Design of structural connections for precast concrete buildings

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ABSTRACT

A proper design of structural connections for precast concrete buildings must be based on a deep understanding of the role of the connection in the structural system, the flow of forces through the connections, and basic force transfer mechanisms. Furthermore, needs with regard to functionality, simplicity, production and easy assembly should be considered

KEYWORDS

Precast concrete, connection, joint, bearing, compression, shear, tension

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1. GENERAL CONSIDERATIONS AND DESIGN PHILOSOPHY

The main purpose of the structural connections is to transfer forces between the prefabricated concrete elements when the structural system is loaded. By the ability to transfer forces, the connections should secure the intended structural behaviour of the superstructure and the prefabricated subsystems that are integrated in it. To reach a proper design of the structural connections, the designer should understand how the connections are parts of the overall system and be aware of the flow of forces through the structure as well as through the connections. The structural layout, the arrangement of stabilising units, the design of the structural system and its sub-systems, and the design and detailing of the structural connections must be made consistently and with awareness of the intended structural behaviour, Fig. 1.

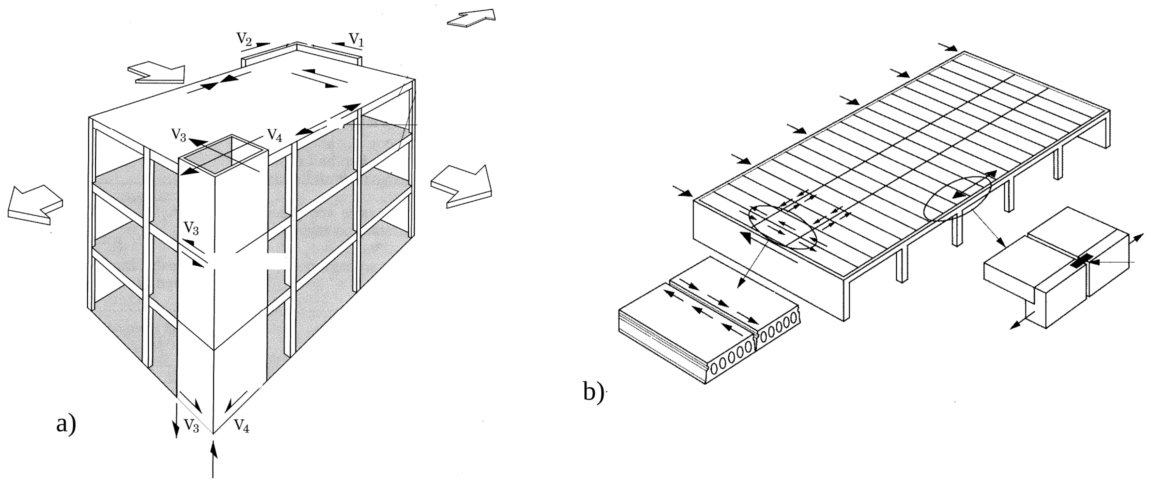

Figure 1. The connections should be designed consistently with the intended structural behaviour, a) global structural system, b) floor diaphragm as a sub-system

The design of the structural connections is not just a question of selecting appropriate dimensions of the connection devises, but the force path through the connection must be considered in a global view of the whole connection including the end regions of the adjacent structural members. Therefore, the connections and the elements must be designed and detailed as a unity where the flow of forces is logic and natural so that the forces that are to be resisted by the connection can be transferred into the elements and further on to the overall load-resisting system. The force transfer from tying devices, support bearings etc. into the adjacent prefabricated concrete elements must be secured by a proper design and detailing of these connection zones, Fig. 2. Hence, it may be necessary to design and reinforce the connection zones with regard to the action of concentrated forces and the corresponding risk of cracks.

The various aspects that should be considered in the design and detailing of structural connections can be related to the following groups:

- the structural behaviour for ordinary and excessive loads
- the performance and appearance of the building in the service state
- structural integrity in case of fire and accidental actions
- production of the concrete elements
- handling, storage, and transportation of the concrete elements
- mounting of the prefabricated structural system

Other key aspects in the design of structural connections are simplicity, standardisation, durability, and aesthetics. Much of the advantages of precast concrete construction are due to the possibility of fast erection of the structure. To fully realise this benefit and to keep the costs within reasonable limits, the connections should be kept simple.

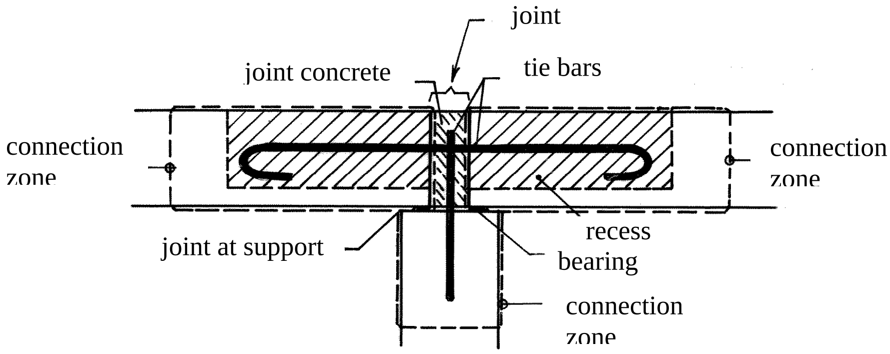

Figure 2. A structural connection consists normally of several components. The structural behaviour and the performance of the connection depend on the interaction between these components

2. BASIC FORCE TRANSFER MECHANISMS AND MECHANICAL BEHAVIOUR

When the behaviour of connections is studied more in detail, it is found that there are some rather few basic force transferring mechanisms that appear quite often in many different types of connections. A deep understanding of those basic mechanisms, of the flow of forces through the connections and of the role of the connections in the overall structural system forms the basis of proper design of structural connections.

2.1 Transfer of compression

Structural connections and connection zones of precast concrete elements are often subjected to high concentrated compressive forces, Fig. 3a. When these forces are transferred through the connection and further into the adjacent elements, they are spread into wider stress distributions. The deviation of forces (i.e. change of directions) and spread of stresses might lead to high transverse stresses. If the concrete tensile strength is reached, cracks will appear in these zones.

In case of improper detailing, these cracks might result in damage, which in turn might limit the capacity of the connection, for instance due to splitting failure in a support region. The 'strut and tie method' is an appropriate tool to design the connection zones and check equilibrium in the ultimate limit state. This method also reveals the flow of forces through the structural connection and, thus, helps the designer to understand the behaviour and find a proper detailing, which is consistent with the intended behaviour.

Connections mainly loaded in compression are often composed of materials in several layers. Depending on the properties of the materials, splitting effects might appear due to different lateral strains, Fig. 3b. On the other hand, splitting effects imposed on one material is balanced by restraining effects on the other material. Soft materials, like plain elastomeric bearing pads, have much larger lateral strain than concrete. In this case the splitting effect on the concrete elements is significant and has to be considered in design by provision of splitting reinforcement. The restraining effect on the soft bearing is also essential and should be considered in the design of the bearing itself.

Soft bearings are essential with regard to the behaviour of precast structures and should be consistently designed especially with regard to service demands. For instance, the size of the bearing pad should be limited so that it will not protrude from the joint when it is subjected to load. Furthermore, the bearing pad should be designed so that expected movements and rotations can take place without problem.

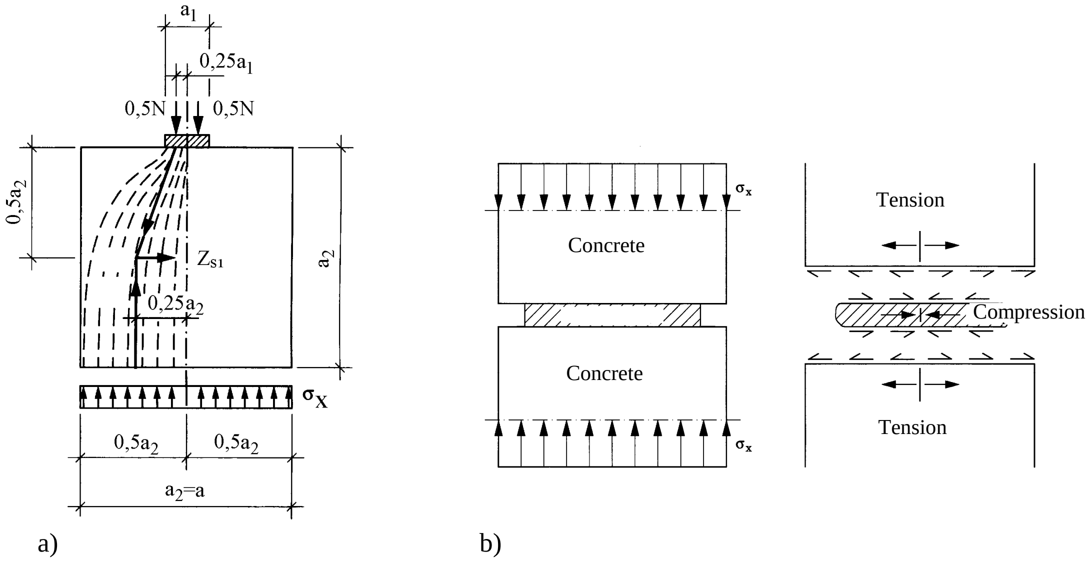

Figure 3. Transfer of compression, a) local compression, b) compression through several layers

2.2. Transfer of shear

Dowel action of partly embedded steel bars is a basic mechanism in the transfer of shear force. The simplest case is a bar embedded at one end and loaded by a shear force acting along the joint face or at some distance from the joint face, Fig. 4a. This load case will give rise to a highly concentrated reaction in the concrete beside the dowel pin. The connection zone must be designed and detailed so that this concentrated force is safely spread and transferred into the element. The concentrated force tends to split the element, but the splitting can be controlled by reinforcement designed to establish an equilibrium system in cracked reinforced concrete, Fig. 4b. The strut and tie method can be used in such design. Depending on the strengths and dimensions of the steel bar and the position of the bar relative to the element boundaries, several failure modes are possible. A weak bar in a strong concrete element might fail in shear of the bar itself. A strong steel bar in a weak element or placed with small concrete cover will more naturally result in splitting of the element itself. However, when the splitting effects are controlled by properly designed splitting reinforcement, the dowel pin will normally fail in bending by formation of a plastic hinge in the steel bar. For this bending failure, in which the steel bar yields and the concrete beside the bar deforms in a plastic mode, an eccentric application of the load reduces the shear capacity significantly and should be avoided when possible.

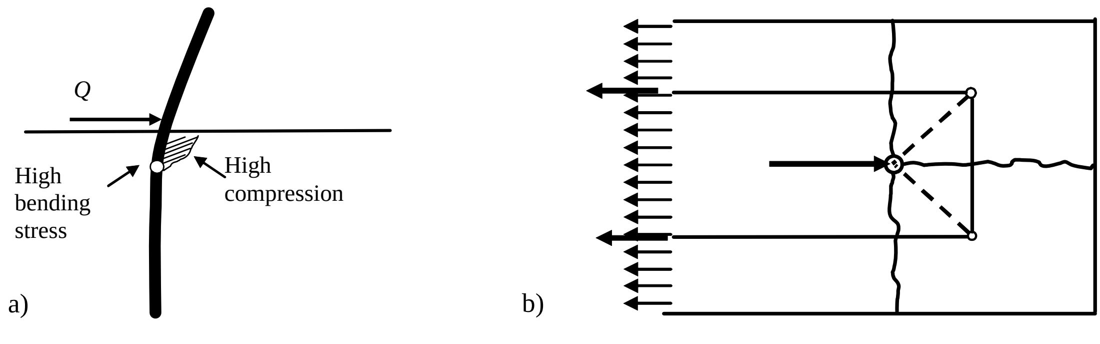

Figure 4. Transfer of shear by dowel action, a) plastic hinge development, b) equilibrium model around dowel pinto balance splitting effects

For a dowel pin embedded in elements on each side of a joint, plastic hinges will be formed on both sides, Figs. 5-6. The behaviour and the ultimate shear capacity are influenced by the detailing. In case of symmetry the two hinges will develop simultaneously and the capacity will in principle be the same

as for a similar one-sided dowel pin loaded with the same eccentricity. However, when the conditions are different on each side of the joint, for instance due to quite different concrete strengths, the plastic hinges will not develop simultaneously, and the ultimate load is reached at the formation of the second plastic hinge, which turns the resisting system to a collapse mechanism, Fig. 5a.

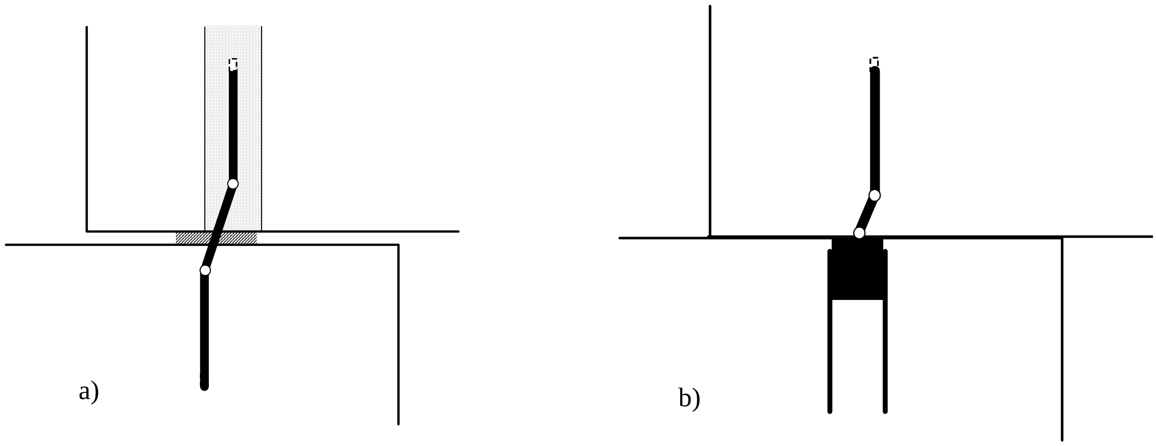

Figure 5. Transfer of shear by dowel action, a) influence of eccentricity, b) influence of end restraint in threaded insert

For a dowel pin in a threaded insert, Fig 5b, plastic hinges cannot develop at the same location as for a plain bar. This restraint will lead to an increased shear capacity, but on the other hand the threads reduce the cross-section and have a negative effect on the capacity.

When a dowel pin is provided with end anchors at both ends, the deformation of the bar is restrained by the end anchors, Fig. 6b. As a result a tensile force will develop in the bolt and this force will increase with increasing shear deformation (slip at the joint interface). This in turn leads to a clamping effect where the connected precast elements are pressed against each other. Hence, shear will be transferred partly by friction at the joint interface and partly by dowel action. It should be noted that since normal stresses develop in the bolt due to this restraint, the capacity in dowel action will be reduced.

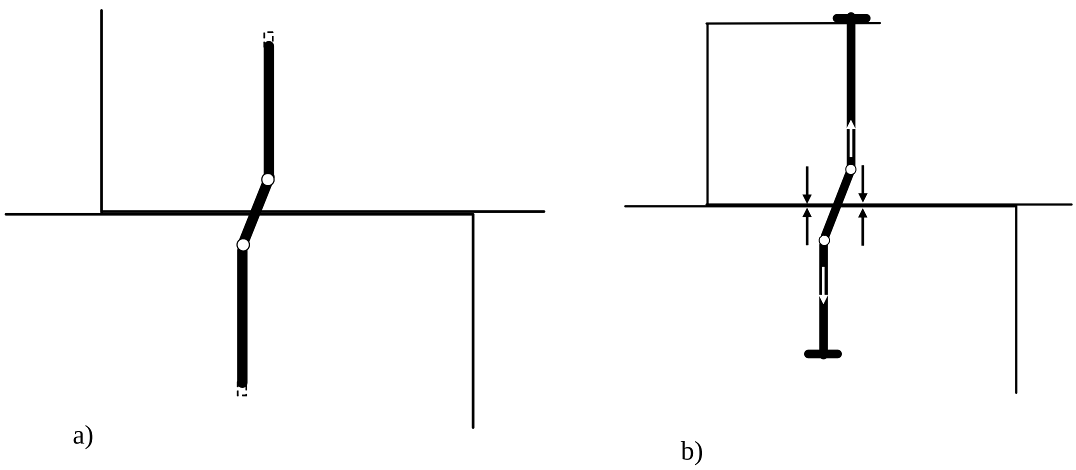

Figure 6. Transfer of shear by dowel action, a) no restraint at the ends, b) influence of restraint from the ends leads to frictional resistance

Another basic mechanism for shear transfer is frictional resistance at joint interfaces. The roughness of joint faces varies but can be controlled by treatment of the fresh concrete. Joint faces can be classified with regard to its natural roughness, roughness after special treatment or even specially formed shear

keys. Under the condition that normal compressive stresses are present at the joint interface or will be generated with increasing shear slip along the joint interface, a shear resistance is possible by friction. The mechanism is principally the same as the so-called aggregate interlock, Fig. 7a.

When under shear loading slip develops along the joint interface, this will be associated with a certain joint separation, because of the irregularities of the rough joint face. If the joint interface is crossed by steel bars that are well anchored on each side of the joint, the steel bars will be tensioned due to this joint separation, Fig. 7b. The tensile force in the bars must be balanced by compression at the joint interface. Thus, the wedging caused by the irregularities generates a compression force that makes shear transfer by friction possible, even in the case when there is no compression at the interface initially.

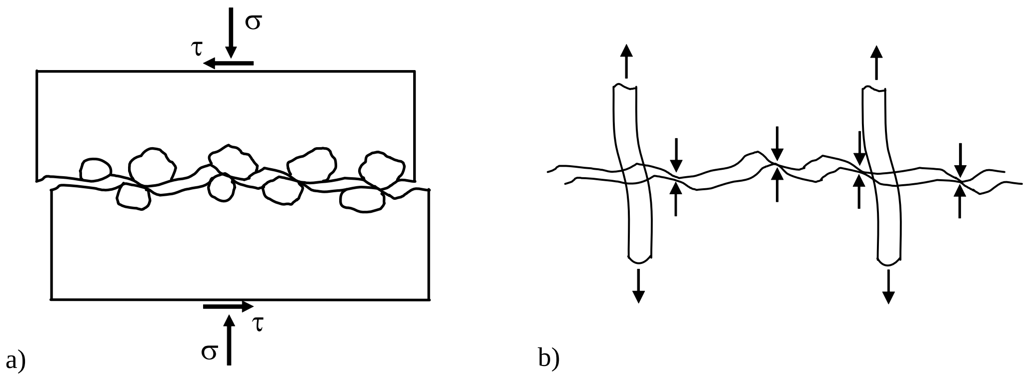

Figure 7. Basic force transfer mechanisms a) shear friction mechanism, b) bar pull-out

The force that develops in the transverse steel bars for a certain joint separation depends on the resistance of the bar to bar pullout, Fig. 9. Here the way the bar is anchored is essential. A plain smooth bar without end anchors will not provide any significant resistance to bar pullout and no compressive forces will be generated by the wedging effect. To achieve a high self-generated compression with as little steel amount as possible, the steel should be forced to yield for a very small joint separation. Then a high resistance to bar pullout is needed. A ribbed bar is effectively anchored on both sides of the joint face by bond and a small joint separation will result in high tensile strains that appear locally around the joint interface. For such a bar yielding can be obtained for a very small shear slip and before a significant contribution to the resistance is achieved by dowel action. Without anchorage of the bar, a resistance in pure dowel action is still possible, see Fig. 6a.

To increase the shear stiffness and the shear capacity of joints, they can be provided with specially formed shear keys, Fig. 8. When such a joint is loaded in shear, principal compressive stresses will develop in a skew angle between the shear keys on each side of the joint and principal tensile stresses will appear in the perpendicular direction. If the joint cracks, the horizontal component of the inclined compressive force must be balanced by transverse forces. For this purpose transverse reinforcement should be provided. The maximum shear force is reached when the effect of the shear keys disappears because of local failure. After this the behaviour of the joint transforms to a frictional mode where the transverse reinforcement plays an important role to provide self-generated compression in a similar way as discussed previously. On the other hand, a plain joint without shear keys will rely on the frictional resistance from the very beginning.

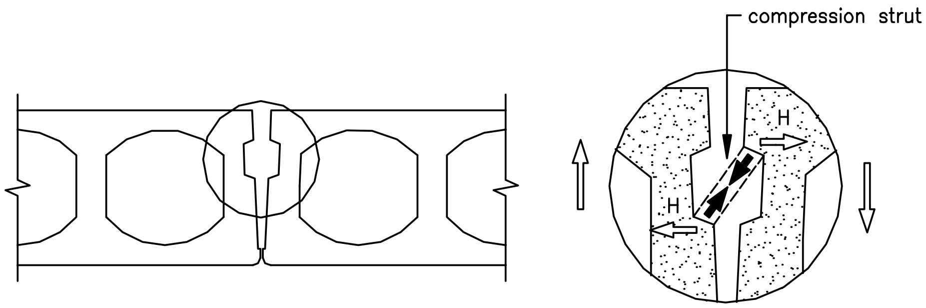

Figure 8. Transfer of shear by means of shear keys, horizontal component of inclined compressive strut needs to be balanced

2.3. Transfer of tension

For precast structures there must be a certain effort undertaken to ensure sufficient structural continuity and structural integrity. The connections act as bridging links between the precast elements. In this respect the ability to transfer tensile forces between elements is essential and tying systems should be arranged to meet these requirements. Furthermore, as mentioned previously, transverse reinforcement is also needed across shear joints to enable self-generated compression and to balance the transverse component of inclined compression forces in struts. Tie bars are also used to anchor welding plates in concrete elements.

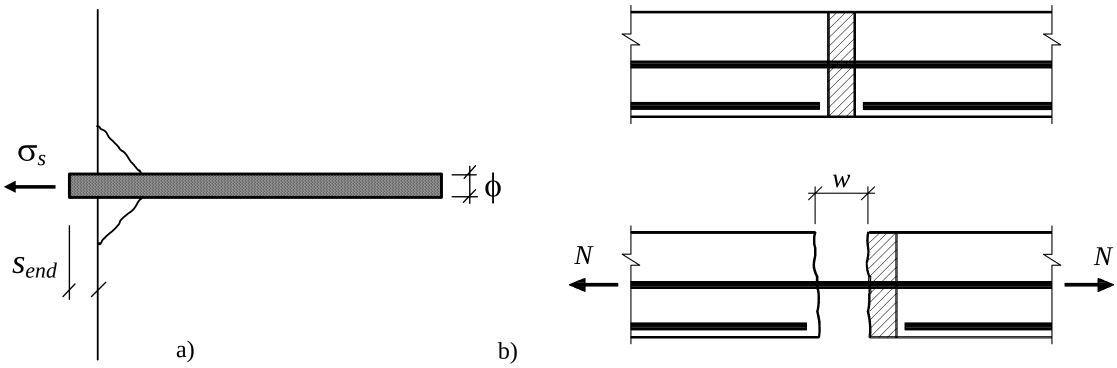

Figure 9. Transfer of tension, a) pullout resistance of anchor bar, b) pullout resistance of tie bar across a joint

Ribbed, threaded or otherwise indented bars are anchored by bond at the steel/concrete interface along the embedment length. Plain bars can be anchored by an end anchor. This can be achieved by bolts with a nut at a threaded end, headed bars, studs etc. Anchorage by bond will introduce the anchored force successively and softly into the concrete element, while in case of end anchor there will be a more concentrated effect.

When a ribbed bar is anchored by bond, inclined bond forces will develop along the interface within the so-called transfer length. The bond forces are in general not uniformly distributed, but are as highest near the loaded end. The continuous development of the slip at the loaded end under increasing load can be used to characterise the global behaviour of the anchorage. The relation between the applied tensile force and the end slip expresses the resistance to bar pullout, which was discussed previously for shear transfer by friction, Fig. 8.

It is typical in precast construction that tie bars are anchored not only directly into the concrete elements, but also quite often indirectly by placement in joints between the elements, Fig. 10. Here the

tensile force in the longitudinal bar must first be transferred by bond stresses from the bar to the joint grout and then by shear stresses across the longitudinal joint interface between the joint fill and the hollow core element. To secure this transfer of forces the transverse reinforcement plays an important role.

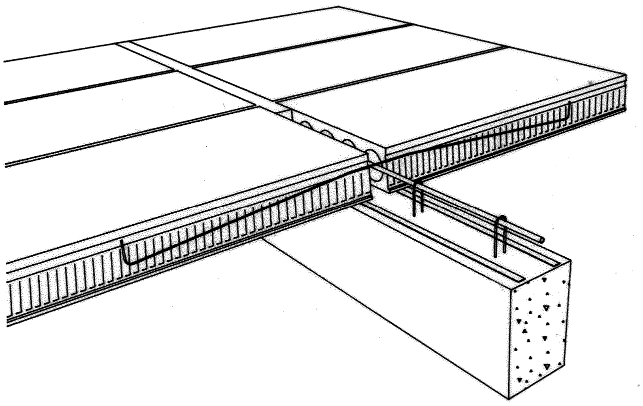

Figure 10. Example of indirect anchorage

In many cases connections consist of many components that act together as links of a chain. All the links contribute to the global load-displacement relationship of the composite connection. However, when a *ductile behaviour* is required from such a connection, it must be designed in a balanced way. Some of the components can be identified as ductile components, while the others have a more brittle behaviour. The aim of a balanced design for ductility is to secure that the full deformation capacity of the ductile links can be utilised. Brittle failures of the other components should be prevented before the full plastic deformation is obtained in the ductile ones. Hence, the other links should be designed to resist not only the yield capacity, but also the ultimate capacity of the ductile ones with a sufficient margin.

3. FIB BULLETIN ON STRUCTURAL CONNECTIONS

In order to encourage good and innovative design of structural connections in prefabricated concrete structures, the fib Commission on Prefabrication has prepared a design guide, which has recently been published as a fib Bulletin [1]. This guide gives basic understanding of how structural connections are parts of the overall structural system and prefabricated subsystems like floors, walls and frames. In this respect it is shown how the design of structural connections is influenced by the design philosophy of prefabricated buildings. Furthermore, the guide expresses a sound design philosophy for the connections as such and gives understanding of basic force transfer mechanisms in structural connections.

REFERENCES

[1] fib Commission 6 – Structural connections for precast concrete buildings. Guide to good practice. Lausanne: International Federation of Structural Concrete, 2008. 360 p. ISBN 978-2-88394-083-3.