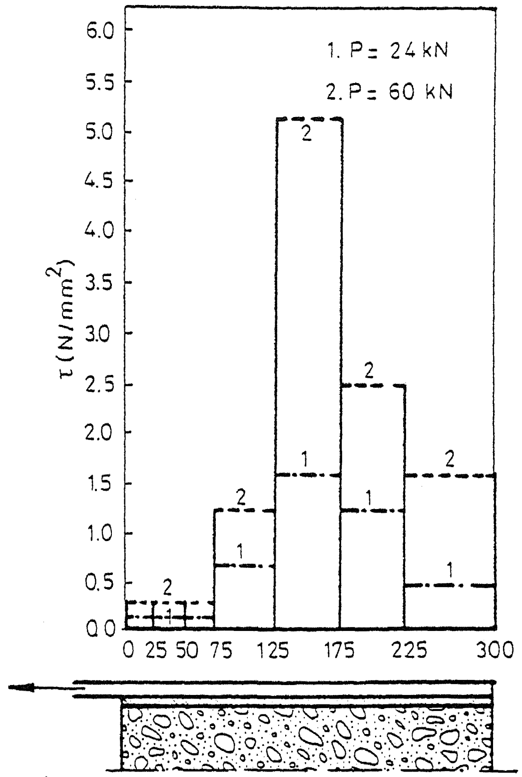


Fig. 4 : Average shearing stresses in a cracked specimen

smaller then the direct tensile strength, measured by a tensile test on a cylinder or prism. No cracking of the concrete is observed up to this value

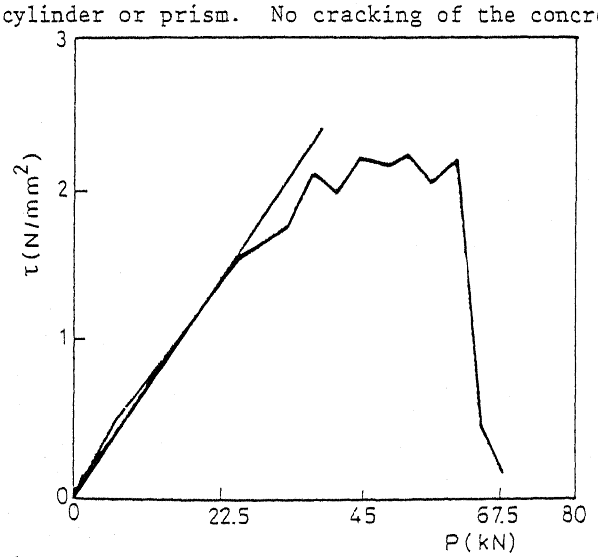


Fig. 5 : Shear stress in initial zone of joint

of the shearing stress. From this it may be concluded that in a safe pure shear design the shearing stress in the initial zone may not exceed the surface tensile strength. Under ultimate load conditions the shearring stress distribution is given in Figure 4. Stresses now reach values of 5 to 6 N/mm2, which is the direct tensile strength of the concrete.

Based on these experimental data, we apply the following design rules in pure shear.

- Under service load P_s a triangular stress distribution with a maximum at A is assumed, Fig. 7.a. The maximum value will be limited to the characteristic surface tensile

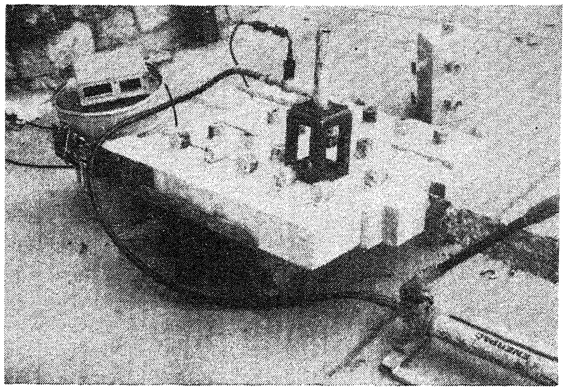


Fig. 6 : Pull-off test for measuring tensile strength at the surface of concrete

strength $R_{sk} = R_{sm} - 1,64$ s. s is the standard deviation calculated for the test results. The value L_1 of the anchoring length can now be calculated from the equilibrium of longitudinal forces.
- At ultimate load P_u we assume a triangular distribution with a maximum in the middle, Fig. 7.b. This distribution nearly approximates the measured stress distribution of Fig. 4 in a cracked specimen. The maximum value is now taken to be equal to the characteristic value R_{bk} of the direct tensile strength of the concrete. With these assumptions a second value L_2 for the anchoring length can be calculated, and the greater value of L_1 and L_2 will be chosen.

BENDING SHEAR

The calculation of the area of the externally bonded steel plates in pure bending is extensively discussed in Ref. 3. From the experiments we concluded that, for the analysis of the stress distribution over the cross-section, one may assume that there is a perfect connection between the external steel and the concrete element, without any shifting. Therefore the design of the section may proceed on the usual manner. In Ref. 3 design graphs are presented, which give the area of the external reinforcement as a function of the characteristics of the section and of the desired degree of strengthening. These graphs are available on simple request.

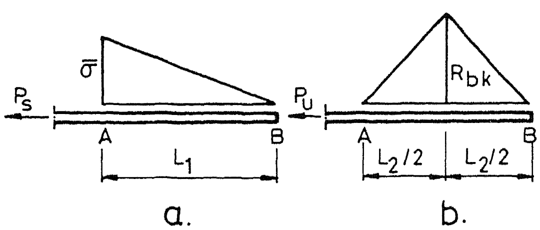


Fig. 7 : Assumed stress-distribution
a. at service load
b. at ultimate load

In bending problems the shearing stresses in the adhesive layer between the external reinforcement and the concrete are partly due to the variation of the bending moments and partly to the introduction of forces in the anchoring zones, Fig. 8. A typical distribution of the shearing stresses in the anchoring zone is given in Fig. 9. The design of the anchorage is now reduced to the pure shear case in the following way. The critical zone is situated near the free end A of the plate. The force $\Delta P = \sigma_A \cdot A_e$ is calculated, where σ_A is the theoretical tensile stress in the external plate at the end A, and A_e is the cross sectional area of the external steel. This force ΔP is the compressive force which much be superposed to the theoretical forces in the external plate following the scheme of Fig. 8, to get the real force distribution with zero force at the free end A. Under service conditions, the joint behaves elastically and we assume that the compressive force ΔP causes a triangular shearing stress distribution wit a maximum τ_a at A.

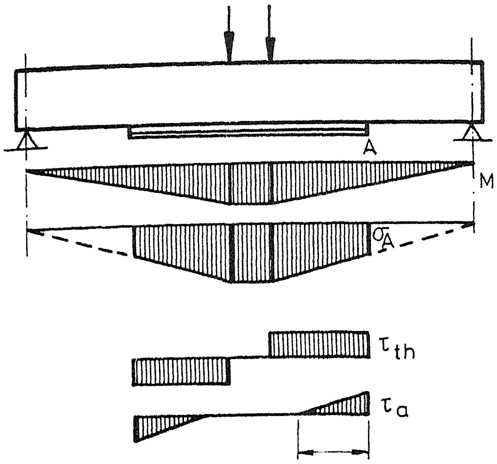


Fig. 8 : Moments and stresses in bending

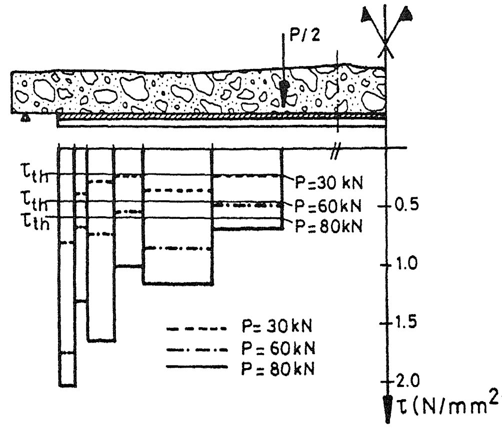


Fig. 9 : Typical shearing stress distribution in anchoring zone

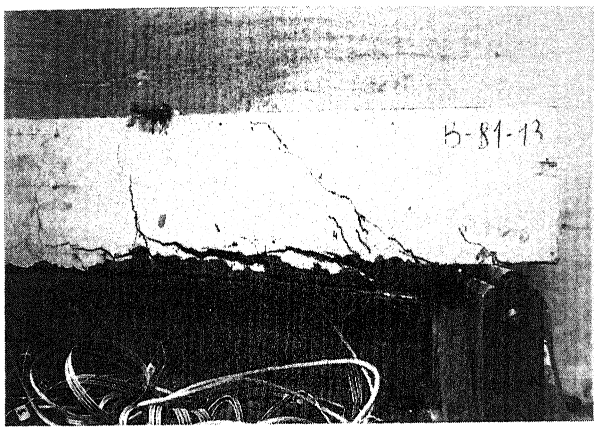


Fig. 10 : Failure pattern of beam, strengthened by epoxy bonded plate

These shearing stresses are added to the theoretical shearing stresses τ_{th}. The resulting value (τ_{th} + τ_a) may not exceed the characteristic value R_{sk} of the surface tensile strength of the concrete. With ΔP and the value (τ_{th} + τ_a) the anchoring length L can be calculated. If this length or the shearing stresses become too large, the thickness of the plate must be reduced and the width of the plate must be enlarged. At the free end A the re-entering edge causes stress concentrations and accelerated cracking in the concrete layer between the external and internal reinforcements, Fig. 10. To avoid this premature cracking, a dowel can be placed in order to anchor the free end of the plate to the interior concrete of the beam or slab.

RETROFIT OF DAMAGED CONCRETE SLAB

Due to a gas explosion in one of the apartments of an apartment building in Tienen (Belgium), four reinforced concrete slabs were severely damaged. Two of them had to be removed and replaced by new plates, the other two are repaired by means of externally bonded steel plates. The repairing works will be discussed for one of the plates. The plate has dimensions 5,8 m x 8,9 m and a thickness of 110 mm.

The deflections of the plate, measured after the explosion, are shown in Fig. 11. The maximum deflection was 67 mm. For a thorough repair the deflections of the plate were to be removed. This was done with hydraulic jacks,

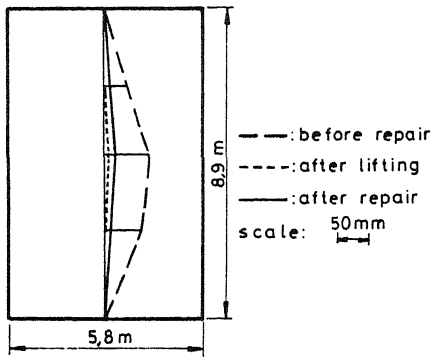


Fig. 11 : Deflections of the plate

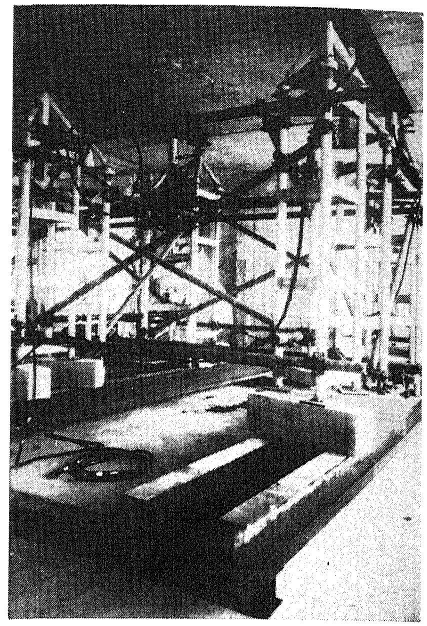


Fig. 12 : Supporting structure with jacks

mounted on a special supporting steel-tube structure, Fig. 12. Next to each jack was placed an adjustable screw. During and after the lifting operation they served to secure the plate in the lifted position. With the hydraulic jacks the plate was put back to a nearly horizontal position, shown in Fig. 11 by the dotted line. At lifting new cracks appeared at the top side of the plate. To prevent these cracks from closing again when the supporting structure was taken away, they were filled with a low viscosity epoxy resin. Given the large width of these cracks, it sufficed to pour the resin on the plate and to spread it over the plate surface. The steel strips were now glued to the bottom face of the plate with the epoxy glue EPICOL U. In this case the steel strips had a section of 5 mm x 250 mm. The distance between the longitudinal axes of the strips was 800 mm. This area of the cross section of the strips was mainly determined by the limitation of the deflections. After a hardening time of seven days the epoxy glue obtains its final strength, and the supporting structure may be removed, Fig. 13. At the removal of the supporting structure the plate underwent a maximum deflection of 13 mm. The final deflections are given in Fig. 11. The deflections corresponded to the calculated values. The plate was therefore considered "good for service".

Fig. 13 : Repaired plate

REPAIR OF TWO PRESTRESSED BRIDGES

Two bridges over the Nete-canal at Lier (Belgium) (Fig. 14), constructed in 1955, have been repaired in 1980 (Ref. 4). Due to corrosion the bridges had lost part of their prestressing. That loss of prestressing was mode good partly by a glued reinforcement along the axis of the beams, partly by a supplementary external prestressing. On the anchorages of these prestressing cables, external stirrups were glued to take up the splitting forces. The efficiency of the glued reinforcements at these imaginary end-blocs was tested in the Reyntjens Laboratory on test specimens having the same T-section as the beams of the real bridges, Fig. 15.

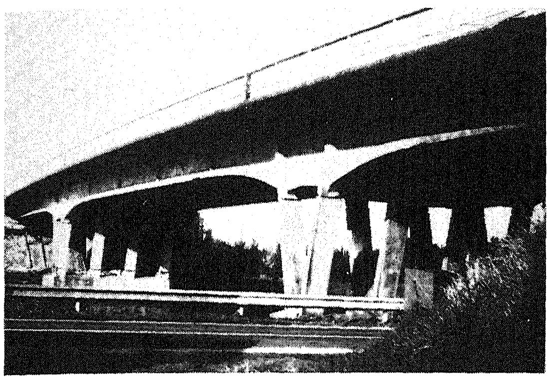
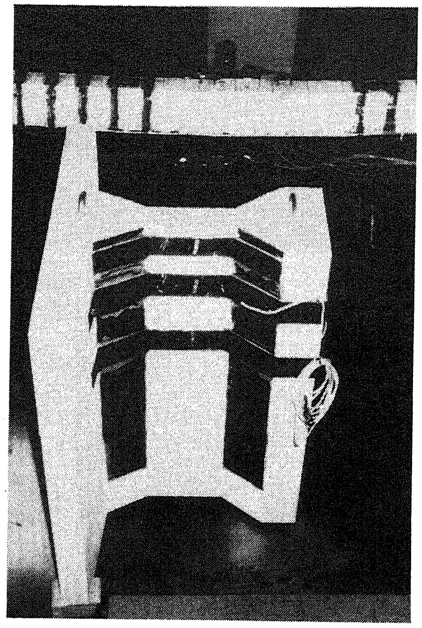


Fig. 14 : Bridge over Nete-canal at Lier (Belgium)

Three test elements were made : one reference element without glued reinforcements, one element with glued strips of 125 mm in width and one element with strips of 250 mm in width. The load was applied uniformly distributed over the central web of the T-section. The tests showed that, even with this complex configuration, concrete and steel act as one composite material.

The rupture load of the reference element was 2320 kN, the rupture load of the element with small strips was 3000 kN, and that of the element with large strips 3680 kN. The prestressing force being 900 kN, these results indicated that a sufficient safety factor was available with the anchoring system of the additional external prestressing cables.

A second series of tests consisted of cyclic loading tests on two prestressed beams, reinforced with a double layer of glued steel plates. The cross section of the beams was 300 mm x 250 mm. A prestressing force of 350 kN was applied by means of one cable, type BBRV-B33, in order to avoid cracking of the concrete in the tensile zone. The glued reinforcements consisted of two plates with cross-section 5 mm x 2000 mm, and with lengths of 5 m and 4 m. The beams were loaded in a four point bending test set-up, Fig. 16. The maximum load was taken in such a way that the maximum stress in the steel strips became 40 N/mm2, the same value as in the real bridges. The loads varied sinusoidally between 5 kN and the maximum load. The frequency was 30 cycles per minute. The beams were subjected to 500.000 cycles, to check the co-operation between the two steel plates in the double layer of glued reinforcements, and to control the durability of the glued connection at repeated loading. The tests showed that no redistribution of stresses took place by deformations in the glue or by any failure of the glued connection. The results of the tests consolidated the confidence in the repair method by means of epoxy-bonded steel strips. In 1983 a third similar bridge over the Nete-canal will be repaired in this way. Whereas bridge support movements with corresponding changes in prestressing level are always to be expected at earthquakes, the repair method by means of epoxy bonded steel strips can offer a valuable alternative.

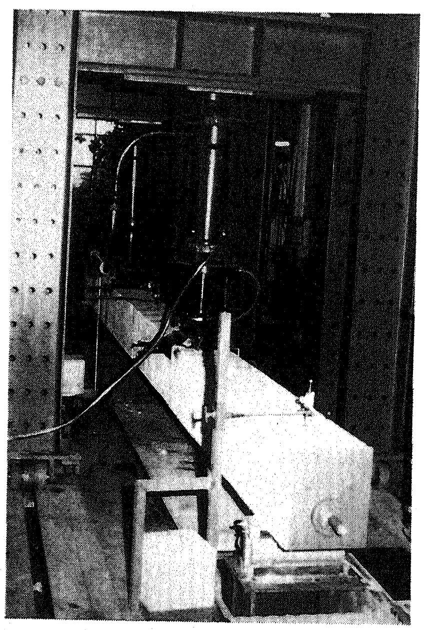


CONCLUSIONS

Epoxy-bonded external steel reinforcements have proved to be reliable structural elements not only in laboratory tests but also in many practical applications. The design rules, derived in this paper, may be used in a wide range of applications. Especially in the field of restoration and retrofitting the system is competitive for reinforcing damaged structures, not only on the financial side but also because the repairing operation can be executed in a short time.

Fig. 15 : End-bloc, created by means of glued stirrups

Fig. 16 : Cyclic loading test set-up



REFERENCES

1. Bresson J. : Nouvelles recherches et applications concernant l'utilisation des collages dans les structures. Annales de l'ITBTP, série BBA/116, 1971, France.
2. Van Gemert D. : Execution and control of epoxy bonded external reinforcements. S&A-publication nr. 5 'Repair of concrete constructions'. Betonvereniging Zoetermeer, The Netherlands, 1983 (in Dutch).
3. Van Gemert D., Vanden Bosch M. : Design of externally bonded steel plate reinforcements for elements, loaded in bending. Tijdschrift der Openbare Werken van België 1982 (in Dutch).
4. De Buck J., Van Essche Th., Van Gemert D., Gamski K. : Design, analysis and experimental investigation of the repair of two prestressed bridges. Tijdschrift der Openbare Werken van België, 1981 (in Dutch and in French).