Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 73/1/73/2 (1995)

Artikel: Strengthening of reinforced concrete beams by external reinforcement

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DOI: https://doi.org/10.5169/seals-55330

Strengthening of Reinforced Concrete Beams by External Reinforcement

Renforcement de poutres en béton armé par précontrainte extérieure

Verstärkung von Stahlbetonbalken mit angeklebten Stahllamellen

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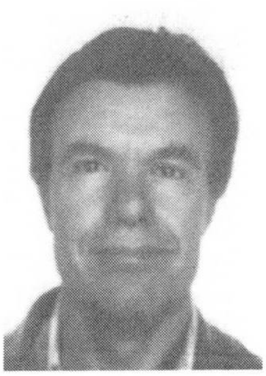

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SUMMARY

The design criteria and the methods of analysis followed in the strengthening of a reinforced concrete structure using external steel plates bonded to the existing members by means of anchor bolts and injected epoxy resin are presented. The results of the strengthening were confirmed by load tests carried out before and after the intervention. The strengthening technique is described, along with job planning and quality control procedures and data on job productivity.

RÉSUMÉ

La conception et la méthode de calcul pour le renforcement d'une structure en béton armé au moyen d'une armature extérieure en tôle d'acier attachée au béton par des boulons d'ancrage et injection d'une résine époxide sont présentés. Les résultats du renforcement ont été confirmés par des essais de charge avant et après l'intervention. La technique de renforcement, la planification et l'organisation des travaux sont présentés, ainsi que des données sur les rendements obtenus.

ZUSAMMENFASSUNG

In diesem Beitrag werden der Entwurf und die Berechnungsmethode vorgestellt, die man zur Verstärkung einer Stahlbetonkonstruktion anstellen muss, bei der eine Aussenbewehrung angewendet wird, die aus Stahlplatten besteht und durch Stahldübel und eine Epoxidharzeinspritzung im Beton fixiert wird. Die Wirksamkeit der Verstärkung wurde durch Lastproben bestätigt, die vor und nach dem Eingreifen durchgeführt wurden. Es werden auch die angewandte Technik, die Planung, Organisation und Qualitätskontrolle der Arbeit und auch einige Daten über die erreichten Ergebnisse beschrieben.

1. INTRODUCTION

In order to correct some design shortcomings, the reinforced concrete structure of the Central Post Office of Lisbon was recently subject to an important strengthening intervention.

The building has two large reinforced concrete floors consisting of a slab 0.22 m thick, supported by a grid of beams spaced 4.5 m. The main beams with a 13.5 m span are supported by circular columns. The building is subdivided by expansion joints in substructures of 40.4 m x 36.0 m (Fig. 1).

Regarding the improvement of the live load capacity and the seismic resistance of each substructure, the central columns were strengthened by jacketing and the beams by the addition of an external reinforcement consisting of bonded steel plates.

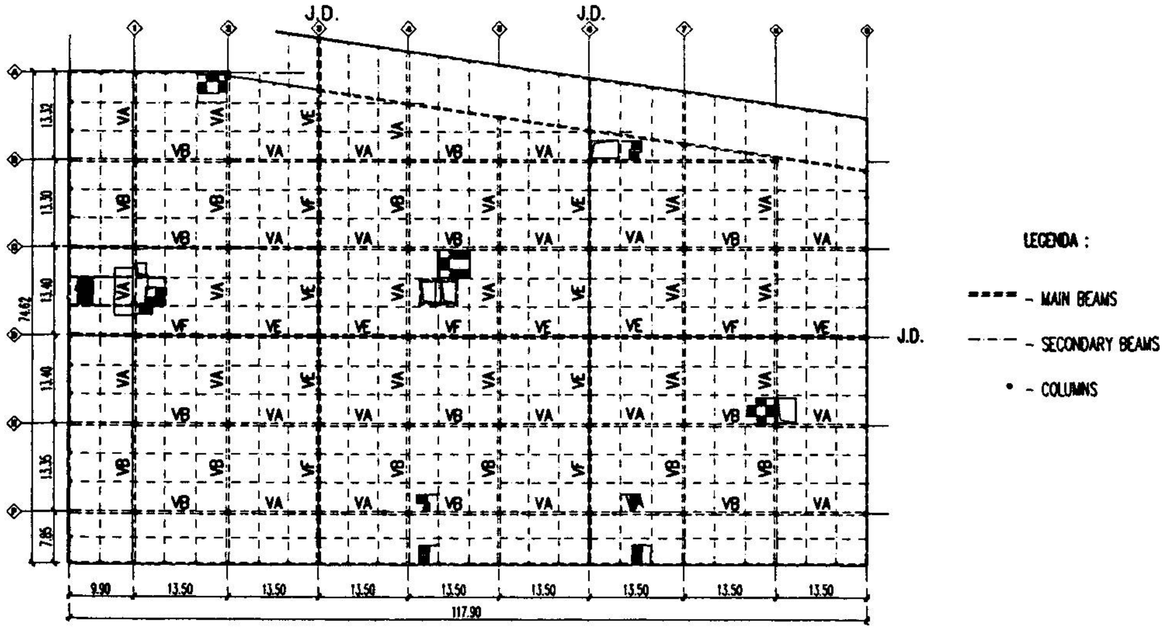

Fig. 1 - Floor level 2 - Structure

In the first phase of the project, involving the floor area of 6 600 m², over 1 500 m² of concrete beam sides were lined with 125 000 kg of steel plates and angles, around 9 m³ of epoxy resin (both for sealing mortar and injection) and around 25 000 anchor bolts were used.

2. STRUCTURAL ASSESMENT

The need to introduce new equipments in the building and the existence of systematic bending and shear cracking lead to the decision of performing an assessment of the structure safety levels.

A three dimensional bar linear elastic analysis was performed of a substructure 36 m x 40.5m with a discretisation of bar elements spaced 1.5 m. From that study, the systematic cracking was explained, as existing long term service deflections of 5 cm was estimated and the checking for the ultimate level states showed that the existing reinforcement was not enough in the critical regions of all structural elements. In some cases it was actually less than 50% of what is required to ensure the code safety levels.

The decision to strengthen the building structure both to increase its live load carrying capacity and its seismic resistance was taken by the Owner, as a result of these findings.

3. SELECTIVE STRENGTHENING AND REDESIGN

The need to maintain the strategic building in service during repairing, the difficults in increasing the beam dimensios ane the existence of a good quality concrete lead to the choice of strengthening the grid by external steel reinforcement.

The need for a significant strengthening of the columns (both the longitudinal reinforcement and stirrups needed to be incresed) lead to the choice of a jacketing solution with ordinary reinforcement and microconcrete. This paper refers only to the strengthening of the building floors.

A selective strengthening was adopted according to the following methodology, as illustrated in Fig. 2.

- The slab was assumed as a series of continuous panels 4.5 m x 4.5 m supported in the grid mesh. The bending moments obtained in this model, usual in building design, are much lower than those obtained in the FEM model where the global behaviour and different stiffness of the main and secondary beams is important. On the basis of this criteria and the acceptability of the structural model, no strengthening of the slab was required.

- For the main and secondary beams the slab load transfer was considered consistently with the slab model and to avoid the need to strength for the negative flexure resistance, redistribution was considered and the strengthening concentrated in the beam soffit.

The levels of redistribution of the linear elastic response are higher than those usually adopted for the design of new structures but are considered acceptable and supported by research which nevertheless requires deeper studies and tests.

Due to the concentration of the existing reinforcement in the beam soffit it was decided to locate the external steel in both sides of the web avoiding difficulties in the application of the mechanical bolts.

The strengthening was dimensioned by applying the monolitism coefficient technique, using the previous experience in designing and testing similar structures and the steel/resin/concrete connection.

Due to the need to restrict the extension of this paper, only bending resistance is refered to, although the grid needed also strengthening for shear.

4. EXTERNAL REINFORCEMENT STRENGTHENING TECHNOLOGY

The strengthening method used in the Lisbon Post Office job has been applied by the contractor in a large number of projects since 1983 with very satisfactory results.

It consists of an improvement of the *plate bonding* technique, allowing for a certain number of advantages in terms of ease of installation and quality of the final product (see Fig.3).

Concrete surfaces are treated using light pneumatic needle hammers, in order to remove surface laitance, loose particles and increase its the roughness.

Steel surfaces are shotblasted in shop and protected with polyethylene film for transport and handling. Protection films are peeled off immediately prior to final installation.

After surface preparation, the reinforcing steel plates are installed free of adhesive, using high strength steel bolts placed into holes drilled in the concrete member. If necessary, a steel bar detector can be used to avoid the rebars when drilling.

The epoxy bonding agent is a very low viscosity liquid which is injected continually, using two component electrical pumps, in the air gap between steel and concrete.

To allow for complete confinement of the air gap, plate boundaries and bolt heads are previously sealed with an epoxy mortar.

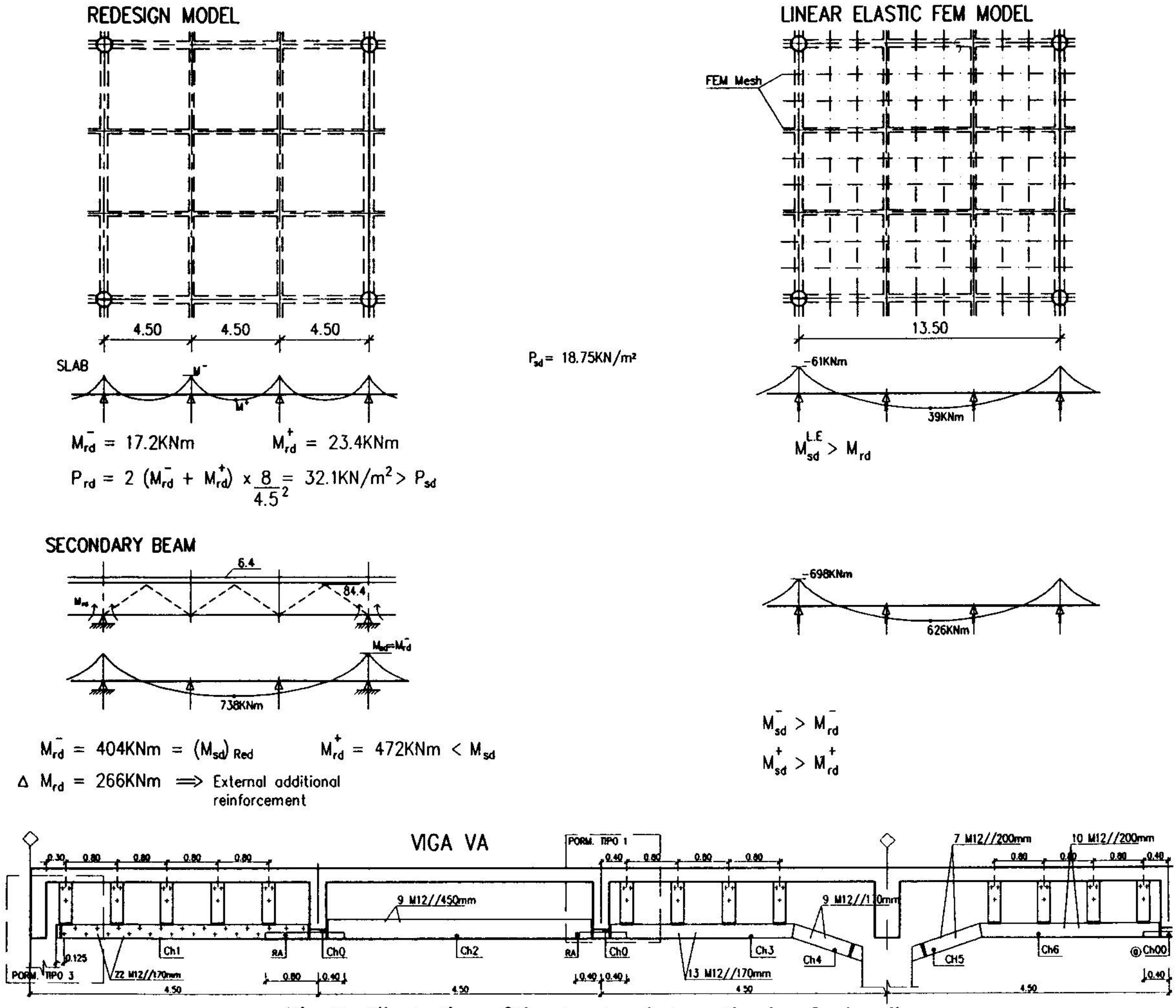

Fig. 2 - Illustration of the structural strengthening for bending

Small diameter tubes are left at chosen locations around the plate boundaries. The injection is made through the lower tubes, which work as injection ports, as the enclosed air escapes through the higher tubes, which work as vents. As soon as the resin shows in the vents flowing continuously without air bubbles, the vents are blocked to allow for some pressure build up in the liquid resin. This facilitates the penetration of resin into the small cavities and cracks in the concrete surface, allowing for a good bond. The injected resin also penetrates at least in the outer portion of the annular space around the steel anchor bolts, enhancing its slip resistance and allowing for immediate mobilization of the plate reinforcement when the beams are loaded. Thickness of adhesive film is kept to a minimum.

A redundant shear connection is thus accomplished between steel plate and concrete: by mechanical grip (anchor bolts) and by adhesion (epoxy bonding agent).

Fire resistance is increased, as the mechanical connection acts as a back up which is not easily affected in the event of a fire.

After hardening of the resin the plastic tubes are broken off and the plates coated with the fire resistant paint for additional protection.

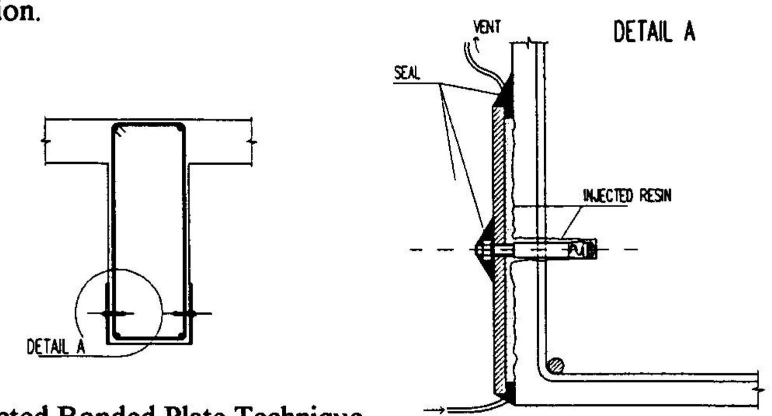

Fig. 3 - Injected Bonded Plate Technique

The low viscosity injected epoxy resin STAPOX IJ was developed in a cooperative program between STAP and LNEC. Its main mean characteristics are the following:

Yield stress in tension - 53 MPa ; Modulus of elasticity - 3570 MPa
Elongation at break - 2.0%; Yield stress in compression - 112 MPa

5. JOB PLANNING, PRODUCTIVITY AND QUALITY CONTROL

One very important constraint was imposed by the Owner on the strengthening project, as the Post Office station was to be kept in operation during the execution of the project.

Sorting machines and other postal processing equipment difficult to remove had to be protected in order to avoid damage. Work areas were sequentially made available, in accordance with the operational needs of the Owner.

Utilities had to be temporarily removed or displaced in each work area, to allow for access to the beams to be strengthened. Some cumbersome utilities as ventilation ducts difficult to remove were only loosened and lowered to allow access to reinforced concrete members.

A total of around 30 000 man hours were spent on the first phase, with the following distribution:

Task	Man hours	Productivity (h/m^2)
Concrete surface preparation	5 100	3.4
Steel plate manufacture and installation, incl. welding	15 400	10.2
Plate sealing	5 700	3.8
Resin injection	2 000	1.3
Other	1 600	1.1
Total	29 800	19.8

The 1 500 m^2 of steel plate reinforcement were completed in a delay of 5 months.

A quality control system was put in practice, involving a number of laboratory and "in situ" tests, in order to meet the high standards required by the Post Office and to ensure the reliability of the strengthening work.

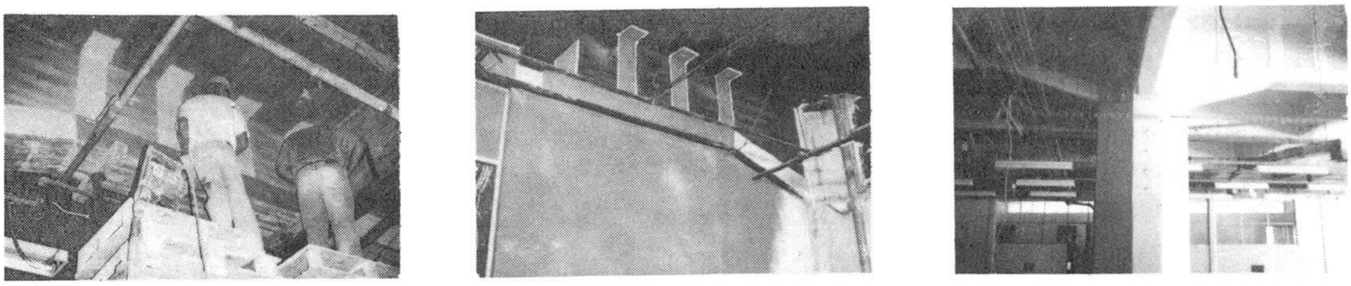

Fig. 4 - Strengthening by plate bonding - details of execution

The laboratory tests on the resin batches are standardized and don't deserve any particular mention. For the site quality control, two types of resin samples were routinely collected for testing:

a) 31 mm diameter cylinders (9 cylinders for each beam).

b) 220 x 220 x 4 (mm) plates (3 for each 200 l drum of epoxy resin).

c) Specimens consisting of three steel plates bonded by injected epoxy resin in two contact areas of 50 x 100 mm², each with a 2 mm epoxy film.

The cylinders allowed for immediate control of resin set time. After setting, its hardening was also controlled using the Barcol hardness instrument. Finally the cylinders were subject to a regular compression test, up to failure.

As for the 4 mm plates, they were used to cut out resin specimens for tensile tests, also up to failure.

The yield shear bond stress between the steel plates and the resin was 4.05 MPa (average).

In order to assess the results of the strengthening work, two load tests were also carried out on the same panel of the concrete floor, before and after the strengthening. A load of 3.5 kN/m² was applied, first in a central panel of 4.5 x 4.5 m², then over one of the main concrete beams, in a 4.5 m strip over its whole length. A reduction of the beam deflections was recorded as shown in Fig. 5.

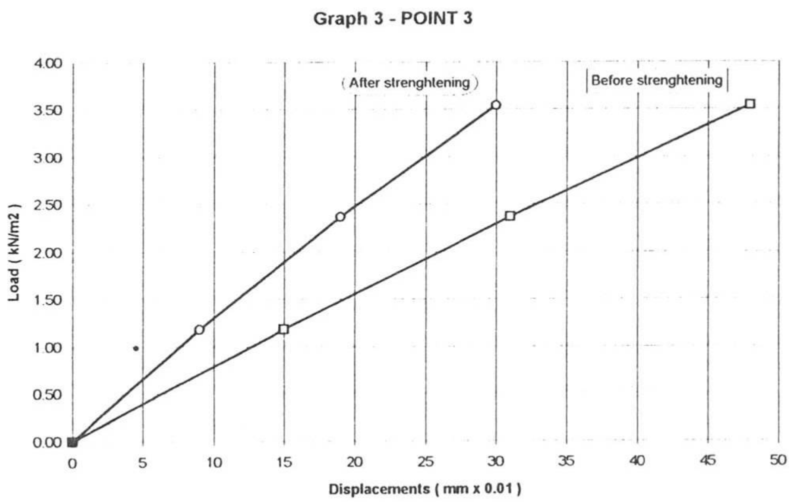

Fig. 5 - Load Test - Before and after strengthening