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Bond behaviour between reinforcing steel and concrete under multiaxial loading conditions in concrete containments

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1 ABSTRACT

The effectiveness of bond strength between reinforcing steel and concrete is the most important requirement of reinforced concrete as composite building material. Thereby, the bond quality is influenced by a wide range of parameters. The focus in the presented paper is on the effect of tensile stresses processing perpendicularly to the bond zone of the embedded reinforcing bars, as it can be found in reinforced concrete walls of containments under increasing internal pressure.

The influence of transverse tension was determined by means of pull-out tests with different concrete covers. Compared to conventional building constructions, concrete covers in containment walls are to be expected considerably greater. The thickness of the concrete cover is an important factor in the bond failure mode. With the experimental results of the described tests the dependency of bond strength under transverse tension on the expected bond failure is shown.

2 INTRODUCTION

Important elements of the safety equipment of nuclear power plants are reinforced and prestressed concrete containments, which generally have been used as protective cover in pressurized-water and boiling-water reactors. For these structures, the leakage rate of hazardous products has to be limited to a maximum allowable rate. Therefore, the verification of integrity and leak tightness of containment structures is of high priority.

During hazardous incidents, the reinforced and/or prestressed concrete containment is exposed to high internal pressure and temperature loads. As a result, tensile loads affect the reinforced concrete structure in the hoop and vertical direction. If the tensile loading exceeds a critical limit, this biaxial stress state could induce a formation of first cracks at a lower level than expected from uniaxial laboratory tests. Additionally, an earlier initial cracking influences the crack formation process and therefore the deformation behaviour of the reinforced concrete structure.

The deformation behaviour of a modern prestressed concrete containment under increasing internal pressure was tested by means of a 1:4 scale model in the Sandia National Laboratories in the USA [Hessheimer (2003)], see Fig. 1. Calculations of the load-deformation-behaviour with Finite-Element-Analysis show a good agreement with the experimental data. However, larger differences between calculated and tested deformations could be observed in the phase of crack formation [Grebner (2005)]. For an accurate determination of leakage rates to a given stress state, an improvement of the analytical propagation of the load-deformation-behaviour during the cracking stage is important. Therefore, a precise knowledge of the cracking process is necessary.

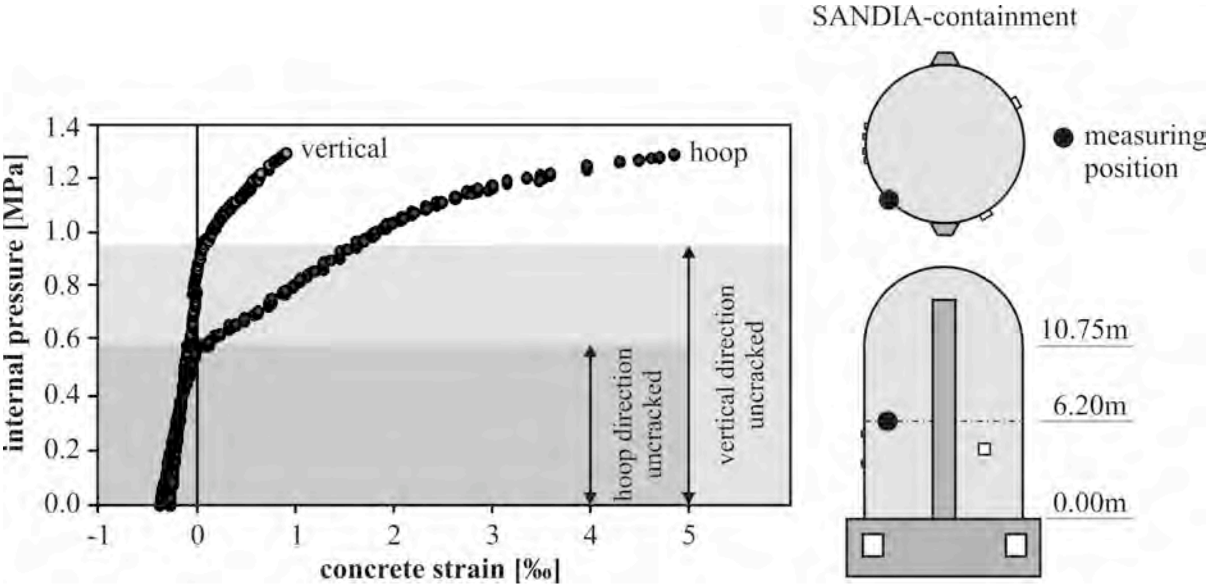

Figure 1. Deformation behaviour of the SANDIA-containment under increasing internal pressure

For realistic modelling of the load-deformation-behaviour of containment structures, multiaxial loading conditions as well as the interrelation and therefore the specific bond conditions between reinforcement and concrete should be considered. By means of a comprehensive experimental program, the bond properties between reinforcement and concrete under transverse tensile loads have been investigated. Pull-out tests with a short embedment length under transverse tension have been carried out. In order to represent the conditions of the primary cracking state, different grades of transverse tension were chosen with transverse tensile stresses lower than the uniaxial tensile strength of concrete.

The experimental results can be used in terms of bond stress-slip relationships for implementation into the FE-containment model. With this application, a more realistic modelling of the deformations in primary and stabilised cracking can be achieved. Furthermore, the test results can be used for the verification of ultimate limit states, e.g. anchorages and serviceability limit states, e.g. deformations and crack control.

3 PREVIOUS INVESTIGATIONS

3.1 Bond behaviour and failure modes

The structural behaviour of reinforced concrete elements basically requires the interaction between steel reinforcement and concrete. Tensile forces in the area of separating cracks and bending cracks are carried by the reinforcement and transferred into concrete by bond action. Crack widths and crack spacing are therefore significantly dependent on the bond properties of the applied reinforcement. Thus, stiffness and deformation behaviour of reinforced concrete elements are directly influenced by the bond properties.

For activation of the bond mechanism, relative displacements (slip) between steel and surrounding concrete are required. Essentially, bond action is achieved by mechanical interlocking of the steel ribs and the surrounding concrete. With initiating relative displacement, the ribs start to penetrate into the mortar matrix. Compressive stresses in the concrete compression struts additionally induce perpendicular tensile stresses and therefore inclined internal bond cracks starting at the ribs, so-called Goto-cracks [Goto (1971)], see Fig. 2a.

The conical concrete compression struts are balanced by circumferential tensile stresses in the concrete cover. In case of exceeding this concrete tensile strength, cracking occurs longitudinal to the bar [Tepfers (1973)], see Fig. 2a. Depending on the confinement effect due to the concrete cover or transverse reinforcement, these longitudinal cracks could result in splitting of the surrounding concrete, which comes along with an abrupt drop of the bond stress. This kind of bond failure is called splitting failure.

If adequate confinement of the bar is given by transverse reinforcement as well as high concrete covers, uncontrolled opening of these splitting cracks can be avoided and the bond strength can be increased further.

With increasing tensile loading of the bar, the concrete teeth between the ribs are sheared off and the maximum bond strength is reached. With progressive slip the concrete teeth will be increasingly destroyed until complete shearing-off, as far as only frictional bond stresses between steel and concrete can be transferred. This bond failure mode is called pull-out failure.

The transition between the two failure modes generally depends on the bar surface, the position of the bar, the bar spacing, the transverse reinforcement and the concrete cover as well. In Vandewalle (1992) the transition of splitting failure to pull-out failure is stated for related concrete covers of $c/d_s = 2.5 – 3.5$.

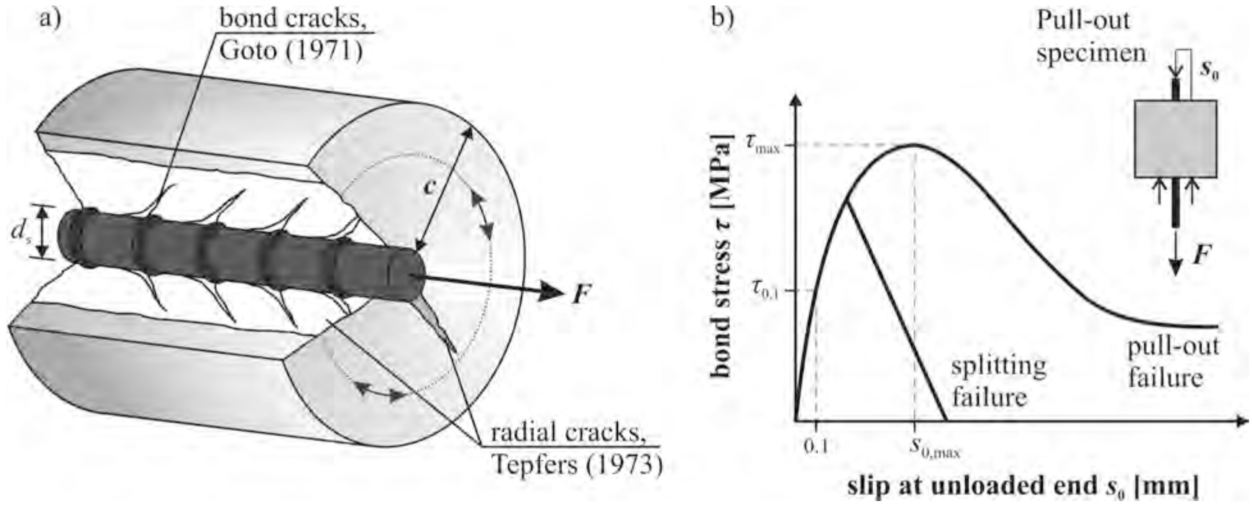

Figure 2. Failure mode and bond stress-slip relationship

In general bond stress-slip relationships are used to describe the bond behaviour, which can be determined on so-called pull-out specimens [RILEM (1994)], see Fig. 2b. In real structural elements, bond stresses for large relative displacements are of minor importance. At this, the bond behaviour for small slip values, which correspond to the dimension of limiting crack widths, is relevant. Based on the assumption that the mean crack width in structural elements is approximately consistent with twice the slip at the unloaded bar end in pull-out tests, for the estimation of the bond behaviour in serviceability limit states the bond stresses corresponding to slip values of $s_0 = 0.1$ mm are used, e.g. Rehm (1970). To characterise the bond behaviour, further parameters are the maximum bond stress $_{max}$ as well as the corresponding slip value $s_{0,max}$, which also can be taken directly from the bond stress-slip relationship, see Fig. 2b.

3.2 Bond behaviour under transverse tension

Increasing internal pressure causes biaxial tensile loading in the containment wall. Therewith, the embedded reinforcing bars are not only affected by axial loads but also by tensile stresses acting perpendicularly to the bar axis. This so-called transverse tension is superimposed by circumferential tensile stresses around the bar caused through bond action. As a result, deterioration of the bond behaviour is possible, depending on the thickness of the concrete cover and the level of transverse tension.

First investigations of the bond behaviour under transverse tension were carried out by Navaratnarajah (1982). He examined different bar types with a bar diameter of $d_s = 25$ mm and different concrete covers of $c/d_s = 1 – 3.5$ conducting pull-out tests with an embedment length of $l_b = 4d_s$. The transverse tension was applied by four continuously embedded steel bars, which additionally acted as transverse reinforcement (see Fig. 3).

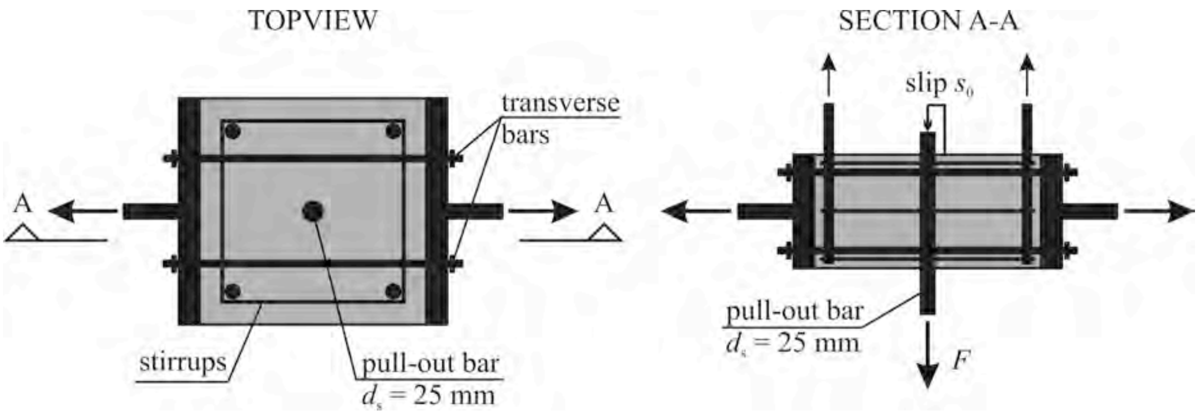

Figure 3. Test setup of Navaratnarajah (1982)

In Fig. 4 the bond stresses for a slip value of $s_0 = 0.1$ mm (a), the maximum bond stresses (b) and corresponding slip values (c) are plotted against the transverse tensile strain for the bar type Hybar and different concrete covers. Because the nature of the measured tensile strain is not specified, only quantitative statements can be made. It becomes evident that the bond stresses ${}_{0.1}$ slightly decrease with increasing transverse tension. With increasing pull-out load, radial cracks started to develop from the steel surface to the edges of the specimens. An increase of the pull-out load even after cracking could be observed because of the existing transverse reinforcement. Further increase of the pull-out load and progressive radial cracking caused abrupt slip and pull-out of the bar. However, the bond stresses and slip values according to the pull-out loads seem to be independent of the transverse tension level and nearly unaffected by the concrete cover.

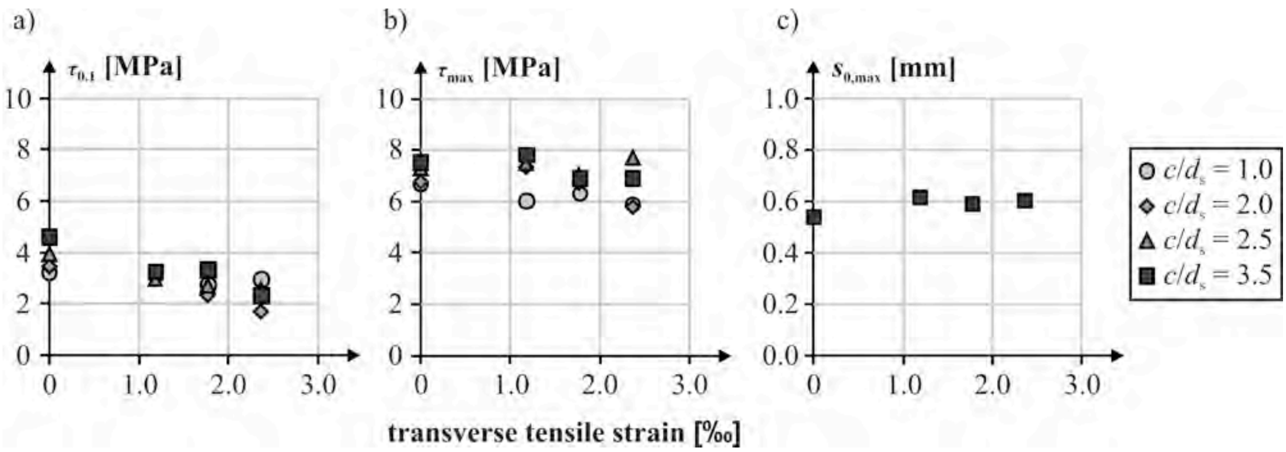

Figure 4. Test results of Navaratnarajah (1982) for Hybar

At the University of Stuttgart [Gerster (1989), Reuter (1992)] the influence of transverse tensile loads on the structural behaviour of splices was investigated. Concrete cuboids, containing four embedded reinforcing bars $d_s = 14$ mm, arranged centrically and spliced in pairs, were tested. The specimens were to represent a reinforcement splice in the flexural tension zone between two cracks. The transverse tensile load was induced by means of glued steel plates (see Fig. 5a). At first, the required transverse tension load was applied and subsequently the splice was loaded until failure. As a reference, tests were conducted without transverse tension (with and without steel plates) as well as tests without splice loading (with and without reinforcing bars).

Because of the steel plates the splice bearing capacity was insignificantly increased, which can be attributed to the constraint of lateral strain. The splice bearing capacity was insignificantly reduced with transverse tensile stresses lower than 20% of the splitting tensile strength of concrete. Though, with higher transverse tension the splice bearing capacity decreased about 60% (see Fig. 5b). All specimens showed a splitting failure with a splitting crack in the splice plane perpendicular to the applied transverse tensile load.

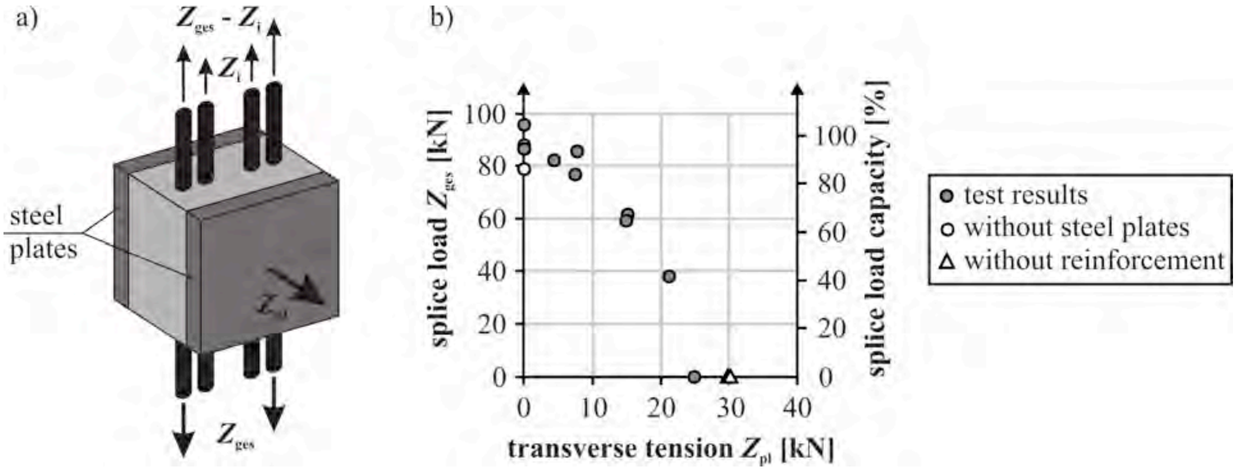

Figure 5. Test setup and results University of Stuttgart [Gerster (1989)]

Nagatomo and Kaku [Nagatomo (1990, 1992)] investigated the bond behaviour of ribbed reinforcing bars d_s = 22 mm depending on the transverse tension level and the concrete cover, using pull-out tests with an embedment length of $l_b = 7d_s$. In this case the transverse tension was applied via bolts into the lateral surface of the specimens. Oval holes and slits should ensure that the confinement effect of the bond area due to compressive reaction forces was minimised and the transverse tension acted constantly in the area of the embedded bar (see Fig. 6). The ratio p/f_{ct} of the applied transverse tensile stresses p and the concrete tensile strength f_{ct} was used to quantify the transverse tension level.

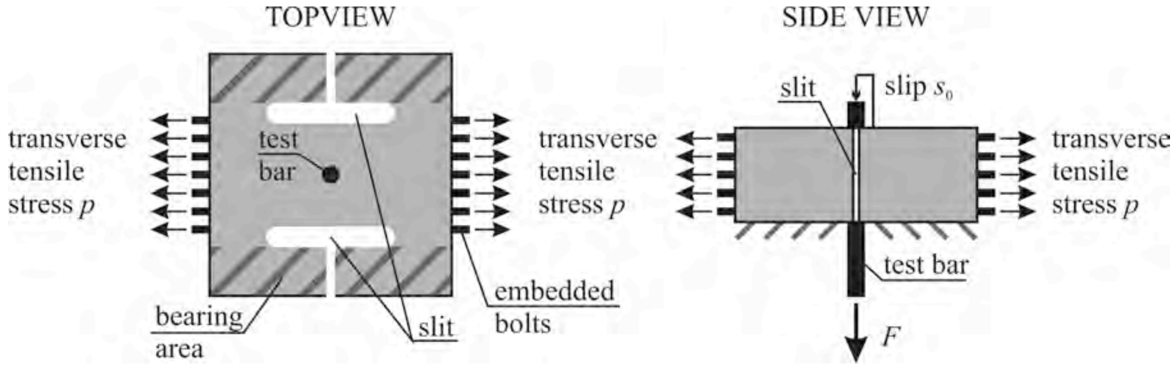

Figure 6. Test specimen of Nagatomo and Kaku [Nagatomo (1992)]

In Nagatomo (1990, 1992) the test results are also presented in terms of the maximum bond stresses and its corresponding slip values as well as the bond stresses for very small slip values s_0 = 0.01 mm. All pull-out tests ended with splitting of the concrete cover, whereas the crack processed longitudinal to the bar and perpendicular to the applied transverse tensile stresses. In Fig. 7b it can be seen that the maximum bond strength decreases rapidly with increasing transverse tension level while the initial bond stresses show no influence (Fig. 7a). In the case of a transverse tension level higher than 50% of concrete tensile strength failure occurs even before a noteworthy relative displacement appears between steel and concrete (Fig. 7c).

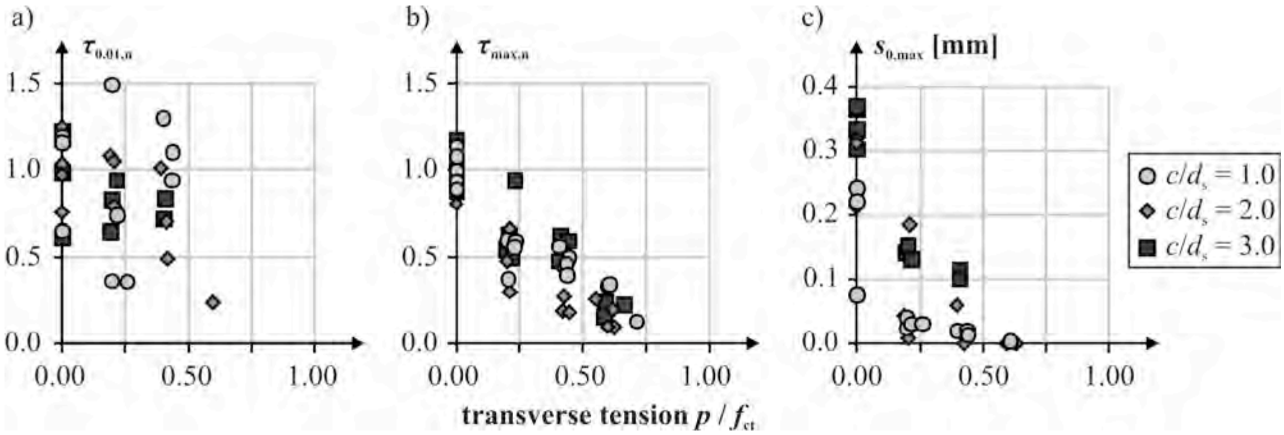

Figure 7. Test results of Nagatomo and Kaku [Nagatomo (1990, 1992)]

In summary, the existence of transverse tension significantly influences the bond behaviour and thus the bond quality. It has to be assumed that the bond failure mode is of major importance. All introduced previous test data are based on tests with relatively small concrete covers. Even without the existence of transverse tension, splitting failure has to be assumed in any case with such concrete covers according to Vandewalle (1992). The splitting tendency is intensified with increasing transverse tension, which is connected to decreasing bond strength.

However, both in real containment walls and in the SANDIA model containment significantly greater concrete covers are available than so far tested ($c/d_s = 2.0 - 6.8$). The existence of high concrete covers considerably influences the failure mode in case of no transverse tension. In this case, a pull-out failure is to reckon principally. But so far it remains unexplained, whether the results concerning bond behaviour under transverse tension for small concrete covers are transferable to higher concrete covers as well.

4 EXPERIMENTAL STUDIES

4.1 Scope of test program

According to the concrete strength of the SANDIA model containment, the pull-out specimens were casted with concrete strength class C40/50 ($f_{cm} = 47$ MPa). In the pull-out tests, bar diameters of $d_s = 16$, 20 and 25 mm were tested analogical to the applied reinforcement in the SANDIA-containment as well. To obtain information about the bond behaviour before longitudinal cracking occurs due to tensile loading in transverse direction, the transverse tension level remained always below the cracking load, meaning that no crack occurred along the pull-out bar. Altogether, the range below the initial cracking load was covered by four to five different transverse tension levels. Four specimens each transverse tension level were tested.

As a reference, pull-out tests without transverse tension were carried out as well as tests without pull-out load to determine the load bearing capacity under transverse tension. Accompanying to all test series, determination of the material parameters compressive strength, splitting tensile strength and Young's modulus took place.

4.2 Test specimen and instrumentation

The shape of the specimens is according to RILEM RC6 [RILEM (1994)]. The pull-out tests were carried out on cubical specimens with an edge length of 200 mm. With constant dimensions of the specimens, three different related concrete covers resulted for the tested bar diameters, see Table 1. To create a constant transverse tensile load in the bond zone, the short embedment length of $l_b = 2\ d_s$ was arranged centrically at the height of the specimens. In the regions above and below the embedment length, zones without bond were produced by means of plastic tubes, which were put over the bar, see Fig. 8a. To minimise frictional influences, the specimens were placed on an anti-friction rubber pad with minimised bearing area and arranged on a load cell. In order to apply the transverse tensile load, very stiff steel plates were glued on two opposite sides of the specimens using a two-component epoxy adhesive.

Table 1. Test program for pull-out tests.

Concrete	d_s [mm]	l_b [mm]	c/d_s [-]
C40/50	16	32	5.75
	20	40	4.50
	25	50	3.50

During bar pull-out the slip was measured at unloaded bar end by means of linear variable displacement transducers (LVDT). Controlling the strain distribution along the surfaces of the specimens, strain gauges with a gauge length of 60 mm were applied on the specimens in direction of the transverse tensile load. Using these strain gauges, circumferential strains induced by the bond action of the bar could be recorded as well. The instrumentation equipment is shown in Fig. 8b.

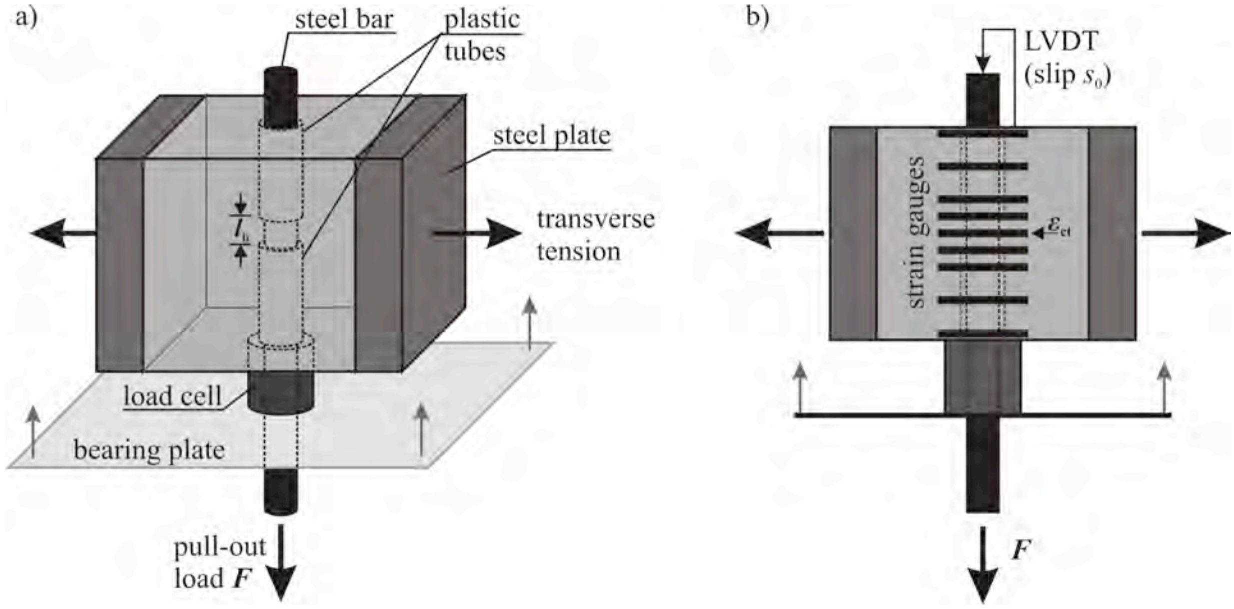

Figure 8. Test specimen for pull-out tests and instrumentation

4.3 Test setup

The pull-out tests were conducted in an electromotive combined tension-compression-testing machine with a load capacity of 250 kN. The bearing of the specimen was realised by an overhead rack installed in the testing machine. The pull-out bar was fixed by means of hydraulic clamping elements and deformation-controlled pulled-out in vertical direction.

A separate steel frame was designed to apply the transverse tensile load in horizontal direction. Thread rods, which were fixed to the steel plates, were anchored on one side behind the steel frame and on the opposite side behind a hollow piston cylinder that was rested on the steel frame. The hollow piston cylinder induced the transverse tensile load into this self contained system. The test setup for pull-out test realisation under transverse tension is shown in Fig. 9.

During the test, the preferred stress level of transverse tension was regulated and kept constant. Afterwards the application of the pull-out load with a loading rate of 0.01 mm/s took place. The pull-out load continued until either splitting of the specimen occurred (splitting failure) or a slip at the unloaded bar end of $s_0 = 10$ mm was reached (pull-out failure). Subsequently, in this case the transverse tensile load was increased until the specimen failed in order to determine the remaining bearing capacity due to transverse tension.

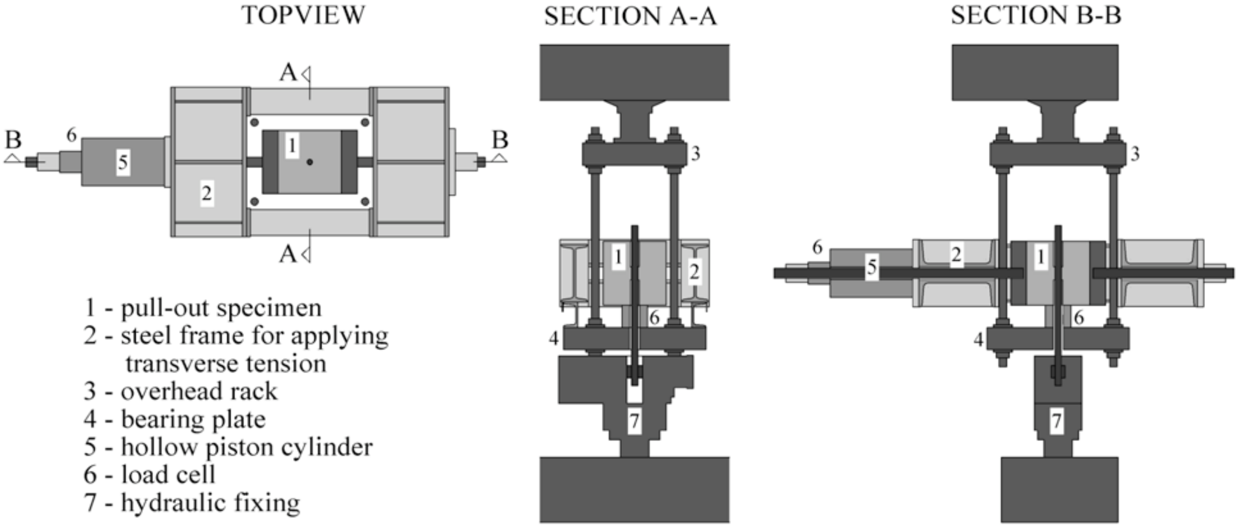

Figure 9. Test setup

5 RESULTS

The bond stress-slip relationship could be determined from each test. Thereby, the bond stress was calculated directly from the pull-out load F using eqn (1). To minimise the influence of the dispersive material properties among the individual test series, the calculated bond stresses were related to the concrete compressive strength. For this purpose it was taken into consideration that the bond stresses in the range of small relative displacements result in a dependency $\sim f_{cm}$ (e.g. Rehm (1970)) as well as an interrelation of the maximum bond strength $_{max} \sim f_{cm}^{1/2}$ (e.g. Eligehausen (1983), CEB (1993)).

$$= F / (u_s \cdot l_b) = F / (\cdot d_s \cdot 2 \cdot d_s) = F / (2 \cdot \cdot d_s^2) \quad (1)$$

… bond stress

F … pull-out load

u_s … bar circumference

d_s … bar diameter

l_b … bond length

In order to show the influence of transverse tension, the test results are normalised to the corresponding results without transverse tension. Fig. 10 shows the normalised bond stresses $_{0.1}$ for an unloaded bar end slip of $s_0 = 0.1$ mm plus the maximum bond stresses $_{max}$ and the corresponding slip values $s_{0,max}$ plotted against the transverse tension level for each bar diameter. Also the bond failure mode is noted in the diagrams by means of different symbols. The transverse tension level is presented in form of the concrete tensile strain $_{ct}$, which was measured at the surface of the concrete cover at half height of the embedment length, see Fig. 8b. According to CEB (1993), a fracture tensile strain of $_{ctu} \approx 0.15$ ‰ is assumed, where a crack would occur longitudinal to the pull-out bar, so that a pull-out test could no longer be conducted.

The common advantages of a short bond length go along with an inevitable scatter of test results. Pull-out tests with very short embedment lengths show a much greater influence of imperfections in the concrete, which can be seen in a wider scatter of the test results. This, by all means, can be up to 20% around the mean value, e.g. Rehm (1961). As observed already by other researchers, the scatters decrease with increasing relative displacement and increasing bar diameter, e.g. Soretz (1972), which is also shown by the presented test results.

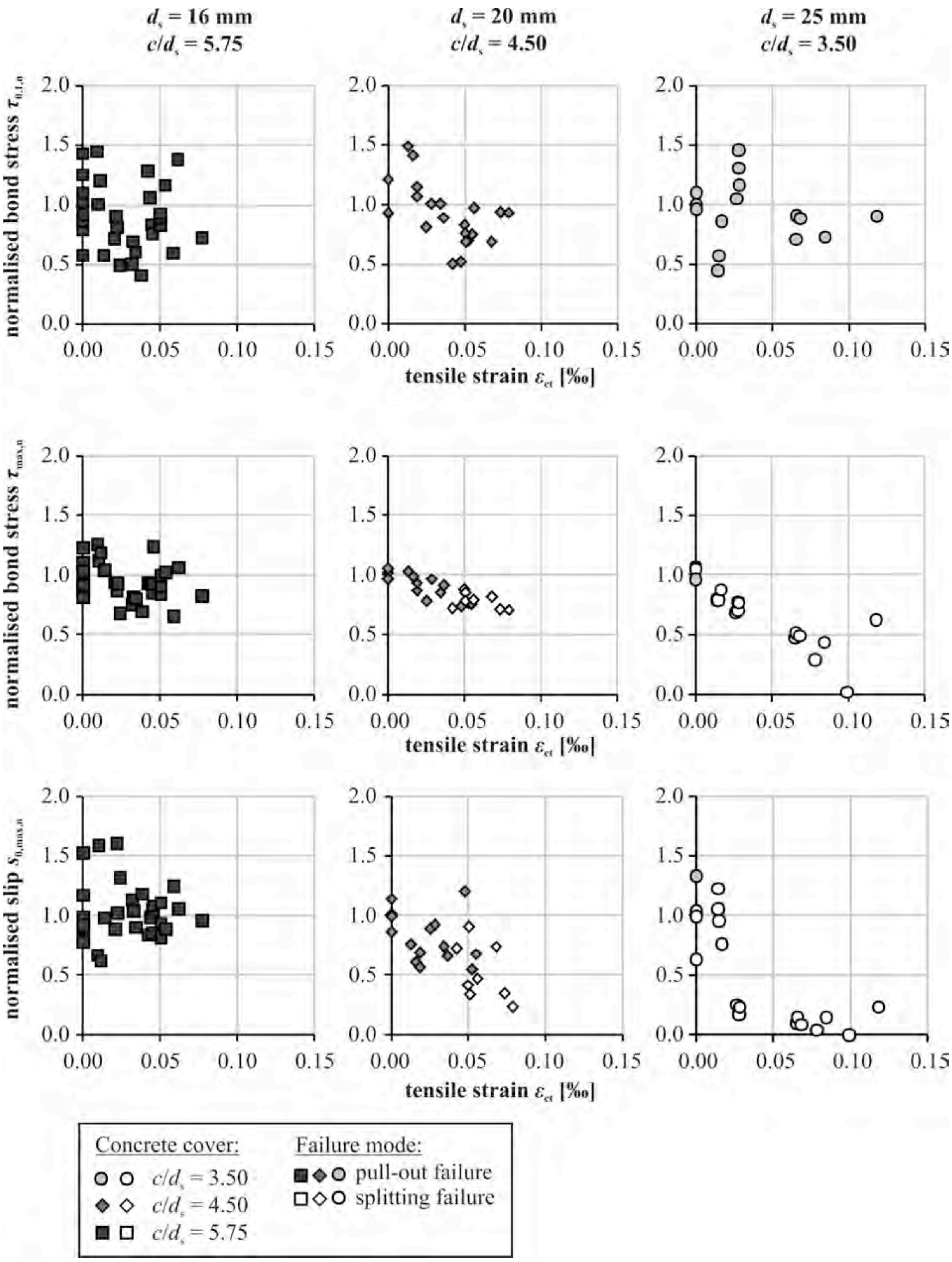

Figure 10. Test results of pull-out tests

According to CEB (1993) a steel bar confinement with concrete covers of $c \geq 5d_s$ ensures adequate guarantee against splitting failure. This is reflected by the test results for a steel bar d_s = 16 mm with a related concrete cover of c/d_s = 5.75. Neither the bond stresses $_{0.1}$ and $_{max}$ nor the slip values $s_{0,max}$ are negatively influenced by the applied transverse tensile load. Thereby, in any case bond failure occurred as pull-out failure.

On the contrary, the influence of transverse tension clearly emerged on tests with a bar diameter of $d_s = 20$ mm and a medium related concrete cover of $c/d_s = 4.5$. For low transverse tension levels the bond behaviour remains largely unaffected. The bond stresses $_{max}$ as well as the slip values $s_{0,max}$ decrease continuously with higher transverse tensile loading. For tensile strains $_{ct} \geq 0.04‰$ the applied transverse tension also affected the failure mode: instead of pull-out failure, splitting failure occurred. In that case, the crack always processed longitudinal to the bar and perpendicular to the transverse tensile stresses.

With the smallest related concrete cover of $c/d_s = 3.5$, splitting failure even without transverse tension was the predominant failure mode. Here, with increasing transverse tension, the maximum transferable bond stress decreased rapidly. Hardly noteworthy relative displacements between steel bar and concrete were measured with pre-adjusted tensile strains $_{ct} \geq 0.05‰$ before failure occurred. The test results correspond very well with the test results of Nagatomo and Kaku for concrete covers $c/d_s = 3.0$ [Nagatomo (1992)] as it is shown in Fig. 11.

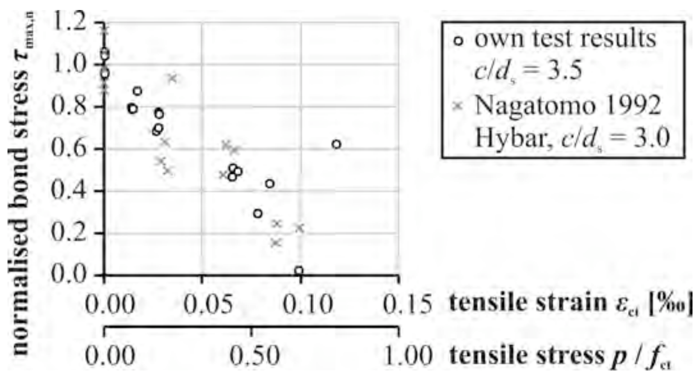

Figure 11. Test results of pull-out tests

To sum up the test results, the influence of transverse tension on bond behaviour between reinforcing steel and concrete depends considerably on the bond failure mode and therefore on the concrete cover. With smaller concrete covers it is to act on the assumption of splitting tendency, which can be enforced by an applied transverse tensile load. As previous investigations showed already, this results in a rapid decrease of the bond strength. The decrease of the bond stresses turns out much clearer in the range of fracture displacements $s_{0,max}$ than for small slip values like $s_0 = 0.1$ mm. For high concrete covers a different behaviour appears. Essentially, pull-out failure occurs, where the entire bond behaviour is hardly affected by transverse tension.

6 CONCLUSION

The structural behaviour of reinforced concrete elements and prestressed concrete elements is significantly affected by the bond properties of the reinforcement. The bond properties are again related directly to the loading conditions of the structural element. In case a biaxial tensile load occurs, e.g. in containment walls, deterioration of the bond properties is possible, which also may affect the cracking and the structural deformation behaviour.

By means of pull-out tests with different concrete covers the influence of transverse tension on the bond behaviour between reinforcing steel and concrete was investigated. The results show that the influence of transverse tension primarily affects the bond failure mode and thus the maximum transferable bond stresses. Furthermore, the experimentally determined bond stress-slip relationships can be used for implementation into FE-models for realistic modelling of the deformation behaviour of reinforced concrete and prestressed concrete structures.

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Symbols

c	concrete cover	mm
d_s	bar diameter	mm
F	pull-out load	kN
f_{cm}	mean compressive strength	MPa
$f_{cm,i}$	mean compressive strength of single test series	MPa
$f_{ct,sp}$	splitting tensile strength	MPa
l_b	bond length	mm
s_0	slip at unloaded end	mm
$s_{0,max}$	corresponding slip value at unloaded end for $_{max}$	mm
$s_{0,max,n}$	normalised slip value $s_{0,max,n} = s_{0,max} / s_{0,max,0}$	-
$s_{0,max,0}$	corresponding slip value at unloaded end for $_{max}$ without transverse tension	mm
$_{ct}$	tensile strain of concrete	‰
$_{ctu}$	fracture tensile strain of concrete	‰
$_{0.1}$	bond stress for slip value s_0 = 0.1 mm	MPa
$_{0.1,n}$	normalised bond stress for slip value s_0 = 0.1 mm $_{0.1,n} = (_{0.1}/f_{cm,i}) / (_{0.1,0}/f_{cm,i})$	-
$_{0.1,0}$	bond stress for slip value s_0 = 0.1 mm without transverse tension	MPa
$_{max}$	maximum bond stress	MPa
$_{max,n}$	normalised maximum bond stress $_{max,n} = (_{max}/f_{cm,i}^{1/2}) / (_{max,0}/f_{cm,i}^{1/2})$	-
$_{max,0}$	maximum bond stress without transverse tension	MPa

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