STRENGTHENING OF CONCRETE STRUCTURES WITH EXTERNALLY BONDED REINFORCEMENT - DESIGN PHILOSOPHY AND PRACTICAL APPLICATIONS

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Abstract

The paper deals with the design philosophy of externally bonded reinforcement. The difference between strength requirements (ultimate limit state) and deformation requirements (serviceability limit state) and its consequences on the use of either steel or CFRP will be clarified.

The strengthening action can be required in bending as well as in shear. The use of either steel or CFRP depends on the specific requirements of additional bending or shear reinforcement. It is also possible to combine the two materials. In that way the specific properties and benefits of both steel and CFRP are used.

Another very important issue is the correct design of the anchorage zone, where the force transfer between the concrete structure and the external reinforcement will take place. In the paper, the determination of the anchorage length, i.e. the length of the force transfer zone, and the plate end shear failure mechanism will be explained in order to enable a proper design of the anchorage system.

Finally, the paper discusses practical examples to illustrate the application of polymer adhesives and strengthening elements.

Key words: Strengthening, externally bonded reinforcement, CFRP, design, anchorage

Introduction

The strengthening of concrete structures with externally bonded reinforcement is generally done by using either steel plates or CFRP laminates. Each material has its specific advantages and disadvantages. Steel plates have been used for many years due to their simplicity in handling and applying and to their effectiveness for strengthening. The properties and behaviour of steel-concrete structures are well known. Steel plates are very effective to be used as bending reinforcement. The high tensile strength and stiffness lead to an increase in bending capacity and a reduction of the deformations. Steel plates can also be used as external shear reinforcement. However, labor costs might rise quickly. Steel stirrups have to be bend or welded and very often anchored with bolts in the concrete compression zone. When several stirrups per meter are needed, these costs can make this technique economically less interesting.

CFRP sheets have very high tensile strength and stiffness, figure 1. Nevertheless, they cannot be used in every strengthening situation. When used in bending, the active stresses in the CFRP laminates have to be kept small in order to prevent the internal steel reinforcement from yielding. This means that the high strength properties of the CFRP sheets are not used effectively. The required increase of bearing capacity can only be reached by adding a considerable number of sheets, which increases the material and labour costs. For limiting the deflections, CFRP sheets are not very effective. Due to their very small cross sectional area per sheet, the moment of inertia will only slightly increase and so the deformation decrease will only be marginal. In these cases, very often steel plates offer a better alternative. On the other hand, CFRP sheets are more appropriate for shear strengthening than steel plates. An orthogonal net of carbon fibres bonded at both sides of a beam is very well able to take shear forces. The applying of the CFRP sheets is very easy. Even complex shapes and geometries can be done. Labour costs are considerably lower for CFRP than for externally bonded steel stirrups.

To combine the features of the two materials, a hybrid steel/CFRP strengthening method can be developed. The additional longitudinal reinforcement consists of externally bonded steel plates, whereas the shear reinforcement consists of externally bonded CFRP sheets. The behaviour of such hybrid strengthening was extensively studied in an experimental program set up at the Reyntjens Laboratory, K.U.Leuven, Belgium (Brosens & Van Gemert, 1999). Even when the external CFRP shear reinforcement is applied only at one side of the beam, a considerable increase of the shear capacity could be obtained.

Bending design

For the design of the externally bonded reinforcement, all material properties and geometrical characteristics of the cross section of the existing concrete element must be known, or have to be determined experimentally. Furthermore, the magnitude of the load acting on the element at the moment of gluing the external reinforcement and the new load acting on the strengthened cross section must be known. The stress distribution at the moment of gluing the external plates is determined by the moment M_0, which is called the unloading moment. This unloading moment can be changed by removing part of the permanent loads, or by completely or partly jacking up the element. The more a structure is unloaded, the more effective the additional external reinforcement will be, which allows a smaller cross sectional area of the external reinforcement (Van Gemert, Vanden Bosch & Ladang).

The design method gives the cross sectional area of the external reinforcement. When steel plates are used, it concerns the thickness and the width of the plate, while with CFRP laminates, it concerns the number and the width of the CFRP sheets. According to the European Standard ENV 1992-1-1 (Eurocode 2, 1995), two limit states have to be checked: the ultimate limit state and the serviceability limit state.

The ultimate limit state is the state where the concrete structure completely fails or collapses. In the calculations, the design values of the loads and the material properties are used. Non-linear stress-strain relationships for steel and concrete are used allowing plastic deformations. However, the CFRP reinforcement can be considered as a perfectly linear elastic material. Once the tensile strength is reached, a brittle fracture occurs suddenly.

The assumption is made that the strains vary linearly over the height of the beam. The ultimate limit state assumes that at least one of the materials attains its maximum allowable strain. The cross sectional area of the external reinforcement and the position of the neutral axis is determined by using the equilibrium of normal and bending forces over the concrete section.

The serviceability limit state is the state beyond which specified service requirements are no longer met. These requirements concern limited deformations or deflections and low vibrations. In the serviceability limit state, plastic deformations are not allowed. Linear stress-strain relationships and nominal values of the loads are used to prevent large deflections and wide crack openings. Excessive deflections are not necessarily dangerous, but people will not accept them for aesthetical and psychological reasons.

Due to large cracks in the concrete cover, the internal steel bars could be exposed to aggressive environmental atmospheres causing steel corrosion. Therefore wide crack openings must be avoided. This can be realised by limiting the stresses under service conditions to a fraction of the limit of elasticity. Eurocode 2 limits the concrete compressive strength to 50% or 60% of the characteristic cylinder compressive strength depending on the environmental circumstances whereas the steel stress is limited to 80% of the characteristic value of the yield strength. The maximal value of the deflections is often imposed by the customer or can be found in design codes.

Shear design

When a concrete element has insufficient internal shear reinforcement, additional shear reinforcement can be bonded to the sides of the element. This additional shear reinforcement can consist of either externally bonded steel stirrups or externally bonded CFRP sheets. The design is done in the ultimate limit state according to Eurocode 2. For the design, it makes no difference whether steel stirrups or CFRP sheets are used for shear strengthening.

Since CFRP laminates are able to transfer forces only in the direction parallel to the fibres, the best solution would theoretically consist in applying externally bonded CFRP shear reinforcement perpendicular to the shear cracks. Generally, these shear cracks form an angle of 45° with the longitudinal axis of the beam. In practice, however, it is nearly unfeasible to apply CFRP laminates with an angle of 45°. Therefore an orthogonal web of carbon fibres has to be used, since the shear transfer between individual carbon fibres is very low. One half of the fibres is oriented horizontally, whereas the other half is oriented vertically, which means that the total number of layers is a multiple of two, figure 2.

The externally bonded CFRP shear reinforcements have to be applied over the complete height of the side of the element. If more than two layers are required, the horizontal and vertical layers have to alternate. The influence of externally bonded CFRP shear reinforcement on the behaviour of concrete beams has been studied extensively in (Ahmed & Van Gemert, 1999).

Strengthening of concrete plates

In general, the force distribution in plates is determined by the ratio of the stiffnesses and the ratio of the spans in both directions. When the stiffness in both directions is equal, the plate is called “isotropic”. A reinforced concrete plate can be considered as isotropic, since the amount of internal steel in both directions generally only slightly differs. The distribution of the bending forces in the plate is then dependent only on the proportions of the spans. The biggest part of the load will be taken by the shortest span. Once the force distribution in each direction is determined, the calculation of the amount of internal or external reinforcement is identical to the design of reinforced concrete beams subjected to bending (Van Gemert, 1996).

When externally bonded steel plates are used for strengthening or stiffening reinforced concrete plates, they generally can only be applied in one direction, which is preferably the shortest span. By doing so, the amount of steel area in the direction of the external steel plates will strongly increase, and consequently the stiffness in that direction will strongly differ from the stiffness in the transverse direction. This orthotropy in the stiffness characteristics has a great influence on the distribution of forces in the plate. The stiffer the plate in one direction, the greater the relative part of the load which will be taken by that direction and also the greater the moments will be in that direction. The new load distribution is given by the orthotropic plate theory .

In the case of an enhancement of the allowable load on a reinforced concrete plate, the unstrengthened plate usually will have insufficient steel reinforcement in both directions. When one direction is strengthened with steel plates, the increased bending moments in that direction have to be carried both by the internal and external steel area. Moreover the bending moment in the transverse direction have to decrease so that it can be carried by the internal steel reinforcement in that direction. This means that one direction has to be overstrengthened in order to unload the other direction.

The advantage of the thin CFRP laminates is the fact that they can be applied in both directions. In that way, the strengthened concrete plate remains isotropic, which means that the relative force distribution will not change. Since reinforced concrete plates are much thinner than concrete beams, the lever arm from the resulting concrete compressive force to the external reinforcement is much larger than the lever arm to the internal reinforcement. This means that the active tensile stresses in the external reinforcement can be much higher than in the internal

steel reinforcement, which is very favourable for the high strength CFRP laminates. Therefore CFRP laminates can often be used more effectively for strengthening concrete plates than for strengthening concrete beams.

However, when CFRP laminates are used, the deformations might become unacceptable. Since the area of the externally bonded CFRP laminates is rather small, the bending stiffness of the concrete plate will only slightly increase, possibly causing important deflections. Therefore it is very important also to check the deformations of a strengthened reinforced concrete plate.

For prestressed concrete plates, strengthening with externally bonded reinforcement is mostly not possible. Since the prestressing already causes considerably high concrete compressive stresses - often close to the concrete compressive strength -, the bearing capacity could not be increased anymore.

Anchorage design

A good understanding of the stress distribution at the end zones of the externally bonded reinforcement is essential for the proper design of the plate and laminate end anchorage. Premature failure often occurs in these zones. The force transfer between the concrete structure and the external reinforcement takes place by means of shear stresses. The knowledge of this shear stress distribution is essential for the design of the end anchorage and the determination of the bearing capacity of the bonded connection. For the practical design, two values have to be determined: the maximum transferable force and the anchorage length. The maximum transferable force is the maximum force that can be transferred by a bonded connection in shear and the anchorage length is the length needed to transfer that maximum transferable force. The presented formulae are based on the theory of non linear fracture mechanics (Brosens & Van Gemert, 1998). A bilinear shear stress-slip relationship for concrete is used and both pre- and post-cracking behaviour is taken into account, figure 3. The mode II-fracture energy G_f is defined as the area under the τ_l-s_l curve and is used to calculate the maximum transferable load. The following equations can be derived:

Maximum transferable load: $P_{\max} = b_l \sqrt{2G_f E_l h_l}$

Anchorage length: $$l_a = \frac{2\lambda + A\tan\left(\frac{\tanh(2)}{\lambda}\right)}{\lambda\omega}$$

with b_l width of the (CFRP) laminate (mm)

h_l thickness of the (CFRP) laminate (mm)

G_f fracture energy (N/mm) ($G_f = (\tau_{lm}\, s_{lm})/2$)

E_l modulus of elasticity of (CFRP) laminate (N/mm^2)

E_c modulus of elasticity of concrete (N/mm^2)

$$\lambda = \sqrt{\frac{s_{lm}}{s_{l0} - s_{lm}}}$$

$$\omega = \sqrt{\frac{\tau_{lm}\left(1 + m_l \gamma_l\right)}{s_{lm} E_l h_l}}$$

τ_{lm} maximum shear stress (N/mm^2)

s_{lm} slip at maximum shear stress τ_{lm} (mm)

s_{l0} slip where shear stress becomes zero (mm)

m_l the stiffness ratio ($m_l = E_l / E_c$)

γ_l the cross sectional area ratio ($\gamma_l = A_l / A_c$)

A_l cross sectional area of (CFRP) laminate (mm^2)

A_c cross sectional area of concrete (mm^2)

The model parameters τ_{lm}, s_{lm} and s_{l0} can simply be derived from the concrete compressive strength and the concrete tensile strength (Brosens & Van Gemert, 1999).

This anchoring length has to be provided at both ends of the external reinforcement. If there is no place to add this supplementary length or if the maximum transferable force of the connection is insufficient to carry the acting forces, an additional mechanical anchorage system is necessary. For steel plates, this mechanical anchorage can be realised by providing a bolt, whereas for CFRP laminates only an external stirrup is possible, figure 4.

Practical applications

Restoration of swimming pool roof structure

The swimming pool of Kalmthout, Belgium, was constructed in 1974. The roof structure was built up with prestressed concrete beams, on top of which the roof is made using prefabricated reinforced concrete plates covered with cast-in-situ concrete. The thickness of the roof slab is 110 mm. The total surface of the roof is 675 m^2.

A partial inspection of the roof in 1996 showed that the concrete was severely damaged at several positions, figure 5. The concrete cover was spalling off and the steel reinforcements were exposed and severely corroded. Because the concrete surface had always been hidden from view by a false ceiling, the damage remained unnoticed for many years.

Tests carried out in the laboratory indicated that chloride ingress and carbonation, combined with an insufficient concrete cover, only about 6 mm on the reinforcement bars, induced steel corrosion. Since the deterioration caused an unacceptable reduction of safety, a thorough repair and strengthening of the roof slab was absolutely necessary.

Because of the high amount of chlorides and the high humidity in the swimming pool atmosphere, a real danger of corrosion of externally bonded steel plates existed. To avoid this problem, the repair and strengthening of the roof slab with externally bonded CFRP-sheets was chosen.

The renovation work started in August 1997. The existing steel rebars were removed from the concrete slab. So the rebars could not corrode any further and the deterioration process of the concrete was stopped. The reinforcement of the concrete slab was taken over by the CFRP reinforcement, glued on the concrete surface.

After the removal of the steel bars and gritblasting of the surface, the concrete surface was leveled again using epoxy mortar. This polymer concrete formed the substrate for the application of the CFRP-sheets. The CFRP-sheets were cut in strips with a width of 25 cm, the distance between two strips varying from 350 mm to 700 mm. This way, only a limited percentage of the total slab surface had to be repaired: all the necessary reinforcement was concentrated in these strips. This resulted in an additional economy. The length of the sheets was 4 meter. For this project, two layers of CFRP were applied in the inner zones of the roof slab, and three layers in the end zones of the slab, figure 6. Finally, the repairs were hidden from view by a completely new false ceiling.

Transformation of former school building to library

In 1998, a former school building in Leuven, Belgium, was transformed into a city library with a considerable increase of load as a consequence. The floor slabs had to be strengthened to increase the bearing capacity from 3 kN/m^2 to 6 kN/m^2. These floor slabs consist of ribs spaced every 55 cm. The thickness of the floor slab is 50 mm.

An extensive material investigation was done to determine the material properties and the condition of the construction. Six concrete cores (Ø113 mm) were drilled to determine the concrete compressive strength, resulting in a characteristic value of 22.1 N/mm^2. The concrete tensile strength at the surface was measured by a pull-off test, giving 2.96 N/mm^2. The location and the dimensions of the internal steel reinforcement were found using electro-magnetic waves. The longitudinal reinforcement in the ribs consists of two rebars Ø16 mm. No internal steel stirrups were found.

The concrete was not affected chemically. No steel corrosion could be observed. The chloride and sulphate content were far below the maximum allowable values, whereas the carbonation depth was restricted to a few millimeters.

The strengthening procedure of the ribbed floor slab was twofold, figure 7. Firstly, externally bonded shear reinforcement had to be provided since no internal steel stirrups were present. The decision was taken to use CFRP sheets. An experimental program revealed that externally bonded CFRP sheets at one side of a beam as shear reinforcement are almost as effective as CFRP sheets bonded at both sides of a beam. For that reason, two layers of CFRP sheets were applied at only one side of the ribs in order to increase the shear capacity of the floor slab. For the first layer the carbon fibres are oriented vertically while for the second layer, the carbon fibres are oriented horizontally. Before bonding the CFRP sheets, the concrete surface was roughened slightly by sandblasting. Thereafter the surface is cleaned carefully and an epoxy primer is used to guarantee good bonding. Then the first layer of CFRP is applied. A roller is used to give a good penetration of the resin through the laminate. It is very important that every fibre is surrounded by epoxy resin to guarantee full composite action. After four or five hours, the second layer is applied.

Secondly, the flexural rigidity of the ribs had to be increased in order to carry higher bending loads. Therefore an externally bonded steel plate (70 x 14 mm^2) was applied at the

bottom of each rib. The anchorage of this steel plate is done by two bolts Ø16 mm at each end. Before gluing the steel plate, the concrete surface was roughened by sandblasting and carefully cleaned. A filled epoxy glue is used to bond the steel plate to the concrete surface. The plate end shear crack (Jansze, 1997) is prevented by a CFRP stirrup with a width of 150 mm, figure 8. Before applying this stirrup, all cavities have to be filled, the corners have to be rounded and the surface has to be smoothened with an epoxy repair mortar.

Figures 9 and 10 give a view of the repair works and the final result. The application of the CFRP sheets was very easy. Especially when there is a high degree of repetition, labour costs can be kept very low. One skilled worker can easily bond the CFRP sheets to one side of the ribs one by one. When he has finished the first layer of CFRP on the last rib of the floor slab, the CFRP sheet on the first rib has already hardened enough and the second layer of CFRP can be applied. In this way, he can complete the whole floor slab without a loss of time. The alternative, bonding steel stirrups, requires much more working hours and is therefore less economical.

Conclusions

A good understanding of the force distribution in externally bonded reinforcement is essential for the design and the application of the technique in practice. The choice of the strengthening material, steel plates or CFRP laminates, is very important. Steel plates are suitable for the enhancement of both strength and stiffness properties whereas CFRP laminates are mostly only suitable for the enhancement of the strength properties.

For the design of the cross sectional area, bending as well as shear forces have to be considered. It is very important to take into account the original stress situation before applying the external reinforcement. Only in that case an appropriate design is possible. According to the eurocode standards, both the ultimate limit state and the serviceability limit state have to be checked.

An important issue is the design of the end anchorage. Since the plate end is a discontinuity, high shear stress concentrations might cause premature peeling failure in the end zones of the external reinforcement. Therefore, the maximum transferable force and the anchorage length have to be determined. If the force capacity of the connection is insufficient, an additional mechanical anchorage, such as bolts or external stirrups, has to be provided.

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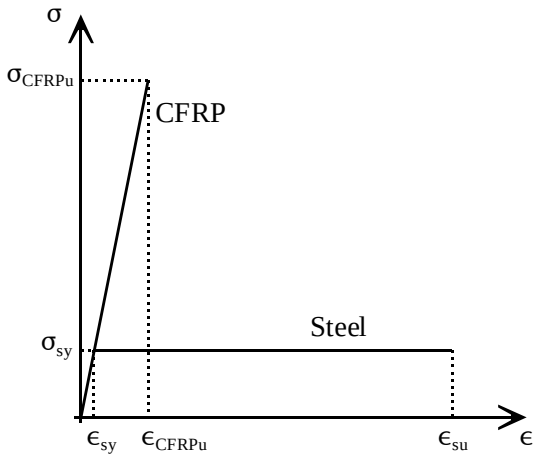

Figure 1 Stress-strain relationship of CFRP in comparison with steel

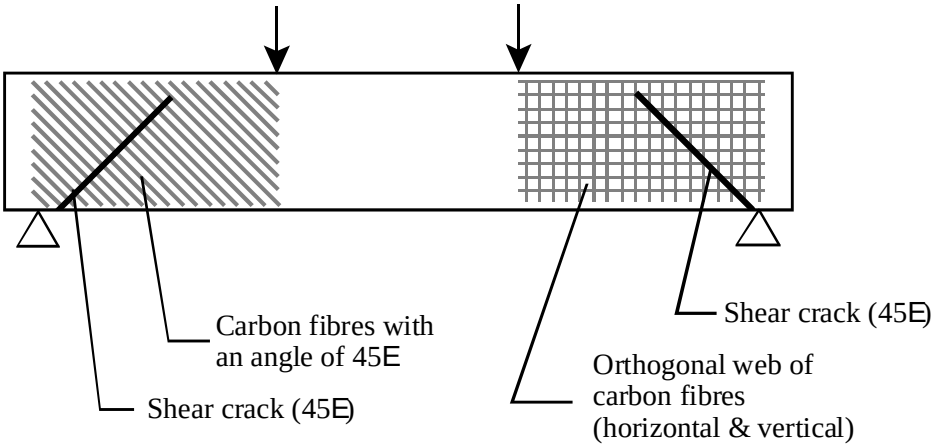

Figure 2 Shear strengthening with externally bonded CFRP laminates

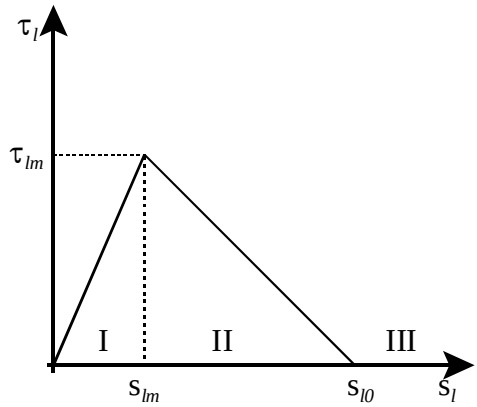

Figure 3 Bilinear shear stress-slip relationship

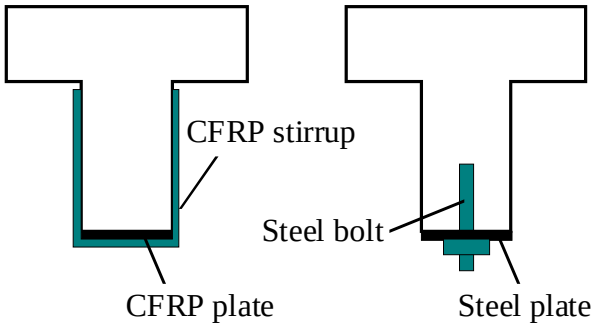

Figure 4 End anchorage of externally bonded reinforcement

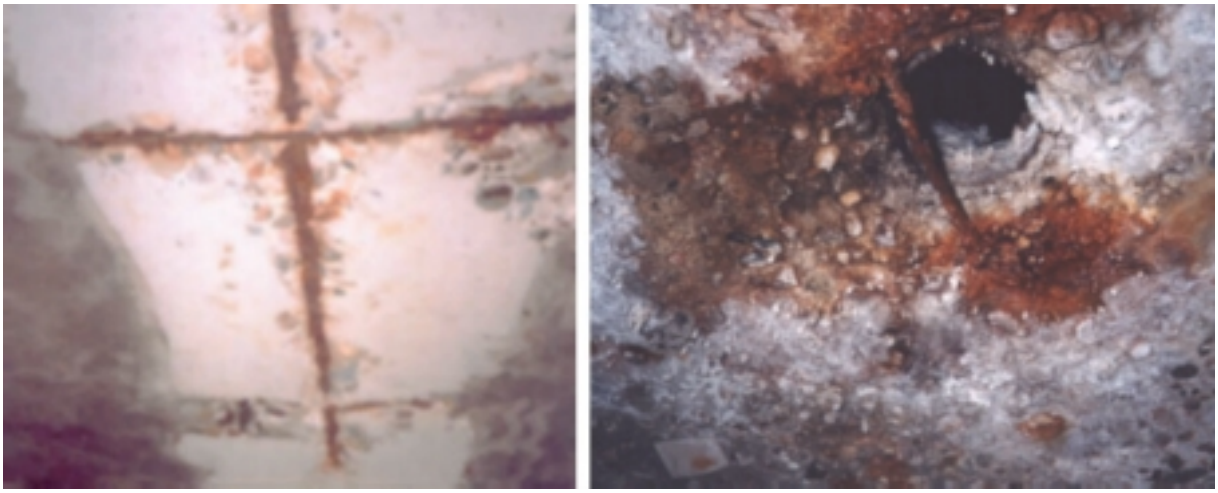

Figure 5 Concrete damage on roof structure of a swimming pool

Figure 6 CFRP strengthening of roof structure (left) and end result (right)

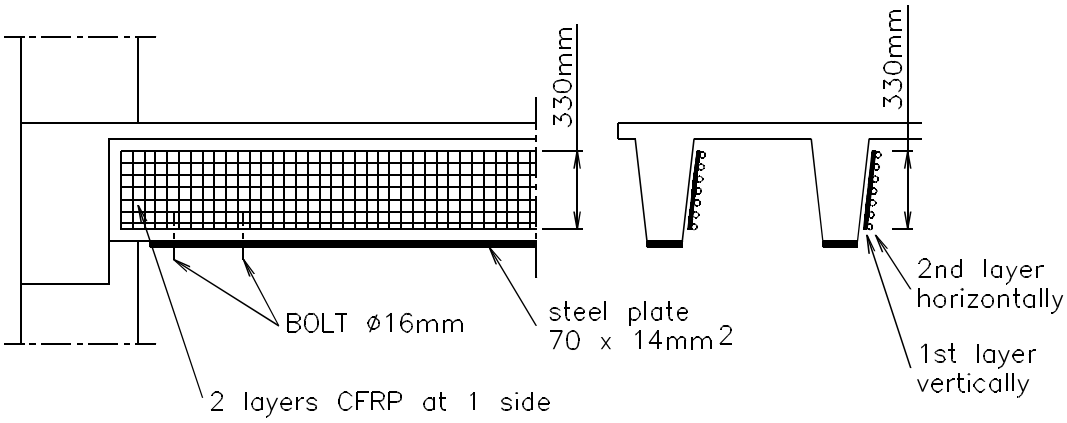

Figure 7 Hybrid strengthening of a ribbed floor slab

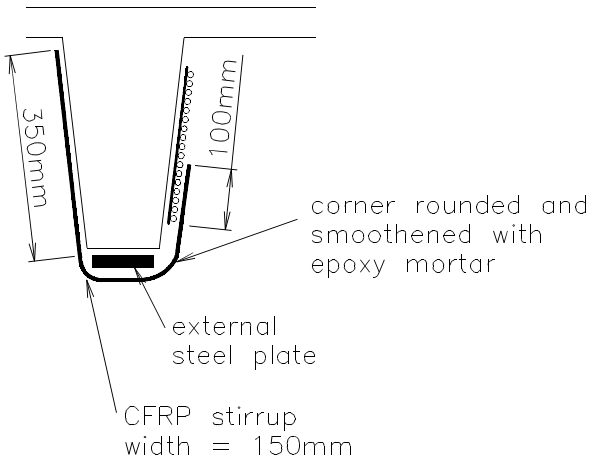

Figure 8 CFRP stirrup to prevent plate end shear crack

Figure 9 Hybrid strengthening of a ribbed floor slab

Figure 10 Application of the CFRP sheets