# Force transfer in epoxy bonded steel/concrete joints

D. Van Gemert

*External steel reinforcements are being used for restoring and repairing concrete structures. The external steel is glued to the concrete with an epoxy adhesive. The joints are usually loaded in pure shear or in bending shear. Experimental results of the stress distribution in the adhesive layer in laboratory test specimens are given and the testing machine, developed for these experiments, is also described. The ultimate load bearing capacity and the phenomena accompanying rupture of the connection are examined. From the experiments, design rules are drafted for the external reinforcements and their anchorage to the concrete.*

In recent years there has been a growing interest in the repair and renovation of buildings and civil engineering structures. Repairing and renovation procedures have always been very problematic, especially in reinforced concrete structures. The development of a wide variety of artificial resins, especially epoxy based adhesives, has given rise to new and extensive possibilities for repairing concrete and brickwork constructions.

Epoxy adhesives are used for injection into cracks, for bonding concrete to concrete, metal to metal and steel to concrete. The ability of gluing steel to concrete makes it possible to repair reinforced concrete structures where the load-carrying capacity is insufficient. This default may be caused by a change of the use of the building, by accident, by corrosion or fire, by faulty design or bad application of material.

This paper deals with an investigation of the effective bond strength in concrete beams or slabs reinforced by externally bonded steel elements. Fig. 1 gives an outline of an external reinforcement. This reinforcement is used to improve the resistance of the structural element against bending moments, shearing forces and normal loads. For normal loads and bending moments, the external reinforcement can be easily designed,[1] except for determining the anchoring lengths. The problem is to know how the force $P$ in the steel plate is transferred to the concrete base by the resin layer (see Fig. 2). It is necessary to investigate how the resultant force varies between $P$ at A, the beginning of the anchoring zone, and zero at the end B. This variation depends on the physical and mechanical properties of the concrete base, the steel plate and the adhesive. Research on this subject was started by R. L'Hermite and J. Bresson,[2] who set up a mathematical model to describe the behaviour of the joint in the elastic region.

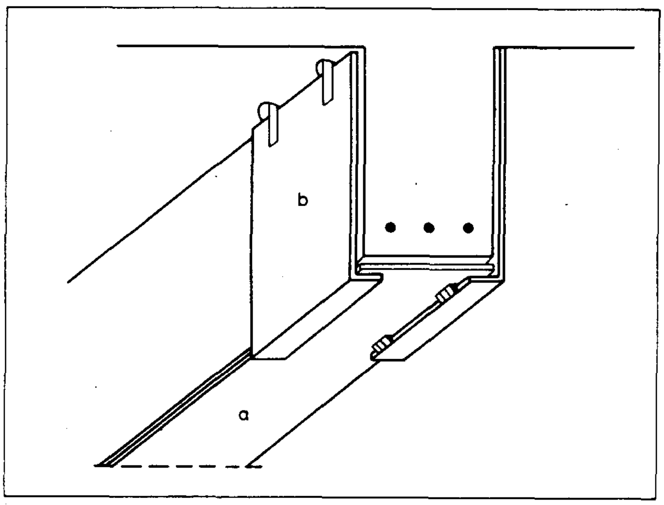


Fig. 1 External reinforcement: (a) longitudinal bending reinforcement; (b) external stirrup

A test programme was set up at the Reyntjens Laboratory of the Katholieke Universiteit at Leuven to provide practical information about the necessary anchoring lengths, 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. In all the tests the epoxy adhesive EPICOL U (N.V. Resiplast, Belgium) was used. The concrete quality was $R'_{wm}$ = 56 N/mm$^2$ in compression and $R_{bm}$ = 4.5 N/mm$^2$

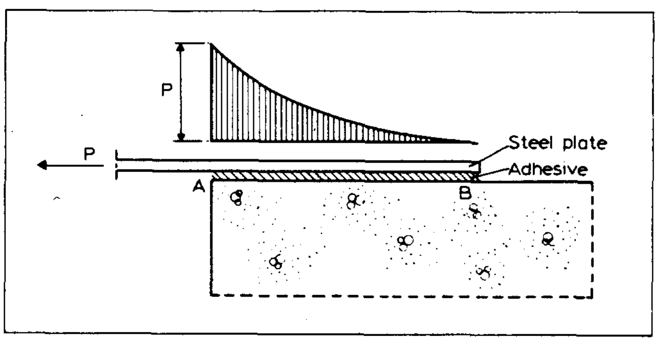


Fig. 2 Steel/concrete joint in pure shear

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in tension. The concrete surface was prepared by manual granulating, whereas the steel surface was sand-blasted. The plates were gradually pressed against the concrete, until no more adhesive was squeezed out. The thickness of the adhesive layer varied between zero and 2-3 mm.

## Pure shear test

A special test piece and testing machine were developed for this purpose (see Figs 3 and 4). The test piece was an unreinforced concrete prism with the dimensions 150 mm x 150 mm x 300 mm. Two pairs of steel plates were glued on the opposite sides of the prism. One pair had a width of 100 mm, and all the measurements were made on these plates. Before testing, two longitudinal cuts with a depth of 5 mm were made in the concrete alongside the plates to get a well-determined surface under loading. The two other plates were 150 mm in width, and served as fixing elements. All the plates were 5 mm thick. To avoid unsymmetrical loading of the plates, the loads were introduced through a universal joint on the upper and lower side of the test piece. In this way a force difference in the plates of only 1% was obtained. The distribution of the forces in the plates and of the shearing stresses in the adhesive layer were obtained from strain-gauge measurements over the length of the plates. These strain-gauges were placed both on the outside and inner side of the plate, which was later glued to the concrete. This was necessary because the deformation of the concrete block caused secondary bending strains in the plate which could reach up to 20% of the normal force strains. The position of the strain-gauges is indicated in Fig. 5. The distance between the gauges was smaller in the initial zone, because there are greater variations between the force and the shearing stresses in that area.

Typical results of the measured force distribution are given in Figs 6 and 7. At low tensile forces ($P < 40$ kN) there is an exponential falling-off of the resultant force in the plate (Fig. 6). At higher loads the curves tend to stay

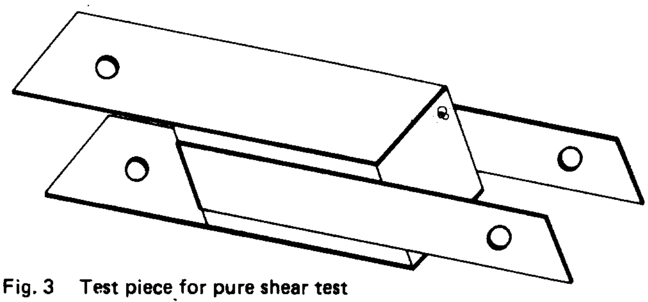

Fig. 3 Test piece for pure shear test

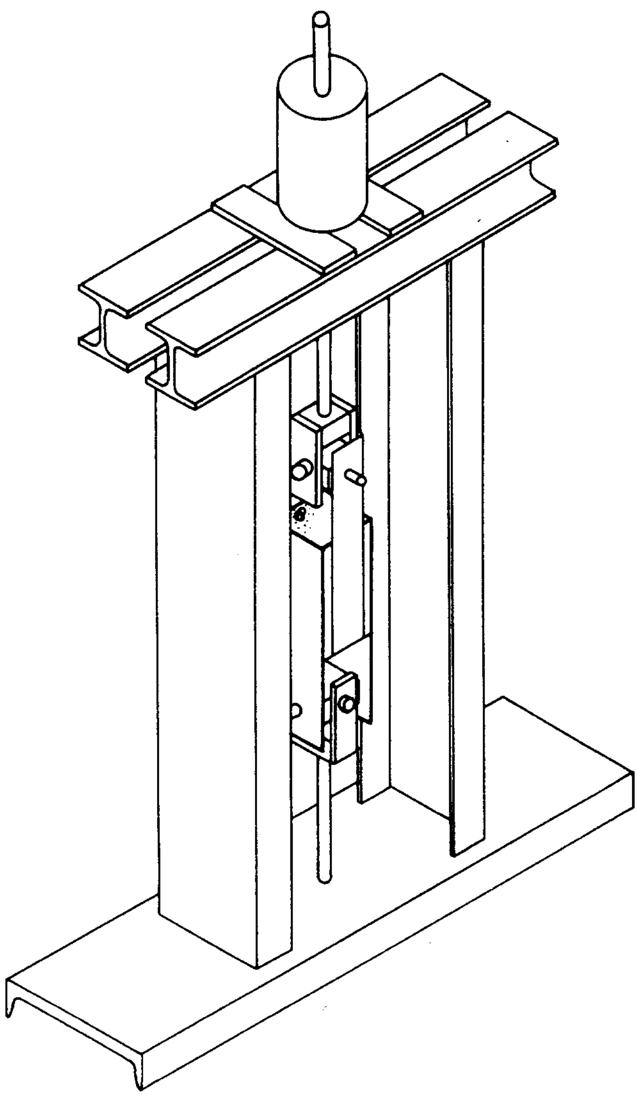

Fig. 4 Testing apparatus

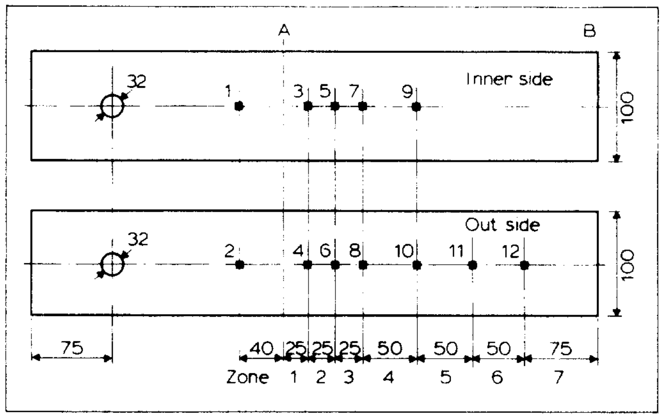


Fig. 5 Position of the strain gauges on the steel plates

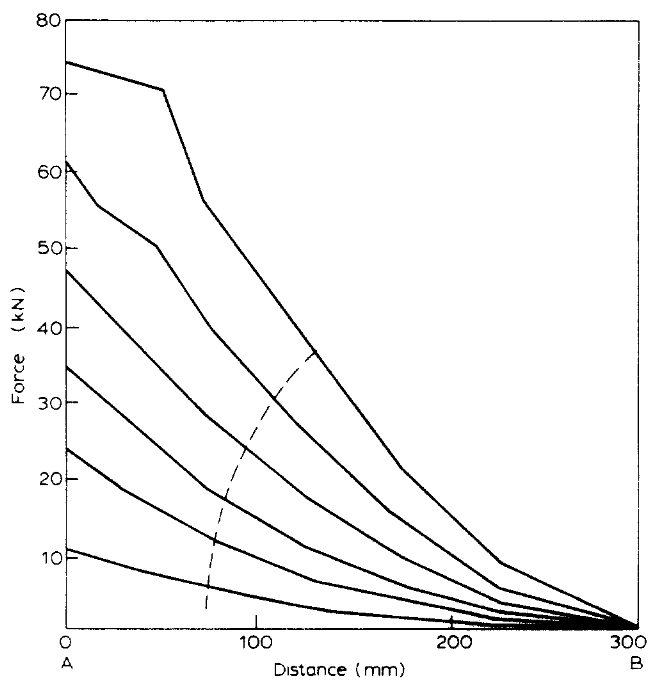


Fig. 6 Force distribution in the plate in a one-way shear test

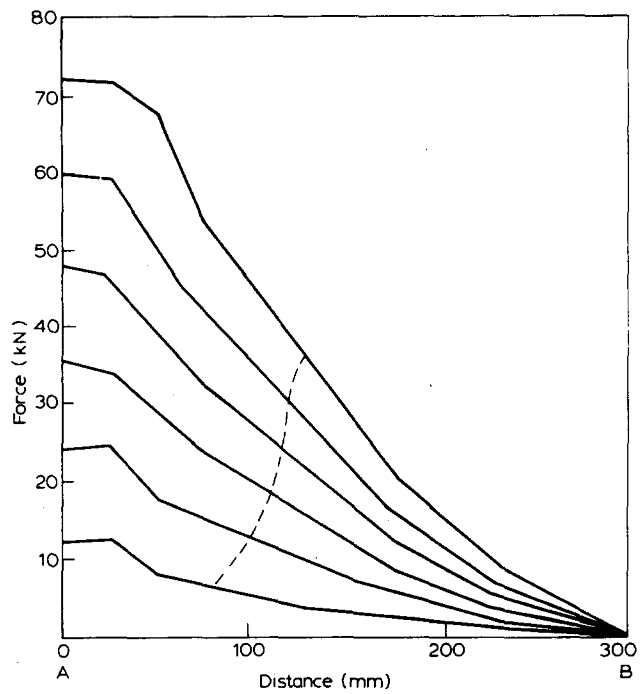


Fig. 7 Force distribution at reloading of a cracked specimen

more and more horizontal in the initial zone. This means that practically no force is transferred from the plate to the concrete, due to cracking of the concrete. The ultimate failure load varied between 65 and 87 kN, with a mean value of 78 kN and a variance of 9.3 kN. In Figs 6 and 7 a comparison is made between the force distribution at a first loading of the test piece until cracking of the concrete, and a reloading up to rupture. It can be seen that the cracked zone, where there is practically no force transfer, extends more and more. This is indicated by the dotted lines, showing the points where half of the force is transmitted to the concrete. This transfer of forces from the steel plate to the concrete causes shearing stresses in the epoxy adhesive and in the contact surface between the adhesive and the concrete. The last stresses determine the strength of the joint. The mean values of these shearing stresses over successive zones are calculated from the forces, and are represented by histograms (Fig. 8). The maximum stresses that occur depend upon the distance from the end A of the concrete prism. In the first zone the shearing stress reaches a maximum of about 2.5 N/mm$^2$, while at a greater distance it can reach 5.5 to 6 N/mm$^2$. This is possible because of the complex three-dimensional stress situation that is created in the concrete block by the two pairs of plates. This high shearing stress is very local, and at reloading of a cracked block its position moves towards the free end B of the plate (Fig. 8b). An interesting characteristic of the apparent shearing stress distribution arises from

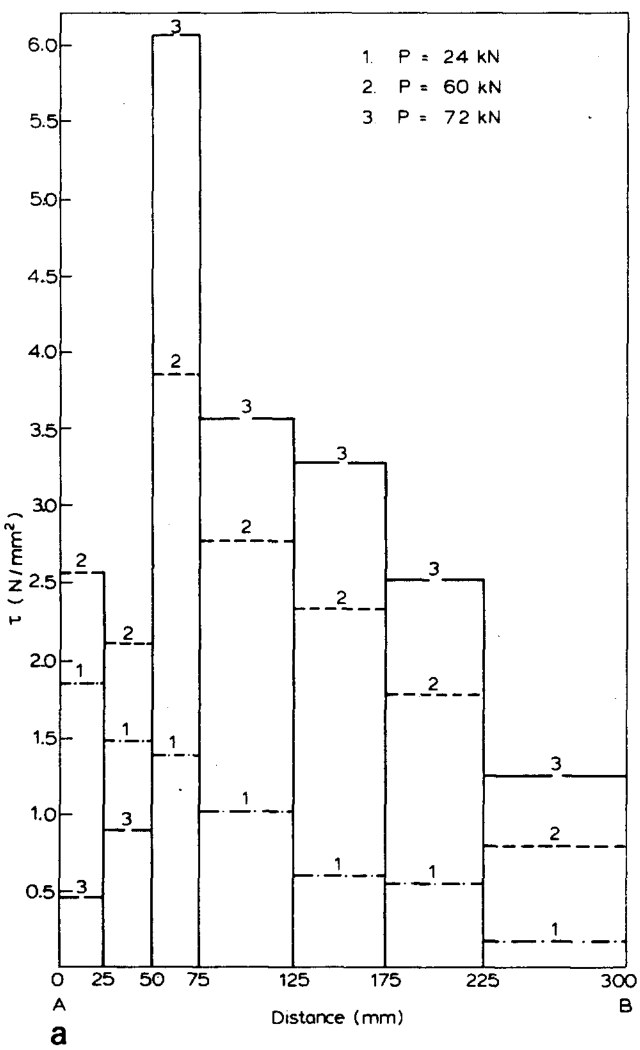


Fig. 8a Average shearing stresses at a first loading

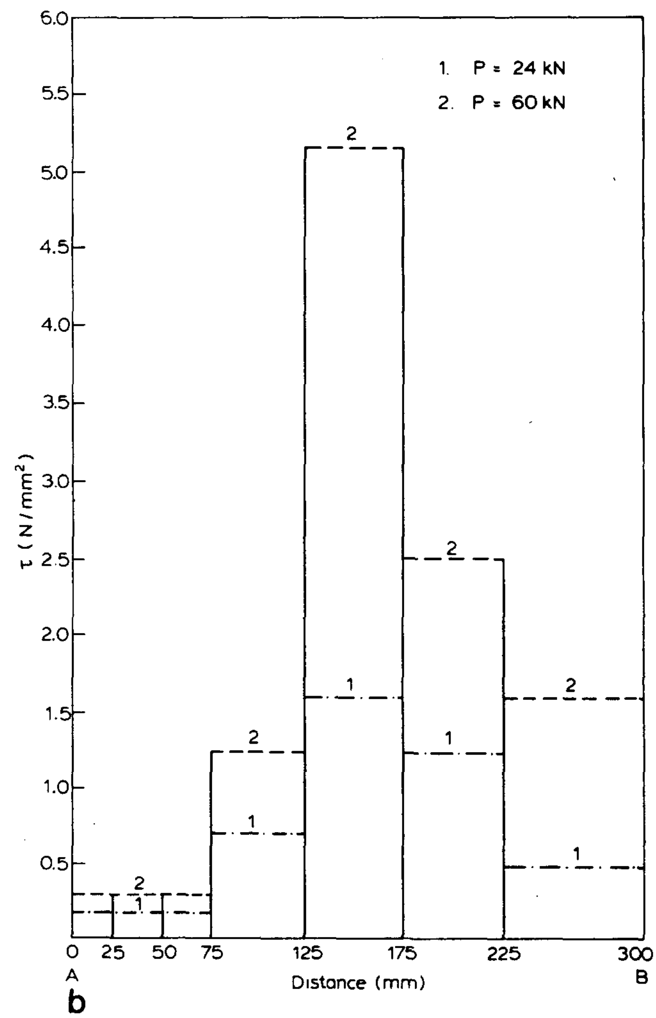


Fig. 8b Average shearing stresses in a cracked specimen

the stress/force diagrams for the different zones (Fig. 9). The figure gives the shearing stress in the initial zone of the joint as a function of the applied force $P$. Up to a value of 1.5 $N/mm^2$ the shearing stress increases linearly with the force, and at repeated loading this relation remained constant.

At higher loads the stresses in zone 1 increased more slowly to reach a maximum value around 2 $N/mm^2$. This is due to the microcracks that originate in the concrete. At a load of about 75% of the ultimate load, which was 87 kN for the test piece of Fig. 9, the cracks became so big that the concrete lost its strength and just a small hooking strength remained.

When analogous curves for the zones at a greater distance from the beginning A of the prism were plotted, different results were obtained. This is due to the cracking of the concrete in the preceding zones (Fig. 10). From this it can be concluded that in pure shear a safe design can be based on the following considerations. The shearing stress in the initial zones may not exceed 1.5 $N/mm^2$. This value corresponds to the concrete tensile strength at the surface, measured by the pull-off method (Fig. 11). This method comprises pulling off a steel cylinder, glued on the surface of the concrete. The tensile strength at the surface is much smaller than the strength measured by a direct tensile test on a cylinder or prism. It may be concluded that the mean value $R_{sm}$ of the pull-off strength must reach at least 1 $N/mm^2$ to ensure a safe reinforcement. This mean value is taken from a number of ten pull-off tests on well distributed points on the surface.

Under service load a shearing stress is produced equal to the characteristic tensile strength $\bar{\sigma} = R_{sk} = R_{sm} - 1.64s$ where $s$ is the variance, calculated for the test results.

Under service load a triangular stress distribution with a maximum at A, the beginning of the anchoring zone, (Fig. 12a) is assumed. With $\bar{\sigma}$ the allowable stress and $P_s$ the force to be transferred at service load, the value $L_1$ of the anchoring length can be calculated. A second calculation is made for the ultimate load $P_u$. In this case a triangular distribution is assumed as shown in Fig. 12b, with a maximum value in the middle. This maximum value is taken to be equal to the characteristic value of the tensile strength of the concrete. $P_u$ is equal to $P_s$, multiplied by the safety factor, normally taken as equal to 1.5 x 1.5 = 2.25. With

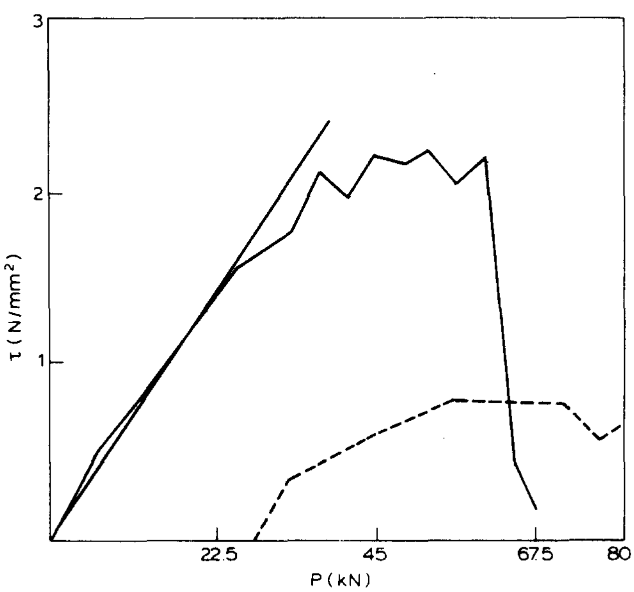

Fig. 9 Shearing stress versus applied force in zone 1

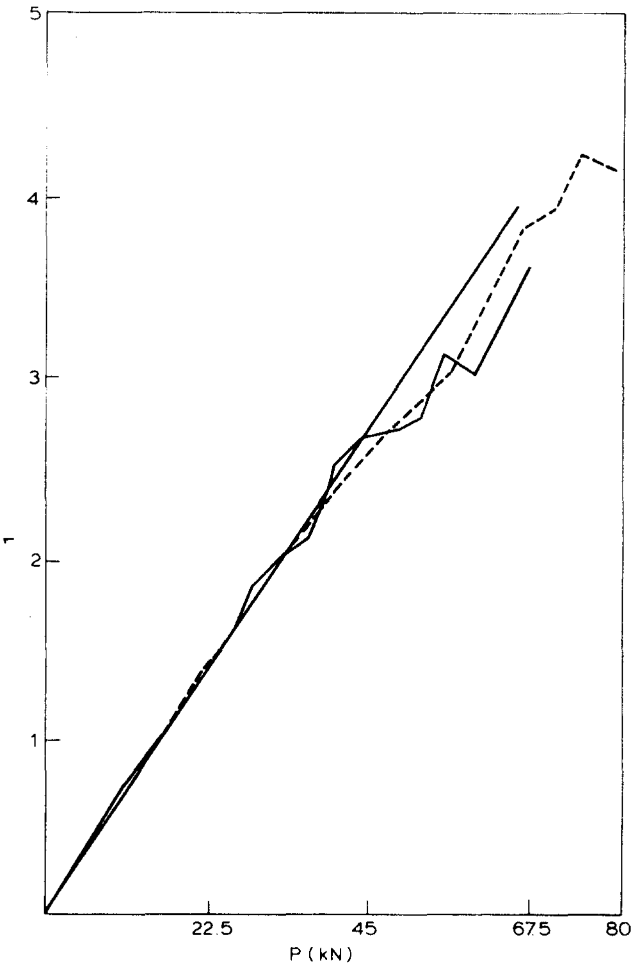

Fig. 10 Shearing stress in zone 3

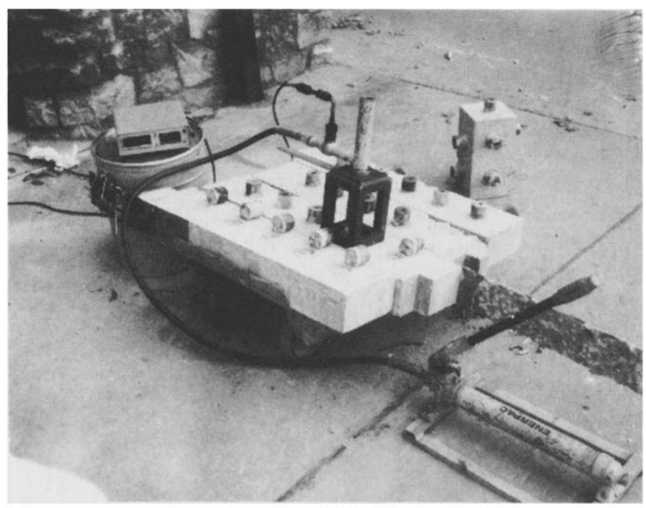
Fig. 11 Pull-off test for measuring the tensile strength at the surface of the concrete

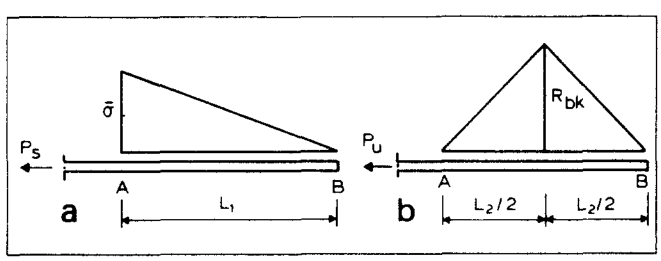

Fig. 12 Assumed stress distribution (a) at service load and (b) at ultimate load

these assumptions a second value $L_2$ for the anchoring length can be calculated.

### Example

The concrete has a surface tensile strength $R_{sm}$ = 1.45 N/mm$^2$ with a variance $s$ = 0.22 N/mm$^2$. The tensile strength $R_{bm}$ is equal to 4.5 N/mm$^2$. The force to be transferred $P_s$ = 20 kN. The plates have a width of 100 mm.

Under service load the allowable stress is given by:

$$\bar{\sigma} = 1.45 - 1.64 \times 0.22 = 1.09\ \text{N/mm}^2$$

The value $L_1$ is found from the longitudinal equilibrium equation:

$$P_s = L_1 \times 100 \times \frac{\bar{\sigma}}{2}$$

which gives $L_1$ = 370 mm.

The characteristic value of the tensile strength is given by:

$$R_{bk} = 4.5 \times (1 - 1.64 \times 0.15) = 3.4\ \text{N/mm}^2.$$

The length $L_2$ is found from the equation:

$$P_u = 2.25 \times 20.000 = L_2 \times 100 \times \frac{3.4}{2}$$

which gives $L_2$ = 265 mm.

The anchoring length in this case will be 370 mm. This method can be used for the design of the anchoring lengths of external stirrups, lap joints *etc.*

## Shear-bending test

In bending problems the shearing stresses in the adhesive 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. How these effects are superposed was studied by bending tests on beams (Fig. 13). The beams are composed of two concrete prisms, linked by a steel plate of 5 mm thickness that is bonded to the lower surface of the prisms with an epoxy adhesive. The internal reinforcement consists of two longitudinal bars, with a diameter of 14 mm, at the bottom and two at the top. The stresses in the reinforcing plate are measured with strain-gauges. A typical force diagram, measured in the plate, is shown in Fig. 14. The straight lines show the distribution of forces, calculated with the formulae of the elementary strength of materials. The broken lines between B and C in Fig. 14 refer to the fictitious force in the plate, if this plate was extended to the support.

At both ends the measured diagrams differ from the calculated ones, due to anchoring effects. The shearing stresses in the end zones A and B are represented in Figs 15

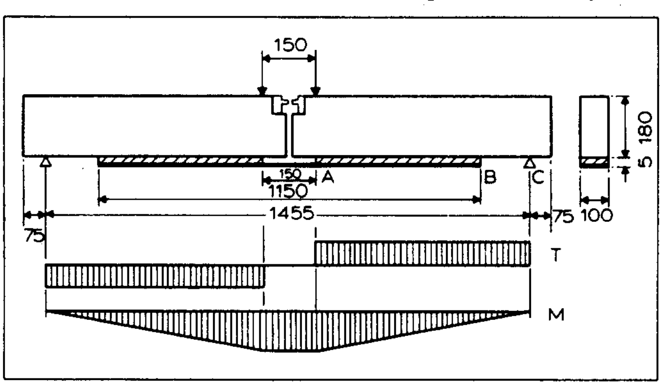


Fig. 13 Bending test set-up

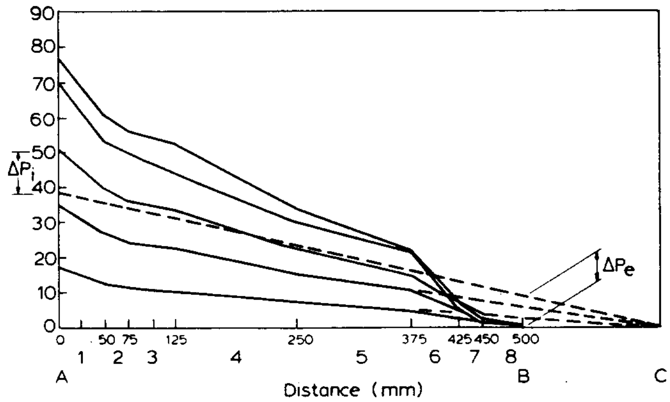


Fig. 14 Diagram of forces in the external plate

and 16 as a function of the tensile force $P$ in the plate. At A, the beginning of the shearing zone, the shearing stress varies practically linearly with the force in the plate up to shear stresses of 3.5–4 N/mm$^2$. At B, the free end of the plate, the same effect as in the pure shear test is observed. The shearing stress increases linearly up to values of 1.0–1.5 N/mm$^2$ and does not exceed 1.7–2 N/mm$^2$. At the end of the plate there is a stress concentration, but comparison must be made with the value calculated by classical methods. At a load $P$, the classical shearing stress is equal to 0.44 N/mm$^2$ and the measured value equal to 1.0 N/mm$^2$ (Fig. 16). This corresponds to the creation of cracks in the concrete. These cracks develop further until the plate becomes entirely loose (Fig. 17).

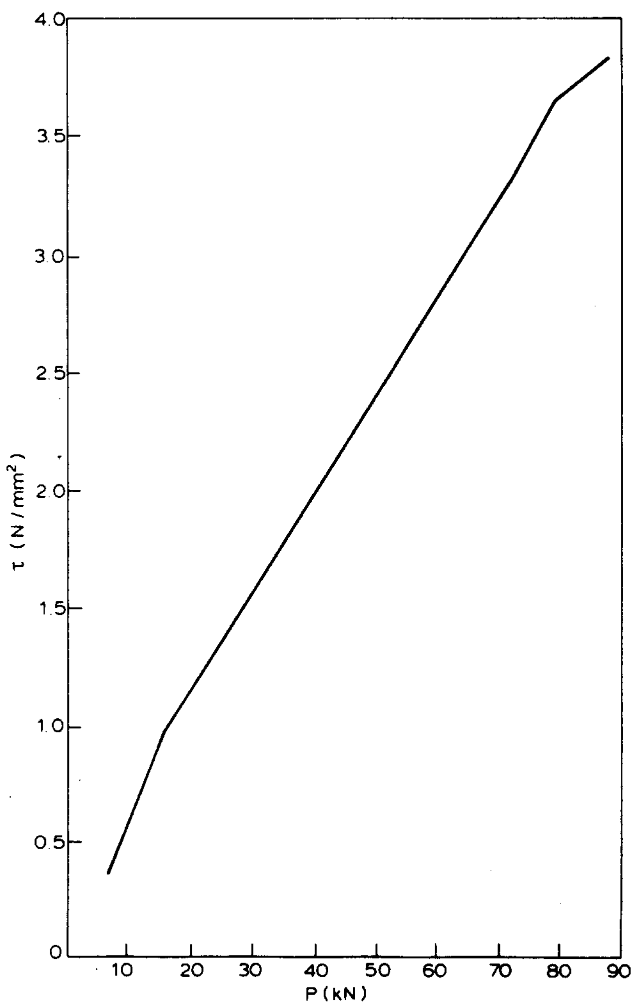


Fig. 15 Shear stress at A

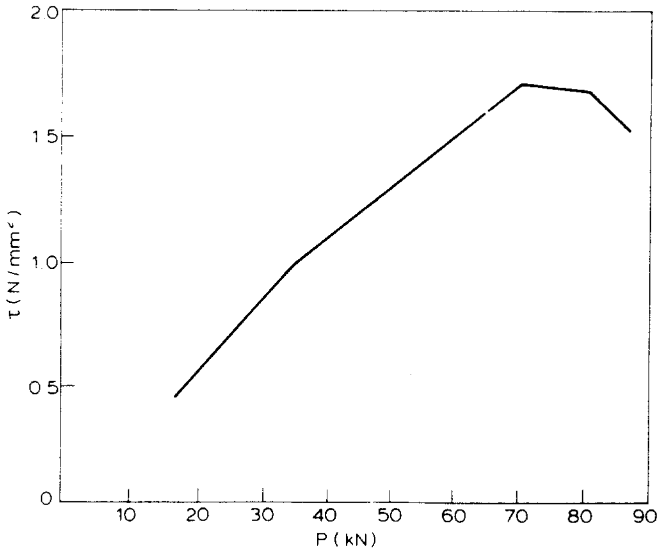


Fig. 16 Shear stress at B

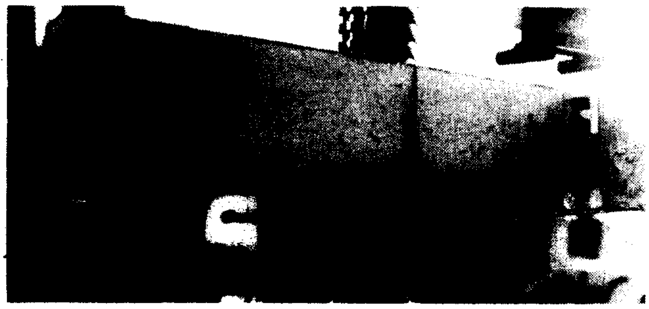

Fig. 17 Rupture of a bending specimen

These effects lead to the following design considerations. By classical calculations the straight lines in Fig. 14 are determined, which give the forces $\Delta P_i$ and $\Delta P_e$ that must be anchored. $\Delta P_e$ is caused by the sudden change of the section at B. At the left side of B the steel plate is present, but not at the right side. $\Delta P_e$ is the resultant of the stresses that would act at B if the plate were continuous. $\Delta P_i$ only originates at places where the longitudinal internal steel reinforcement is not continuous, as is the case in this test or at vertical joints in multilayer reinforcements. As in the pure shear test it is assumed that a triangular distribution of the anchoring stresses exists. For $\Delta P_i$ the stresses will be limited to the characteristic value of the tensile strength of the concrete, divided by the safety factor. At the free end B the re-entering edge causes stress concentrations and accelerated cracking. Therefore a dowel was used to anchor the free end of the plate to the interior concrete of the beam or slab (Fig. 18). With this precaution the same allowable stress as in the pure shear test, *ie* up to 1.5 $N/mm^2$ can be assumed. The shearing stress, due to $\Delta P_e$, must be added to the shearing stresses, caused by the variation of the bending moment.

### Example

The beam of the bending test has a force of $P = 35$ kN in the plate. At this load the shearing stress due to bending is equal to 0.14 $N/mm^2$ and the force $\Delta P_e = 6.7$ kN. If a total stress of 1.5 $N/mm^2$ is allowed, then the anchoring length may be calculated from the equation:

$$L \times \frac{100}{2}(1.50 - 0.44) \geqslant 6700$$

which gives $L \geqslant 126$ mm.

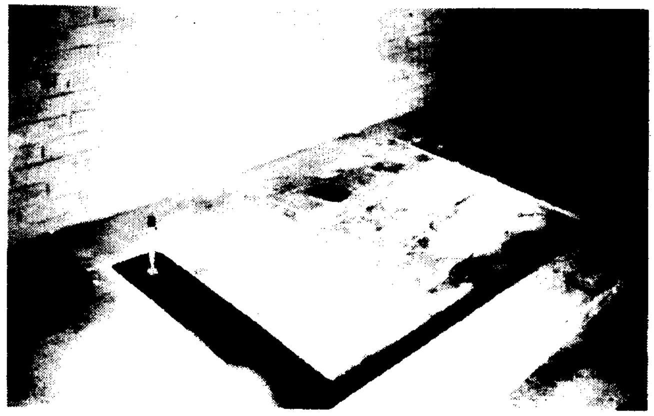

Fig. 18 Dowel at the end of the steel plate

This length corresponds very well with the length of the influenced zone in Fig. 14, while above the force of 35 kN the cracking of the concrete at the free end starts (see Fig. 16). If the shearing stresses or the anchoring length become too large, the thickness of the plate must be enlarged.

## Conclusion

The results of the experiments indicate the possibilities of using epoxy bonded steel/concrete joints. They can be regarded as reliable structural elements beneficial in the field of restoration and the structural repair of concrete constructions. The design rules, derived in this contribution, may be used in a wide range of applications. Several practical applications have already been made by the author.[3]

This research will now be extended to joints composed of a steel plate, epoxy adhesive, resin mortar and concrete, a combination of materials which occurs in many cases where damage is due to corrosion, fire or accidents.[4]


## Acknowledgements

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## Author


Professor Van Gemert is with Department Constructie Afdeling Bouwkunde, Katholieke Universiteit, Leuven, de Croylaan 2, 3030 Haverlee, Belgium.