

**EXPERIMENTAL STUDY ON ANCHORED BARS IN
R.C. ELEMENTS WITH TRANSVERSE
REINFORCEMENT**

Giovanni A. Plizzari
Professor

Massimo A. Deldossi
Structural Engineer

Stefano Massimo
Structural Engineer

Dept. of Civil Engineering
University of Brescia - Via Branze, 38 - Brescia 25123 - Italy

Published on:
Materials and Structures, Vol. 29, pp. 534-542

April 25, 2002

1 Introduction

In anchorages and overlapped splices with ribbed bars having a diameter larger than $12\div 14$ mm (roughly no.4,5), splitting cracks are often present in the concrete cover because of the radial pressure due to the ribs of the highly-stressed rebars [1, 2]. Starting from flexural cracks where the bar-to-concrete slip reaches the maximum value, the splitting cracks propagate along the anchored bar and, in doing so, they damage the bond between the steel rebar and the surrounding concrete (Fig. 1a).

Concrete splitting makes bond behaviour very sensitive to confinement. In order to control splitting and to improve bond efficiency, a confining action along the anchored bar is needed. This confining action could be provided by the residual stresses transmitted between the faces of the split concrete cover [3], by an external transverse pressure (if any) [4, 5, 6], and by transverse reinforcement distributed along the anchorage [7] (Fig. 1b). If the confining action is not adequate, splitting cracks develop abruptly along the anchored bars, and a sudden anchorage collapse occurs [1, 8, 9, 10] (“splitting failure”, Fig. 1c). On the contrary, when an adequate confining action is present, bond stress increases up to the compressive failure of the concrete corbels between the ribs [9] (“pull-out failure”, Fig. 1d).

The research work on concrete splitting control in anchorages available in the literature, mainly regards the local bond behaviour related to a very short length of an anchored bar. With regard to this, a theoretical model was proposed in [9]. This model takes into account both the split concrete and the transverse reinforcement confinements which are governed by several phenomena, studied individually in [11, 12, 13, 14]. As far as long anchorages are concerned, the numerous experimental results available in the literature, to the best of the authors’ knowledge, have mainly given information on the overall anchorage strength but little on splitting cracking, so that they do not allow to shed light on the problem in all its aspects. In fact, the bond stress, the bar-to-concrete slip and thus the splitting crack opening vary along the the anchorage length [15]. In particular, the splitting crack is not

present where the slip is very small, and tends to be first partially and then completely propagated (transversely) close to the flexural crack (Fig. 1a), where the slip reaches the maximum value. Hence, anchorage behaviour can be correctly studied only if splitting is taken into account [16].

In the present paper, further results in the research work on split anchorages are shown. Anchorages with more than one transverse reinforcement are analyzed and particular attention is devoted to gathering more detailed results on bar-to-concrete slip and splitting crack propagation along the anchored bar with the aim of providing useful information for further theoretical modelling. The interferometric Moiré technique is adopted to obtain a full displacement field and thus crack openings [17, 18].

2 Experimental model and materials

2.1 Specimen geometries

Two different specimen geometries were tested as shown in Fig. 2a. Six specimens with one anchored bar and six stirrups (three at each side) having different diameters were tested to study the anchorage response for different amounts of transverse reinforcement (Series 1, Fig. 2a). Series 2, with specimens containing two anchored bars and six stirrups, 6 mm in diameter, had the purpose to study the contribution of the concrete cover confinement on anchorage behaviour. Two of the specimens of this second series had a preformed ideal splitting crack. In two additional specimens the concrete was uncracked so that it was able to transmit confining stresses between the split faces, before and after cracking. In all specimens the anchored bars were 20 mm in diameter and had an anchorage length of 180 mm (14 ribs); as a consequence, the stirrup distance Δz was 60 mm. The principal bars were placed with the ribs oriented towards concrete blocks C1 and C2 in order to have a wedging action and thus the splitting crack in plane AA (Fig. 2a); the stirrup ribs were oriented in a way to avoid radial pressures towards the concrete surface [19]. Tab. 1

shows some specimen characteristics such as the principal and transverse bar number and diameter, the concrete cover and the following bond indexes of confinement [9]:

- “stirrup index of confinement” Ω , which is defined as the ratio between the total area of stirrups and the total area of the longitudinal section of the anchored bars in the splitting plane:

$$\Omega = \frac{A_{st}}{A_p^*} = \frac{n_{st}A_{st}}{n_p\phi_p\Delta z} \quad (1)$$

where n_p e ϕ_p are the number and diameter of principal bars, and n_{st} e A_{st} are the number and diameter of the transverse bars in the influence zone Δz ;

- “concrete index of confinement” B , which is defined as the ratio between the total area of concrete cover and the area of the longitudinal section of the anchored bars in the splitting plane:

$$B = \frac{b - n_p\phi_p}{n_p\phi_p} \quad (2)$$

where b is the specimen width.

The concrete was poured into wooden forms with the principal bars in a vertical position, as illustrated in Fig. 2a; since the pour direction was opposite to the direction of the pull-out force, better bond characteristics were obtained [20].

The concrete mix proportions are shown in Table 2. Tab. 3 shows the geometrical and mechanical properties of the principal bars and the stirrups.

The forms were stripped 36 hours after casting. The specimens were then stored in the laboratory at $\approx 70\%$ humidity and temperatures ranging between $15^\circ C$ and $25^\circ C$ until the time of testing. During the pour, six cylinders (10 cm in diameter, 30 cm in length), and two cubes (15 cm sides) were cast for each specimen and stored in the same manner as the specimens. After 28 days of curing, compressive $f_{c,28}$, (direct) tensile strength $f_{ct,28}$ and

tangent modulus $E_{ct,28}$ were determined on cylinders. At the time of the tests, also compressive strengths $f_{c,cube}$ were determined on cubes. The values obtained are summarized in Tab. 4.

2.2 Instrumentation

The instrumentation adopted allowed to measure the relationship between the pull-out force, the bar slip at the loaded and unloaded ends and the splitting crack opening at the stirrup levels [19] (Fig. 2b). In particular, the anchored bars were equipped with strain gauges to determine the applied load while the splitting crack opening and the bar-to-concrete slip of the loaded and unloaded ends of the bars were measured by means of inductive transducers (Fig. 2b).

In order to evaluate the entire splitting crack pattern on the specimen surface, the interferometric Moiré technique [17, 18] was adopted in specimens 2S6P2 and 2S6NTP2; the Moiré lines were vertically oriented on the front side to measure the horizontal displacements and thus the splitting crack openings. In the other specimens, the concrete surface was previously prepared with a thin layer of gypsum and the splitting crack propagation was controlled by means of a magnifying glass (6x). The Moiré fringes were obtained by means of the same technique adopted in [21].

3 Experimental set-up and loading modalities

The test equipment shown in Fig. 3 is similar to the one adopted by Giuriani and Plizzari [22]. It is suitable to apply the load by means of a hydraulic servo-controlled testing machine. The bench allows blocks C1 and C2 to have relative displacements for making splitting cracking possible and to perform both pull-out and push-in tests.

The specimen acted against steel angles which were connected to the upper part of the bench by means of hinges obtained by decreasing the thickness of the steel angles (Fig. 3).

These hinges allow a free displacement between concrete blocks C1 and C2, which are therefore connected only by the concrete cover and the transverse bars.

The load was applied imposing a continuous displacement at one anchored bar end up to a maximum displacement of $4\div 5$ mm ($\phi_p/4 \div \phi_p/5$). The average displacement rate, up to the peak load, was $0.6 \mu\text{m}/\text{min}$ so that the specimens can be considered as subjected to a quasi-static load. During the test, some loading and unloading cycles were performed.

The measurements from the strain gauges and inductive transducers were stored in a PC at a frequency of 1 Hz by means of a data acquisition system. For the specimen with Moiré grids, pictures were taken every ≈ 2.0 kN ($\approx P_{max}/75$).

Further details about the experimental set-up can be found in [19].

4 Results and Discussion

The results concern: 1) the pull-out force on the anchored bar; 2) the slip at the loaded and unloaded ends of the bar and 3) the splitting crack openings measured at the stirrup levels.

Figs.4a,b show typical results of two specimens of the first series of tests. In particular, the upper part shows the pull-out force versus the slip of the loaded and unloaded ends whereas the lower part shows the splitting crack opening measured at the stirrup levels versus the loaded end slip.

The curves shown in Fig. 4a, which refers to specimen 1NSP2 without transverse reinforcement, stopped just after the peak load when the splitting collapse of the anchorage occurred. In fact, when the splitting crack propagated along the whole anchorage length, a sudden free bar slip occurred, and the servo hydraulic controlled machine was not stiff enough to control the post-peak response. Fig. 4b, which refers to specimen 1S8P2, shows the anchorage response up to the final push-in of the bar; notice the remarkable residual splitting crack opening after unloading.

The values of the peak load F_{max} , the slip at the peak load s_{max} , the anchored bar

stress σ_p and the average value of the evenly distributed ultimate bond stress $\bar{\tau}$, obtained from all the specimens, are summarized in Tab. 6. The complete set of experimental results can be found in [19].

A comparison between the curves of the first series of tests in terms of pull-out load versus loaded and unloaded end slips is shown in Figs. 5a,b up to the peak load. It should be noted that specimen 1NSP2 shows both lower stiffness and peak load because of the lack of transverse reinforcement which caused a splitting collapse of the anchorage. In the other specimens, the transverse reinforcement percentage was such that a pull-out failure of the anchorage occurred. The difference between the specimens with stirrups 6 mm and 8 mm in diameter is negligible since stirrups $\phi_{st} = 6 \text{ mm}$ at a distance of 60 mm already provide a strong confinement and, as a consequence, a larger amount of transverse reinforcement (as with $\phi_{st}=8\text{mm}$) has little influence on the anchorage behaviour. All the specimens with transverse reinforcement show a load-slip relationship which is nearly linear up to a value of the pull-out load of 80 kN ($\approx 2/3F_{max}$) where the loaded end slip is $\approx 0.15 \text{ mm}$. The curves of the pull-out load versus the loaded end slip for the second series of tests are shown in Fig. 5c. Notice that the curves for specimens with preformed splitting crack are characterized by a lower stiffness and a similar peak load. This behaviour is better evidenced in Fig. 5d which shows the average curves of the pull-out load versus loaded end slip for the specimens with and without preformed splitting crack, respectively. In the same diagram the difference between the two curves is evidenced; such a difference represents the effect of the confining contribution of the concrete cover. It should be noted that such contribution, negligible at peak load because of the small concrete cover and the large splitting crack opening, is relevant in the initial part of the curve which corresponds to the anchorage behaviour under service loads.

Fig. 6 shows the ultimate bond stress $\bar{\tau}$, assumed as being evenly distributed along the anchorage length and normalized to the square root of the compressive strength, versus the

stirrup index of confinement Ω [9] (Eq. 1), as obtained by both the first and second series of tests. In specimens 1NSP1 and 1NSP2, without stirrups ($\Omega = 0$), the confining action was due to the concrete cover only. Although the few results obtained in this research program do not allow to draw final conclusions, it is already evident that the larger the stirrup index of confinement is, the higher the anchorage strength becomes; however, beyond a certain value Ω_{max} , no significant increase of anchorage strength occurs. If the relationship between the bond strength $\bar{\tau}$ and the stirrup index of confinement Ω were approximated by a bilinear relationship, the threshold value Ω_{max} would be ≈ 0.05 . In comparison, the ultimate bond stress f_{bd} given in EC2 [23], for concrete having the same compressive strength as the tested specimens, is shown; according to this code, the bond strength is independent of the amount of transverse reinforcement (only a minimum area of stirrups is required) so that the anchorage strength is represented by a horizontal line.

In Figs. 7a,b,c the splitting crack openings w_{s1} , w_{s2} and w_{s3} from the first series of tests, measured at the transverse reinforcement level, are plotted versus the loaded end slip. Once a slip of ≈ 0.1 mm was reached, the splitting crack openings in specimen 1NSP2, without transverse reinforcement, became larger than in the other specimens with transverse reinforcement. The larger crack openings w_{s1} of specimen 1S8P1 and w_{s2} of specimen 1S6P2 are probably caused by a slight bar inclination with respect to the concrete surface. This is confirmed by the smaller crack opening w_{s3} of specimen 1S8P1. One should note the negative values of crack opening w_{s3} for slips smaller than ≈ 0.15 mm (Fig. 7c); this behaviour is caused by compression in the concrete provoked by specimen bending due to load eccentricity [19]. Figs. 8a,b show the results of w_{s1} and w_{s2} from the second series of tests; the authors have no explanation for the anomalous behaviour of specimen 2S6P1.

Figs. 7d and 8c show the length Y of the splitting cracks, measured from the loaded end of the anchored bars, versus the pull-out force. A bilinear trend of all the curves should be noted; this indicates two different crack propagation rates: slower at the beginning (up

to $\approx 50\%$ of the peak load) and then faster afterwards. As mentioned above, splitting crack opening of specimen 1NSP2, without transverse reinforcement, shows a faster crack propagation rate. Fig. 8d shows the splitting crack shape for three different loading steps, as obtained from an evaluation of the Moiré fringes; the 40 lines/mm of the adopted grids allowed for a precision of 1/100 mm.

5 Conclusions

Two series of specimens with anchored ribbed bars and transverse reinforcement were tested with the aim of studying the confining effects of stirrups and concrete cover. The primary goal of the first series, six specimens with one anchored bar and stirrups having different diameters, was to investigate the confining contribution of transverse reinforcement on bond response. The second series, four specimens with two anchored bars 20 mm in diameter and six stirrups 6 mm in diameter, had the purpose of studying the confining contribution of the concrete cover. To this extent, in two specimens, an ideal splitting crack was preformed by means of an aluminum plate placed in the wooden form before casting.

The principal results can be summarized as follows:

- In specimens of the first series without transverse reinforcement, a splitting collapse of the anchorage occurred at the onset of the slip at the unloaded end of the anchored bar. Viceversa, in all the other specimens, the transverse reinforcement percentage was such that a pull-out failure of the anchorage occurred (Figs. 5a,b).
- The larger the stirrup index of confinement Ω was, the higher the ultimate bond stress value $\bar{\tau}$ resulted; however, beyond the value $\Omega_{max} \approx 0.05$, no significant increase of bond strength occurred (Fig. 6).
- The splitting-crack propagation rate exhibited a bilinear trend with a faster crack propagation when the load was larger than $\approx 50\%$ of the peak load (Fig. 7d,8c).

- The proposed test modalities and set-up make it possible to extend the investigation to other important aspects of bond, such as the effects of various arrangements of the anchored and transverse bars, the bond properties when high performance concretes (HSC and FRC) or non-metallic reinforcement are used, and also bond deterioration due to cyclic loading.

6 Acknowledgments

The financial support provided by the Italian Ministry for University and Research is gratefully acknowledged. Also, the authors thankfully acknowledge Prof. Ezio Giuriani for his useful suggestions during the present research work. Finally, the authors wish to thank all the technicians and in particular Mr Luca Martinelli of the laboratory P. Pisa of the University of Brescia for their help in carrying out the experiments.

References

1. Tepfers, R., “A theory of bond applied to overlapped tensile reinforcement splices for deformed bars”, Ph.D. thesis, *Chalmers University of Technology, Goteborg* (1973) pp.328.
2. Tepfers, R., “Cracking of concrete cover along anchored deformed reinforcing bars”, *Magazine of Concrete Research* 31(106) (1979) 3-12.
3. Plizzari, G.A., Schumm, C. and Giuriani, E., “The effect of residual tensile strength of cracked concrete on the local bond-slip law after splitting”, *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology* 9 (1987) 129-155.
4. Untrauer, R.E. and Henry, R.L., “Influence of normal pressure on bond strength”, *ACI Journal, Proceedings* 62(5) (1965) 577-586.

5. Schmidt-Thrö, G., Stöckl, S. and Kupfer, H., “Einfluß einer einachsigen Querpressung- und der Verankerungslänge auf das Verbundverhalten von Rippenstählen im Beton”, *Deutscher Ausschuß für Stahlbeton (D.A.f.St)* 389 (1988) 99-174, in German.
6. Malvar, R.J., “Bond of reinforcement under controlled confinement”, Technical Report N-1833, *Naval Civil Engineering Laboratory, Port Hueneme, California* (1991) pp.40.
7. Eligehausen, R., Bertero, V.V. and Popov, E. P., “Local bond stress-slip relationships of deformed bars under generalized excitations: tests and analytical model”, Technical Report UCB/EERC-83, *Earthquake Engineering Research Center, University of California, Berkeley*, (1983).
8. Morita, S. and Kaku, T., “Splitting bond failures of large deformed reinforcing bars”, *ACI Journal, Proceedings* 76(1) (1979) 93-110.
9. Giuriani, E., Plizzari, G.A. and Schumm, C., “Role of stirrups and residual tensile strength of cracked concrete on bond”, *ASCE, Journal of Structural Engineering*, 117(1) (1991) 1-18.
10. Reinhardt, H.W. and Van der Veen, C., “Splitting failure of a strain-softening material due to bond stresses”, in “Applications of Fracture Mechanics to Reinforced Concrete”, Alberto Carpinteri Ed., Turin, October, 1990 (Elsevier Applied Science) pp. 333-346.
11. Gambarova, P.G., Rosati, G.P. and Zasso, B., “Steel-to-concrete bond after splitting: test results”, *Materials and Structures* 22 (1989) 35-47.
12. Modena, C., Coltro, T. and Rossaro, G.P., “A study of steel-to-concrete bond after concrete splitting: experimental results at constant confinement”, *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology* 10 (1988) 179-218, in Italian.

13. Giuriani, E., "On the effective axial stiffness of a bar in cracked concrete", in "Bond in Concrete", Bartos P. Ed., 1982, (Applied Science Publishers, London, England) pp.107-126.
14. Giuriani, E. and Rosati, G.P., "An analytical model for the study of crack propagation in plain concrete elements under bending", *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology* 9 (1987) 107-127.
15. Plizzari, G.A., Marchina, E. and Giuriani, E., "Experimental study of splitting and flexural cracks in a RC beam with overlapped splices", *Materials and Structures* (1995), in print.
16. Gambarova, G.P. and Giuriani, E., "Discussion of 'Study of the transfer of tensile forces by bond.' by D. H. Jiang, S. P. Shah, and A. T. Andonian.", *ACI Journal, Proceedings* 82(3) (1985) 381-383.
17. Giuriani, E. and Ronca, P., "The grid Moiré method applied to study a reinforced concrete beam", in "Atti del VII Convegno Nazionale A.I.A.S.", Cagliari (Italy), September, 1979, pp.655-668, in Italian.
18. Tassios, T. P. and Koroneos, E. G., "Local bond-slip by means of the Moiré method", *ACI Journal, Proceedings* 81(4) (1984) 27-34.
19. Deldossi, A.M., Massimo, S. and Plizzari, G.A., "Studio sperimentale su barre ancorate in elementi di cemento armato con armatura trasversale di contenimento", Technical Report 5/1993, *Department of Civil Engineering, University of Brescia* (1993) pp.72, in Italian.
20. Rehm, G., "Ueber die Grundlagen des Verbundes zwischen Stahl und Beton", *Deutscher Ausschuß für Stahlbeton (D.A.f.St)* 138 (1961), in German.

21. Giuriani, E. and Plizzari, G.A., "Propagation and distance of cracks in R.C. beams with a bending moment gradient", *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology* 11 (1989) 61-106.
22. Giuriani, E. and Plizzari, G.A., "Local bond-slip law after splitting of concrete", *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology* 7 (1985) 57-118, in Italian.
23. Commission of the European Communities, "EUROCODE No.2: Design of concrete structures - Part 1: General rules and rules for buildings", 1989.

References

- [1] R. Tepfers. *A Theory of Bond applied to Overlapped Tensile Reinforcement Splices for Deformed Bars*. PhD thesis, Chalmers University of Technology, Goteborg, 1973.
- [2] R. Tepfers. Cracking of Concrete Cover along Anchored Deformed Reinforcing Bars. *Magazine of Concrete Research*, 31(106):3–12, 1979.
- [3] G.A. Plizzari, C. Schumm, and E. Giuriani. The Effect of Residual Tensile Strength of Cracked Concrete on the Local Bond-Slip Law after Splitting. *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology*, 9:129–155, 1987.
- [4] R.E. Untrauer and R.L. Henry. Influence of Normal Pressure on Bond Strength. *ACI Journal, Proceedings*, 62(5):577–586, 1965.
- [5] G. Schmidt-Thrö, S. Stöckl, and H. Kupfer. Einfluß einer einachsigen Querpressung und der Verankerungslänge auf das Verbundverhalten von Rippenstählen im Beton. *Deutscher Ausschuß für Stahlbeton (D.A.f.St)*, 389:99–174, 1988. in German.
- [6] R.J. Malvar. Bond of Reinforcement under Controlled Confinement. Technical Report N-1833, Naval Civil Engineering Laboratory, Port Hueneme, California, June 1991.
- [7] R. Eligehausen, V.V. Bertero, and E. P. Popov. Local Bond Stress-Slip Relationships of Deformed Bars Under Generalized Excitations: Tests and Analytical Model. Technical Report UCB/EERC-83, Earthquake Engineering Research Center, University of California, Berkeley, California, 1983.
- [8] S. Morita and T. Kaku. Splitting Bond Failures of Large Deformed Reinforcing Bars. *ACI Journal, Proceedings*, 76(1):93–110, 1979.

- [9] E. Giuriani, G.A. Plizzari, and C. Schumm. Role of Stirrups and Residual Tensile Strength of Cracked Concrete on Bond. *ASCE, Journal of Structural Engineering*, 117:1–18, 1991.
- [10] H.W. Reinhardt and C. Van der Veen. Splitting Failure of a Strain-Softening material due to Bond Stresses. In Alberto Carpinteri, editor, *Applications of Fracture Mechanics to Reinforced Concrete*, pages 333–346, Turin, October 6 1990. Elsevier Applied Science.
- [11] P.G. Gambarova, G.P. Rosati, and B. Zasso. Steel-to-Concrete Bond after Splitting: Test results. *RILEM Materials and Structures*, 22:35–47, 1989.
- [12] C. Modena, T. Coltro, and G.P. Rossaro. A study of Steel-to-Concrete Bond after Concrete Splitting: Experimental Results at Constant Confinement. *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology*, 10:179–218, 1988. in Italian.
- [13] E. Giuriani. On the Effective Axial Stiffness of a Bar in Cracked Concrete. In P. Barros, editor, *Bond in Concrete*, pages 107–126. Applied Science Publishers, London, England, 1982.
- [14] E. Giuriani and G.P. Rosati. An analytical model for the study of Crack Propagation in Plain Concrete Elements under Bending. *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology*, 9:107–127, 1987.
- [15] G.A. Plizzari, E. Marchina, and E. Giuriani. Experimental Study of Splitting and Flexural Cracks in a RC Beam with Overlapped Splices. *RILEM Materials and Structures*, 29:19–27, 1996.

- [16] G.P. Gambarova and E. Giuriani. Discussion of ‘Study of the transfer of Tensile Forces by Bond.’ by D. H. Jiang, S. P. Shah, and A. T. Andonian. *Proceedings, American Concrete Institute Journal*, 82(3):381–383, 1985.
- [17] E. Giuriani and P. Ronca. The grid moiré method applied to study a reinforced concrete beam. In *Atti del VII Convegno Nazionale A.I.A.S.*, pages 655–668, Cagliari (Italy), September 26-29 1979. in Italian.
- [18] T. P. Tassios and E. G. Koroneos. Local Bond-Slip by means of the Moiré Method. *Proceedings, American Concrete Institute Journal*, 81(4):27–34, 1984.
- [19] A.M. Deldossi, S. Massimo, and G.A. Plizzari. Studio sperimentale su barre ancorate in elementi di cemento armato con armatura trasversale di contenimento. Technical Report 5, Department of Civil Engineering, University of Brescia, Brescia, Italy, 1994. in Italian.
- [20] G. Rehm. Ueber die Grundlagen des Verbundes zwischen Stahl und Beton. *Deutscher Ausschuß für Stahlbeton (D.A.f.St)*, 138, 1961. in German.
- [21] E. Giuriani and G.A. Plizzari. Propagation and distance of cracks in r.c. beams with a bending moment gradient. *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology*, 11:61–106, 1989.
- [22] E. Giuriani and G.A. Plizzari. Local Bond-Slip Law after Splitting of Concrete. *Studi e Ricerche, School for the Design of R.C. Structures, Milan University of Technology*, 7:57–118, 1985. in Italian.
- [23] European Committee for Standardization. *EUROCODE No.2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings-ENV 1992-1-1*. Brussel, 1991.

Contents

1	Introduction	1
2	Experimental model and materials	2
2.1	Specimen geometries	2
2.2	Instrumentation	4
3	Experimental set-up and loading modalities	4
4	Results and Discussion	5
5	Conclusions	8
6	Acknowledgments	9

List of Figures

1	Splitting crack propagation in anchorages a): (1) splitting crack onset, (2) partially propagated splitting crack, (3) completely propagated splitting crack; splitting crack and confining actions around ribbed bar [9] b); scheme of local bond failure: “pull-out failure” (c) and “splitting failure” (d).	28
2	Geometrical characteristics of the specimens tested (a); instrument placement on specimens of the second series (b).	29
3	Test setup.	30
4	Diagram of the pull-out force and the splitting crack opening versus the bar slip for specimes 1NSP2 (a) and 1S8P2 (b) of the first series of tests.	31

5	First series of tests: comparison between the curves of the pull-out load versus loaded end (a) and unloaded end (b) slips up the peak load; second series of tests: comparison between the curves of the pull-out load versus loaded end slip up to the peak load (c); comparison between the average curves of the pull-out load versus the loaded end slip for specimens with and without preformed splitting crack (d).	32
6	Diagram of the ultimate bond stress $\bar{\tau}$ versus the stirrup index of confinement Ω	33
7	First series of tests: splitting crack openings w_{s1} (a), w_{s2} (b) and w_{s3} (c) versus the loaded end slip; splitting crack length Y versus the pull-out load (d).	34
8	Second series of tests: splitting crack openings w_{s1} (a) and w_{s2} (b) versus the loaded end slip; splitting crack length Y versus the pull-out load (c); splitting crack shape in specimen 2S6P2 at three different loading steps (d).	35

List of Tables

1	Geometrical characteristics of the specimens tested.	18
2	Concrete mix design.	19
3	Geometrical and mechanical properties of the reinforcing bars.	20
4	Mechanical properties of the tested specimens.	21
5	Values of the peak load F_{max} , the loaded end slip at the peak load s_{max} , the anchored bar stress σ_p and the ultimate bond stress $\bar{\tau}$ assumed as being evenly distributed along the anchored bar.	22

Table 1: Geometrical characteristics of the specimens tested.

Series	Specimen	Anchored bar(s)	Transverse bars	Concrete cover	Ω	B
First series	1NSP1	1 ϕ 20	none	80 mm	0	-
	1NSP2	1 ϕ 20	none	80 mm	0	-
	1S6P1	1 ϕ 20	6 ϕ 6	80 mm	0.047	4
	1S6P2	1 ϕ 20	6 ϕ 6	80 mm	0.047	4
	1S8P1	1 ϕ 20	6 ϕ 8	80 mm	0.084	4
	1S8P2	1 ϕ 20	6 ϕ 8	80 mm	0.084	4
Second series	2S6P1	2 ϕ 20	6 ϕ 6	80 mm	0.023	2
	2S6P2	2 ϕ 20	6 ϕ 6	80 mm	0.023	2
	2S6NTP1	2 ϕ 20	6 ϕ 6	preformed crack	0.023	0
	2S6NTP2	2 ϕ 20	6 ϕ 6	preformed crack	0.023	0

Table 2: Concrete mix design.

Series	Cement (R325) [kg/m^3]	Water [l/m^3]	W/C	Aggregates [kg/m^3]	Superplasticizer [l/m^3]	Slump [cm]
no. 1	325	175	0.54	1853	3.3	11
no. 2	325	194	0.597	1853	3.3	7

Table 3: Geometrical and mechanical properties of the reinforcing bars.

Nominal diameter ϕ [mm]	6	8	20	$I_r = \frac{2a_m l_r \sin\beta}{\pi D c_s}$
Core diameter D [mm]	6.29	8.15	19.25	
Average rib depth a_m [mm]	0.26	0.314	1.13	
Rib inclination β	52°	55°	58°	
Rib spacing c_s [mm]	5.0	5.6	12.7	
Rib length l_r [mm]	11	15	35.0	
Related rib area I_r	0.0479	0.055	0.0842	
Yield strength f_{sy} [MPa]	505	542	463	
Tensile strength f_{st} [MPa]	731	614	740	

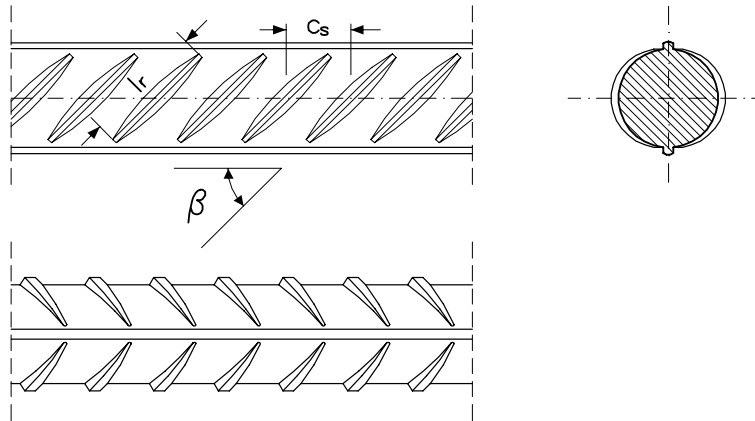


Table 4: Mechanical properties of the tested specimens.

Specimen	$f_{c,28}$ [Mpa]	$f_{ct,28}$ [MPa]	$E_{ct,28}$ [MPa]	$E_{cs,28}$ [MPa]	Curing time [days]	$f_{c,cube}$ [MPa]
1NSP1	34.5	2.75	306000	262000	52	39.4
1NSP2					60	37.3
1S6P1					39	38.1
1S6P2					75	39.4
1S8P1					68	40.0
1S8P2					81	39.7
2S6P1					28.3	2.61
2S6P2	49	32.1				
2S6NTP1	42	33.0				
2S6NTP2	54	33.6				

Table 5: Values of the peak load F_{max} , the loaded end slip at the peak load s_{max} , the anchored bar stress σ_p and the ultimate bond stress $\bar{\tau}$ assumed as being evenly distributed along the anchored bar.

Specimen		Peak Load F_{max} [kN]	Slip at F_{max} s_{max} [mm]	σ_{max} [MPa]	$\bar{\tau}$ [MPa]
1NSP1		74.84	/	238.3	6.61
1NSP2		50.45	0.209	160.7	4.46
1S6P1		128.90	/	410.5	11.39
1S6P2		131.00	0.923	417.2	11.58
1S8P1		~125.0	0.6÷0.75	~398.	~11.0
1S8P2		135.40	0.781	431.2	11.97
2S6P1	right side	73.65	0.490	234.5	6.51
	left side	71.57	0.413	227.9	6.32
2S6P2	right side	75.85	0.513	241.6	6.70
	left side	78.88	/	251.2	6.97
2S6NTP1	right side	75.68	0.588	241.0	6.69
	left side	68.13	0.481	217.0	6.02
2S6NTP1	right side	78.73	0.533	250.7	6.96
	left side	79.68	/	253.7	7.04

Abstract

In anchorages and overlapped splices with ribbed bars having a diameter larger than 12÷14 mm (roughly no.4,5), splitting cracks are often present in the concrete cover because of the radial pressure due to the ribs of the highly-stressed rebars. Starting from flexural cracks where the bar slip reaches the maximum value, the splitting cracks develop along the anchored bar and, in doing so, they damage the bond between the steel rebar and the surrounding concrete.

In order to control splitting and to improve bond efficiency, a confining action along the anchored bar is needed. This confining action could be provided by the residual stresses transmitted between the faces of the split concrete-cover, by an external transverse pressure (if any) and by transverse reinforcement distributed along the anchored bars.

Anchorage behaviour can be correctly studied if splitting is taken into account. The research work on concrete splitting control available in the literature, mainly regards the local bond behaviour (very short anchorage length) for which theoretical models have been proposed.

In order to extend the study to the whole anchorage response, more specific tests are needed to analyze cracking phenomena which develop along an anchored bar. In fact, most of the experimental results available in the literature, to the best of authors' knowledge, mainly regard anchorage strength but, giving little information on splitting cracking, do not allow to shed light on the problem in all its aspects.

In the present paper, the experimental results of pull-out tests on anchorages are presented. The experiments allow for the evaluation of bar-to-concrete slip and splitting-crack opening in several points along the anchored bar. Particular attention is devoted to the confining contribution of both transverse reinforcement and concrete cover. Two series of tests have been performed: in the first series (6 specimens), the influence of the confining contribution of transverse bars is studied, while in the second series (4 specimens), the confining contribution of the concrete cover is analyzed.

The principal results can be summarized as follows:

In specimens of the first series without transverse reinforcement, a splitting collapse of

the anchorage occurred at the onset of the slip at the unloaded end of the anchored bar. Viceversa, in all the other specimens, the transverse reinforcement percentage was such that a pull-out failure of the anchorage occurred.

The larger the stirrup index of confinement Ω was, the higher the ultimate bond stress value $\bar{\tau}$ resulted; however, beyond the value $\Omega_{max} \approx 0.05$, no significant increase of bond strength occurred.

The splitting-crack propagation rate exhibited a bilinear trend having a faster crack propagation when the load was larger than 50% of the peak load.

Factual Summary

In the present paper, the experimental results of pull-out tests on anchorages are presented. The experiments allow for the evaluation of bar-to-concrete slip and splitting crack opening in several points along the anchored bar. Particular attention is devoted to the confining contribution of both transverse reinforcement and concrete cover. Two series of tests have been performed: in the first series the influence of the confining contribution of transverse bars is studied while, in the second series, the confining contribution of the concrete cover is analyzed.

In specimens of the first series without transverse reinforcement, a splitting collapse of the anchorage occurred at the onset of the slip at the unloaded end of the anchored bar. Viceversa, in all the other specimens, the transverse reinforcement percentage was such that a pull-out failure of the anchorage occurred.

The larger the stirrup index of confinement Ω was, the higher the ultimate bond stress value $\bar{\tau}$ resulted; however, beyond the value $\Omega_{max} \approx 0.05$, there was no significant increase of bond strength.

The splitting-crack propagation rate exhibited a bilinear trend having a faster crack propagation when the load was larger than 50% of the peak load.

Bref compte-rendu

Cet article présente des résultats relatifs à l'essai en tension des ancrages. Les essais permettent d'évaluer le glissement entre le béton et la barre d'armature, ainsi que l'ouverture des fissures le long de la barre. Une attention particulière a été dévouée à l'effet du confinement du béton, ainsi que celui de l'acier transversal. Deux séries d'essais ont été effectuées: dans la première l'influence du confinement causé par les barres transversales a été étudiée, tandis que la seconde série a regardé l'influence du confinement du béton.

Dans les ancrages de la première série, sans armature transversale, la rupture causée par le fendage du béton a eu lieu dès que le glissement de la barre était arrivé à l'extrémité opposé à celui où la force était appliquée. D'autre côté, tous les ancrages avaient un pourcentage d'armature tel que la rupture était induite par l'endommagement de l'ancrage.

La capacité ultime des ancrages (représentée par l'effort moyen d'adhérence $\bar{\tau}$) augmente toujours au fur et à mesure que l'on accroît l'indice de l'armature transversale Ω . Par contre, au delà de $\Omega_{max} \approx 0.05$, il n'y a pas eu d'augmentation substantielle en ce qui concerne la résistance de l'adhérence.

Enfin, le taux de propagation des fissures dues au fendage montre une tendance bilinéaire, avec une propagation plus rapide lorsque les charges dépassent le 50% de la charge maximale.

Keywords

Reinforced Concrete Structures, Bond, Anchorages, Splitting Crack, Transverse Reinforcement.

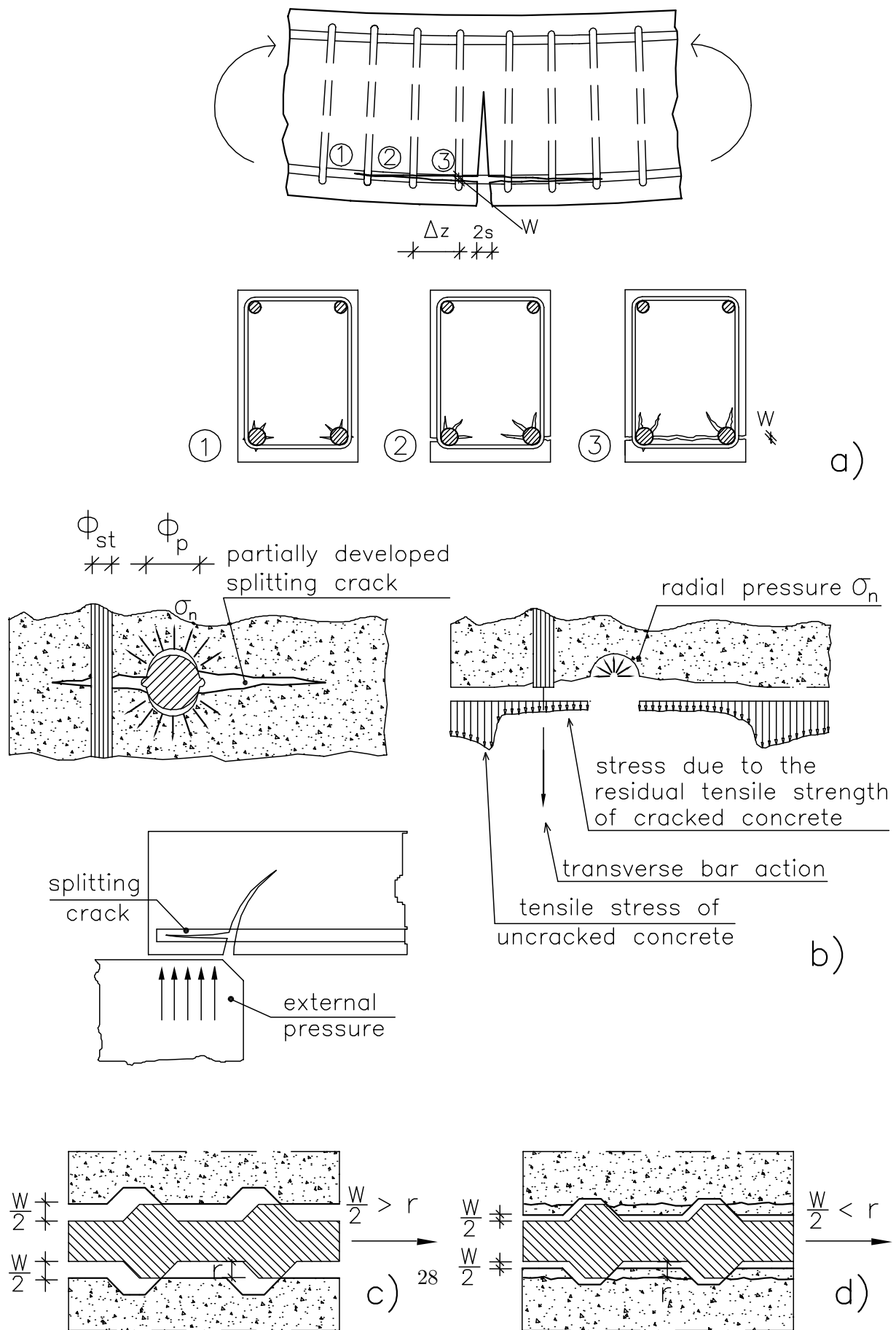


Figure 1: Splitting crack propagation in anchorages a): (1) splitting crack onset, (2) partially propagated splitting crack, (3) completely propagated splitting crack; splitting crack and confining actions around ribbed bar [9] b); scheme of local bond failure: “pull-out failure” (c) and “splitting failure” (d).

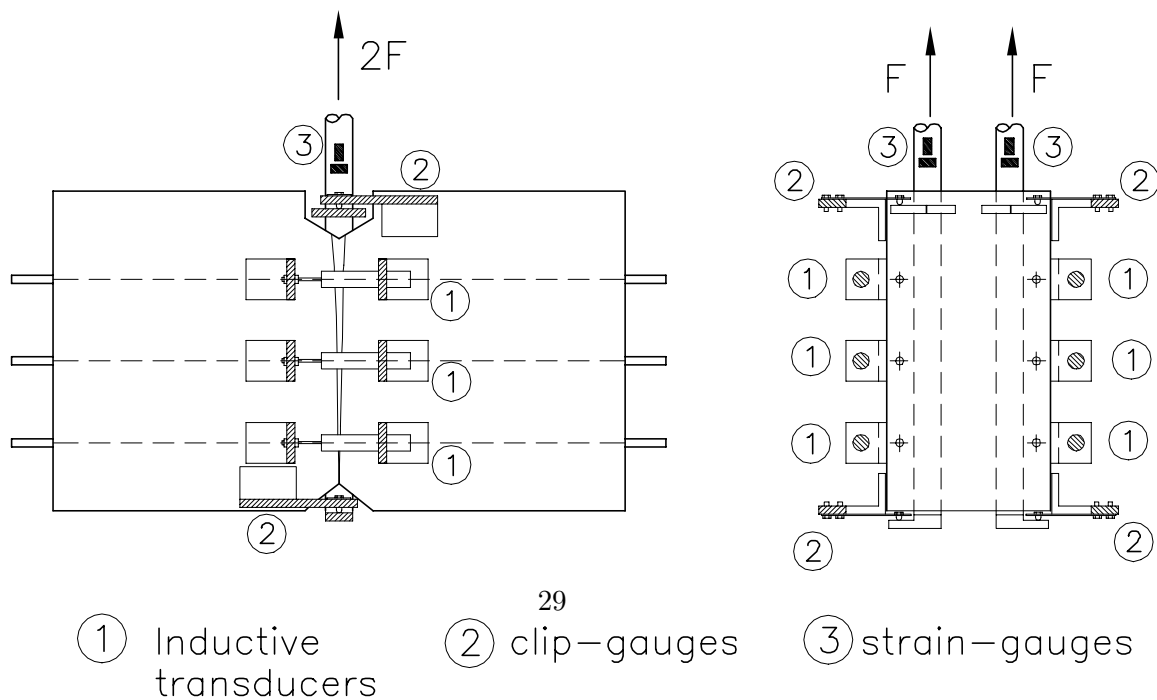
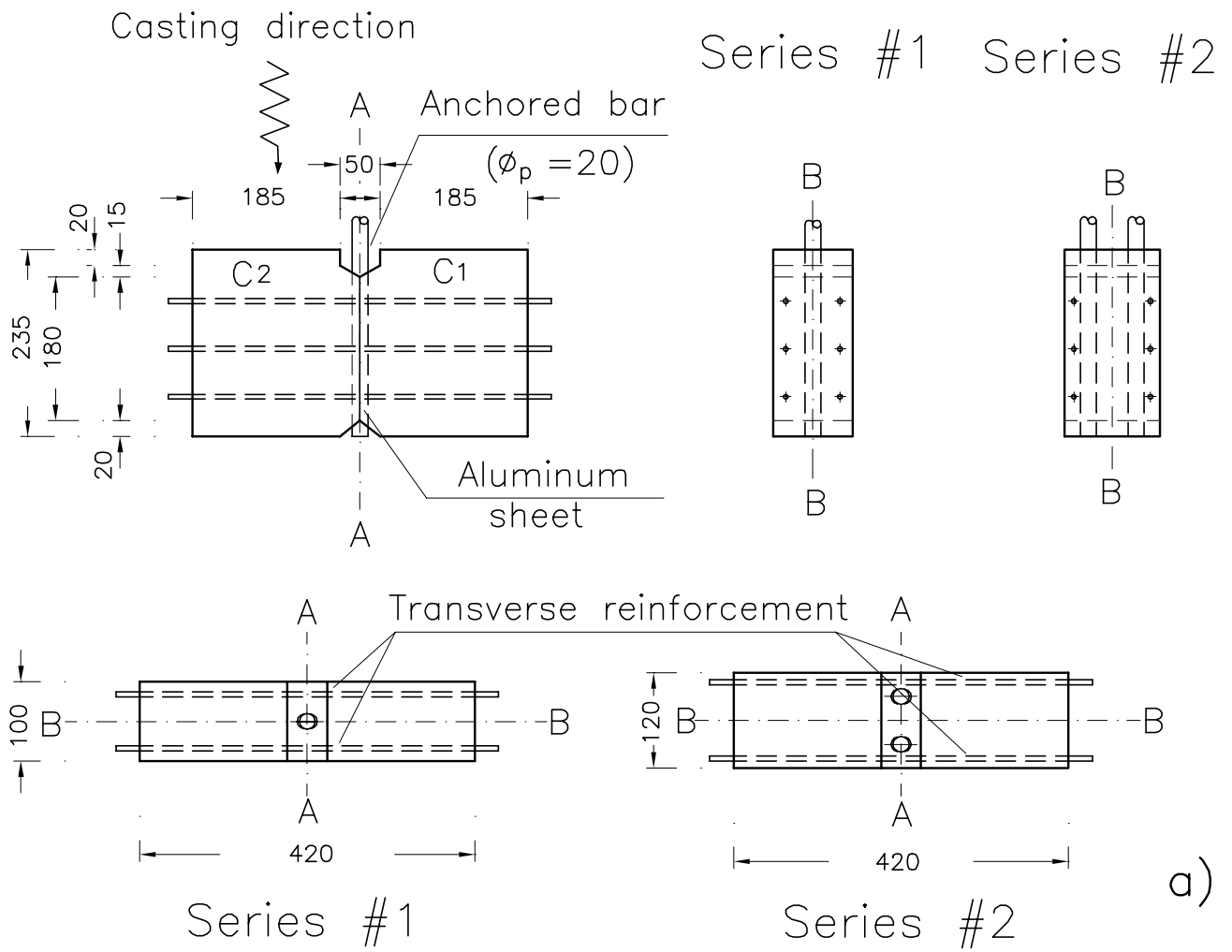


Figure 2: Geometrical characteristics of the specimens tested (a); instrument placement on specimens of the second series (b).

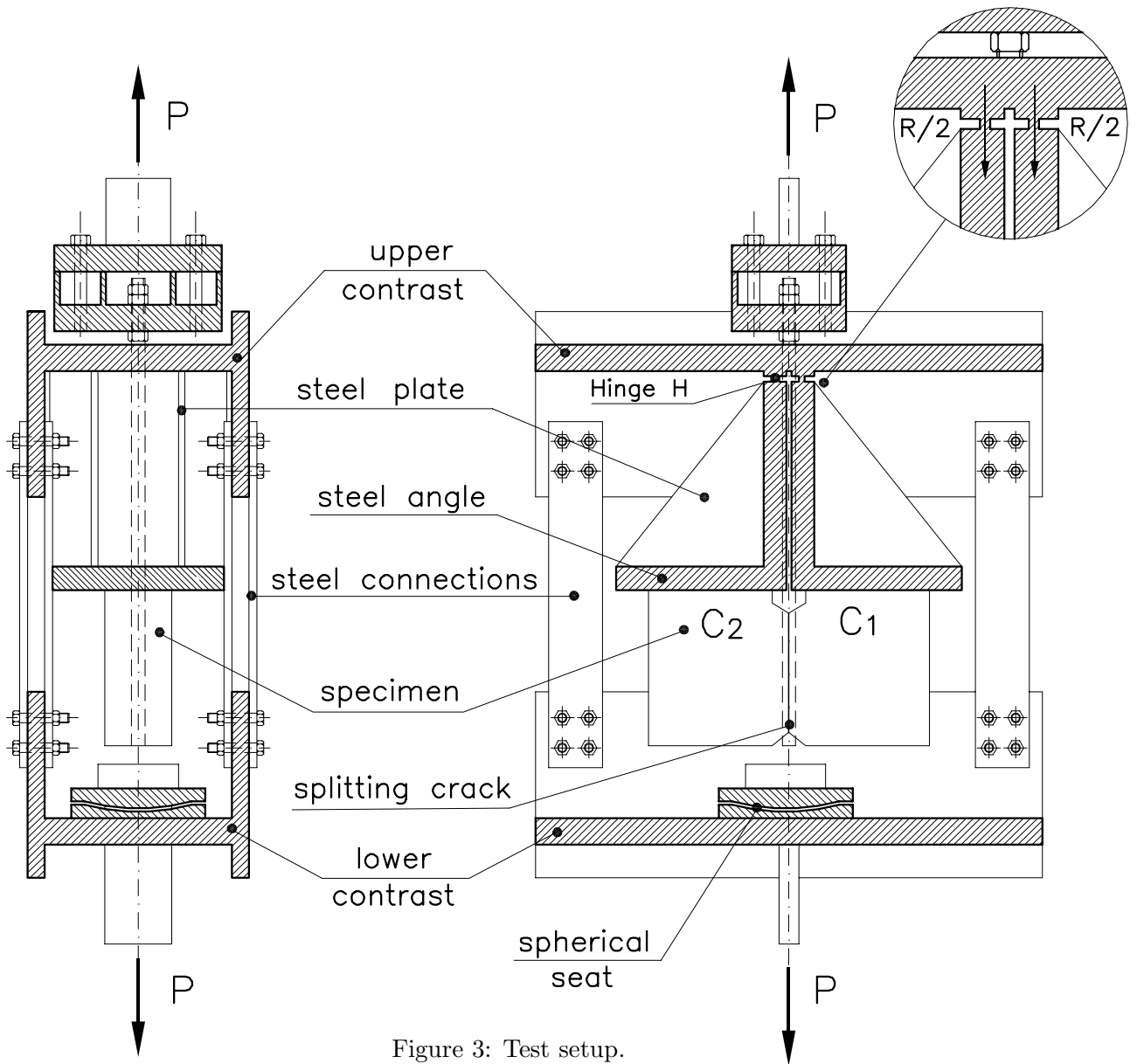


Figure 3: Test setup.

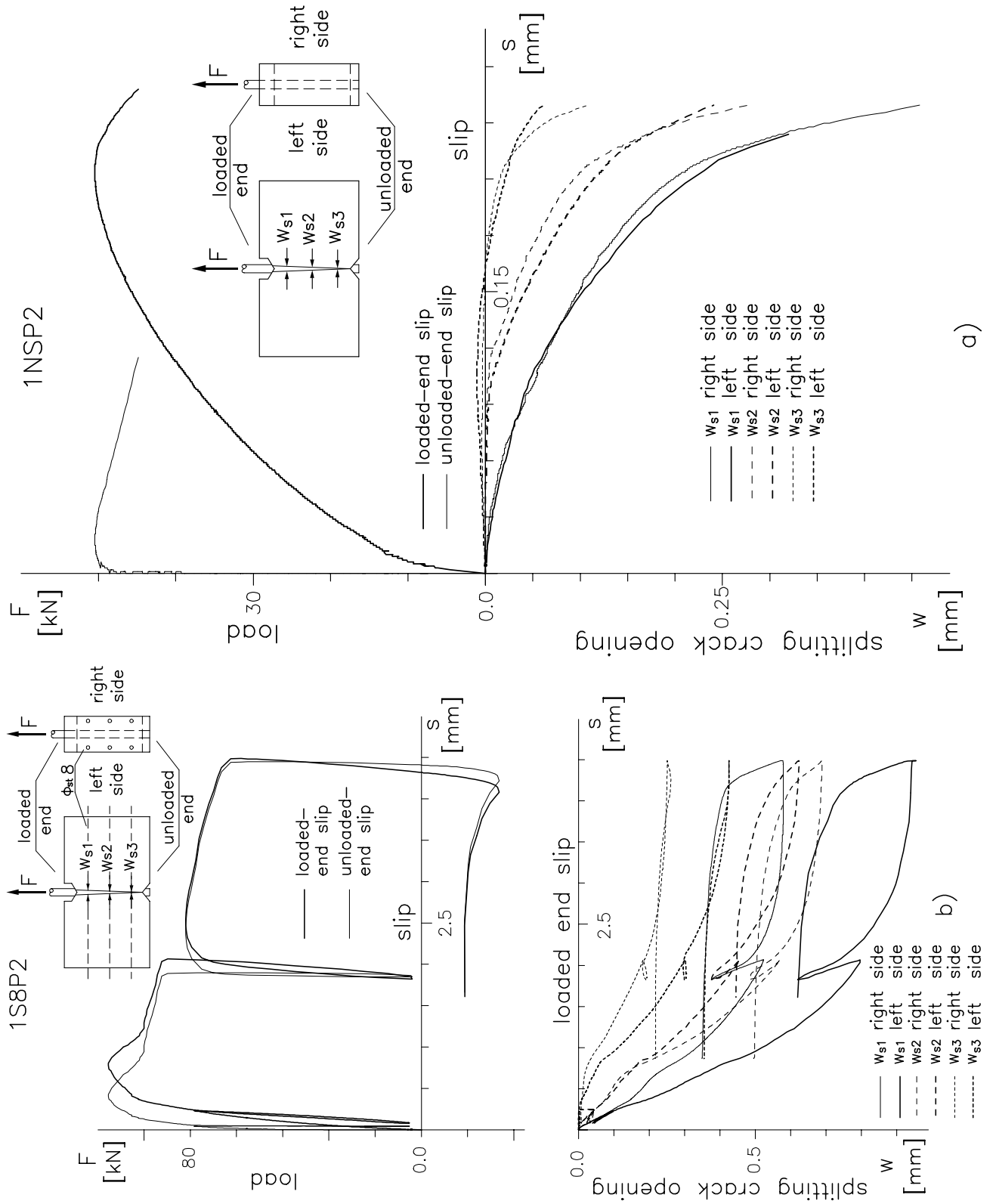


Figure 4: Diagram of the pull-out force and the splitting crack opening versus the bar slip for specimens 1NSP2 (a) and 1S8P2 (b) of the first series of tests.

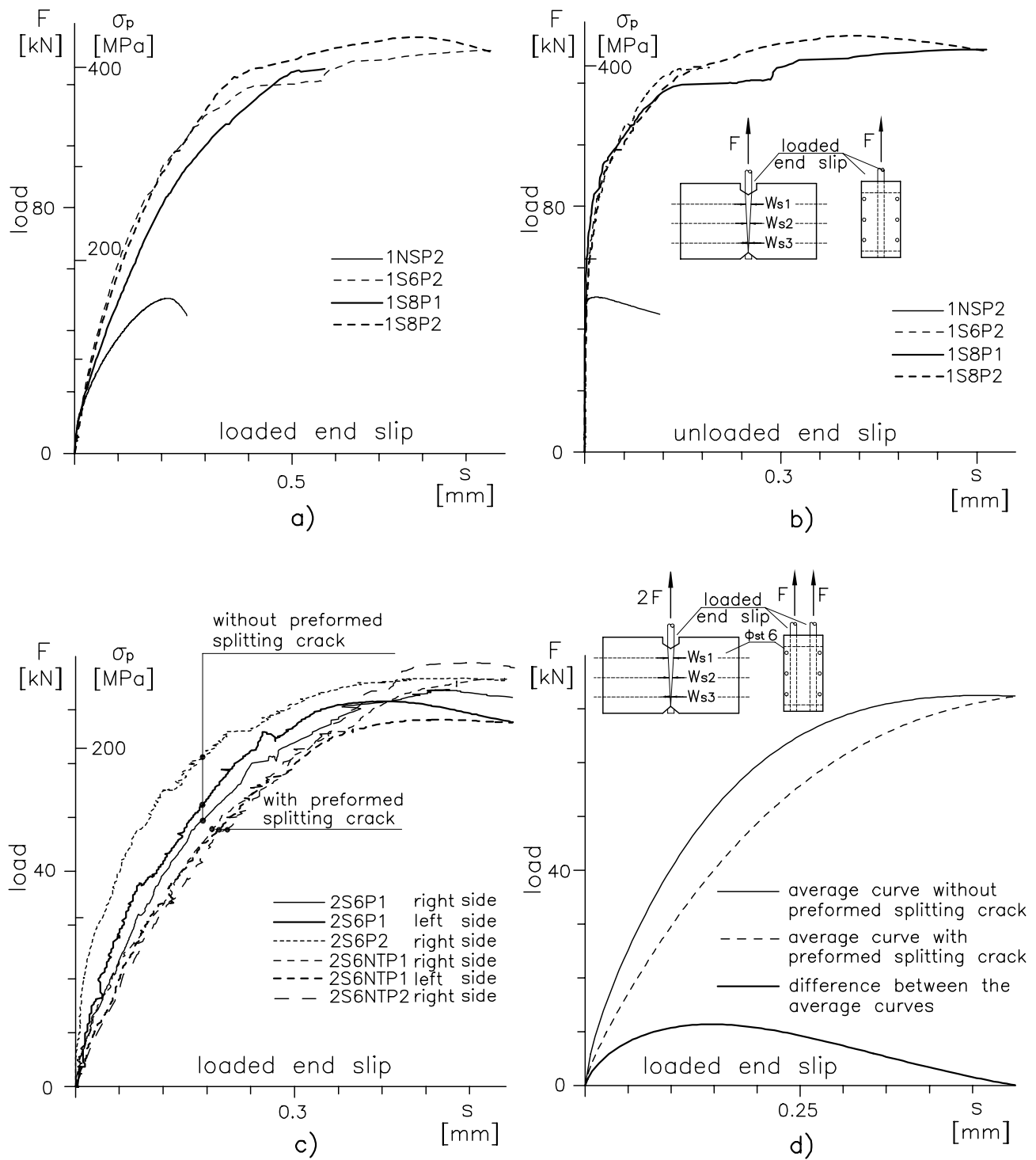


Figure 5: First series of tests: comparison between the curves of the pull-out load versus loaded end (a) and unloaded end (b) slips up the peak load; second series of tests: comparison between the curves of the pull-out load versus loaded end slip up to the peak load (c); comparison between the average curves of the pull-out load versus the loaded end slip for specimens with and without preformed splitting crack (d).

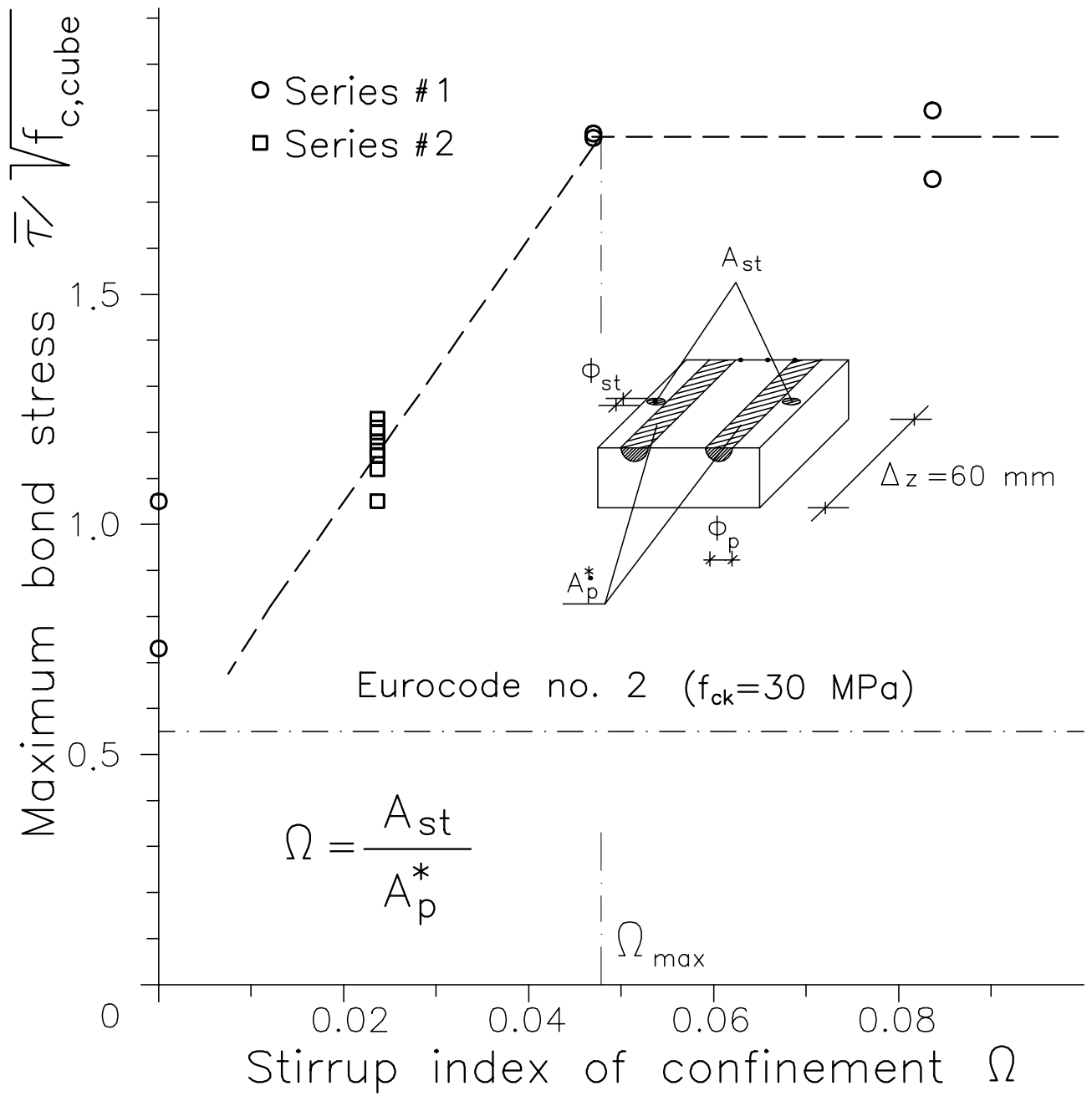


Figure 6: Diagram of the ultimate bond stress $\bar{\tau}$ versus the stirrup index of confinement Ω .

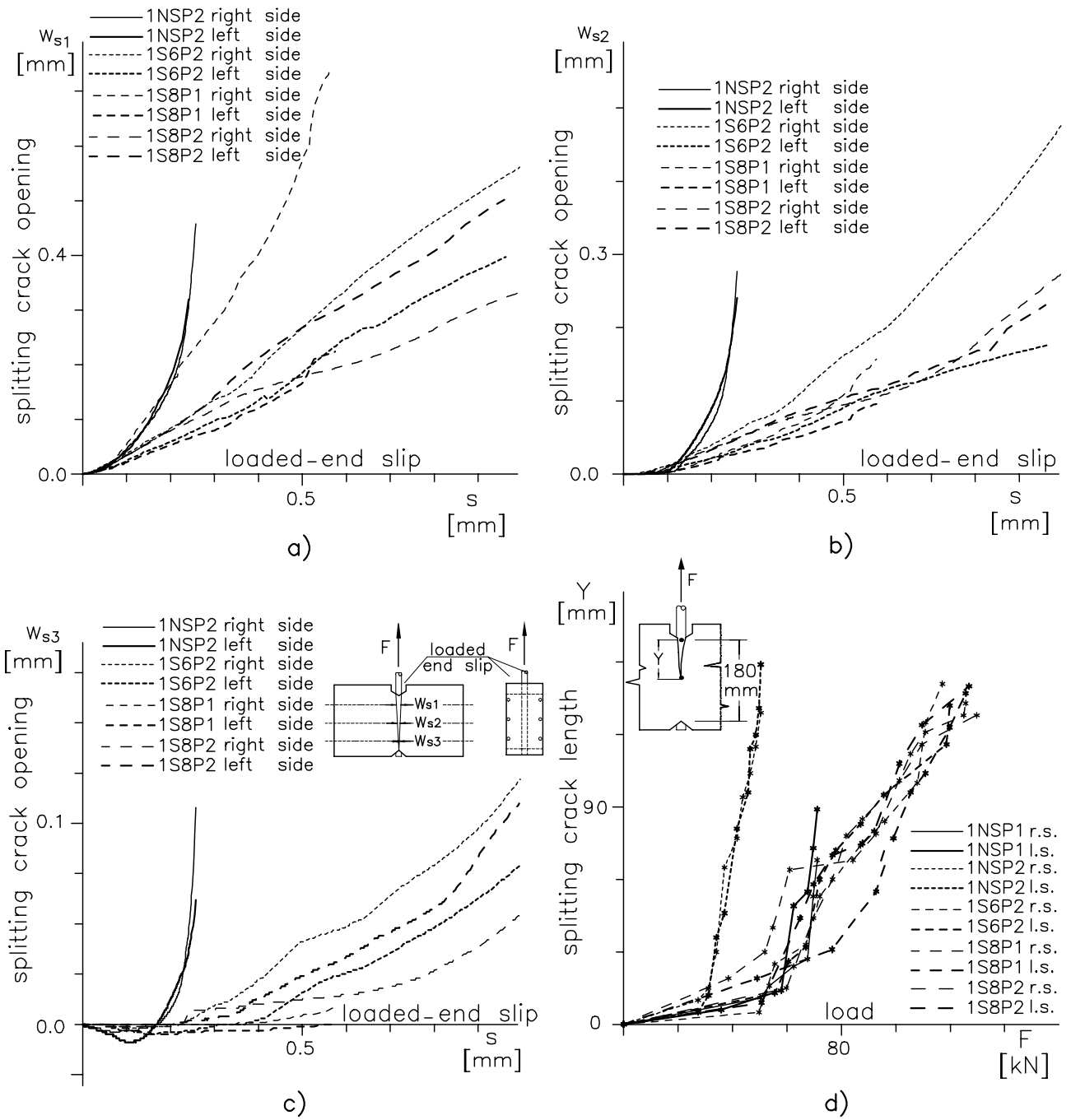


Figure 7: First series of tests: splitting crack openings w_{s1} (a), w_{s2} (b) and w_{s3} (c) versus the loaded end slip; splitting crack length Y versus the pull-out load (d).

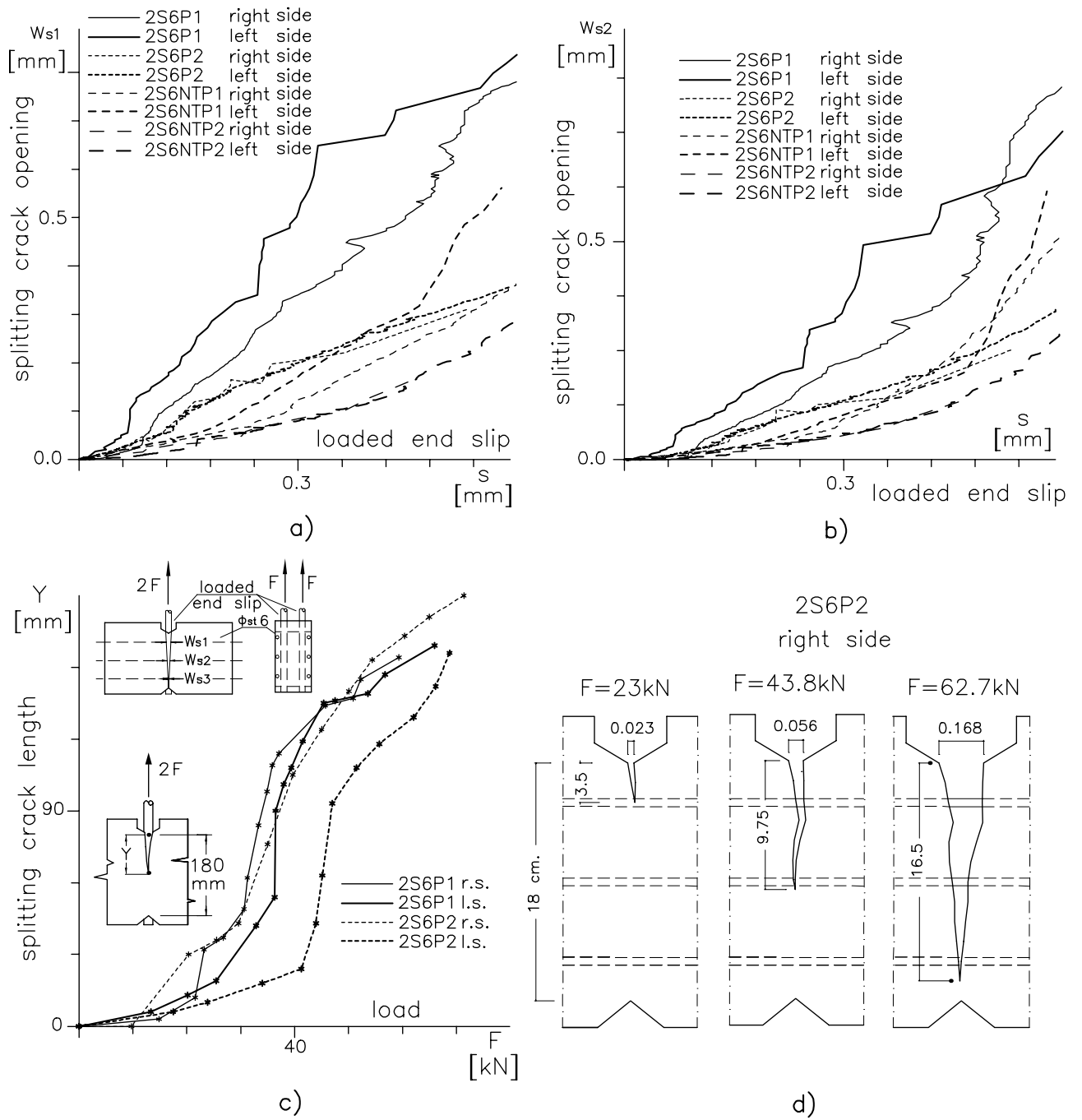


Figure 8: Second series of tests: splitting crack openings w_{s1} (a) and w_{s2} (b) versus the loaded end slip; splitting crack length Y versus the pull-out load (c); splitting crack shape in specimen 2S6P2 at three different loading steps (d).