ANCHORAGE OF STAGGERED REINFORCEMENT

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ABSTRACT

The anchorage of staggered reinforcement has been investigated in reinforced concrete beams with vertical and with in 45 degrees inclined stirrups. The stirrups have been designed to cover the full shear force. The anchorage lengths for the curtailed reinforcement have been varied. The influence of the "shift rule" has been investigated. Inclined (45°) stirrups give a positive influence upon the overall performance of the beams in comparison with those with vertical. Taking into account the "shift rule" it is possible to anchor the staggered reinforcement without using an anchorage length outside the point, where the moment load does not require the staggered bar. For the anchorage however there is a limitation in the intensity of moment change, which is the same as the stress build up in the anchored bar.

KEY WORDS: Concrete, reinforcement, bond, staggering.

NOTATION

Ast	area of transverse reinforcement bar or bundle of bars
Es	modulus of elasticity of reinforcement
a	spacing of transverse reinforcement
fcb	bond strength
fcc	compressive cylinder strength of concrete
fc,cube	compressive cube, side 200 mm, strength of concrete
fct	splitting tensile strength of concrete
fsu	tensile reinforcement stress at ultimate load on beam
fsy	yield stress of reinforcement
l	onloading length
Ø	diameter of reinforcing bar
ε cu	ultimate tensile strain of concrete

INTRODUCTION

In a concrete beam reinforcement can be staggered according to the acting moment. In sections where moment and shear are acting together, the influence of inclined cracks must be taken into consideration for determination of the force in tensile reinforcement - the "shift-rule". In most codes the bar must be anchored with an anchorage lengt outside the section where it takes force. The anchorage length should enable the bar to carry its yield force in ultimate limit state or the necessary force if the reinforcement is not fully utilized. However it has been observed that high bond bars can be loaded by force faster than the increase in moment requires in most cases. The presented series of tests investigated the anchorage capacity of staggered bars. The results obtained were used for the staggering rule in the Swedish Code BBK79. A similar rule is also proposed for the CEB, Model Code 1990.

AIM OF INVESTIGATION

The aim of the investigation was to estimate the bond capacity of the staggered reinforcement. Special interest was devoted to the bond of that part of the bar which is only partly used for taking moment load. The necessity of having an anchorage length outside the point where the bar is not needed to carry moment load was also to be judged.

DEFINITIONS

In this investigation the part of the reinforcing bar from the point of full utilization to the point, where it is theoretically not more needed, is called "onloading length" and the length outside the point, where it theoretically does not take force, is called "overlength", according to FIG. 1.

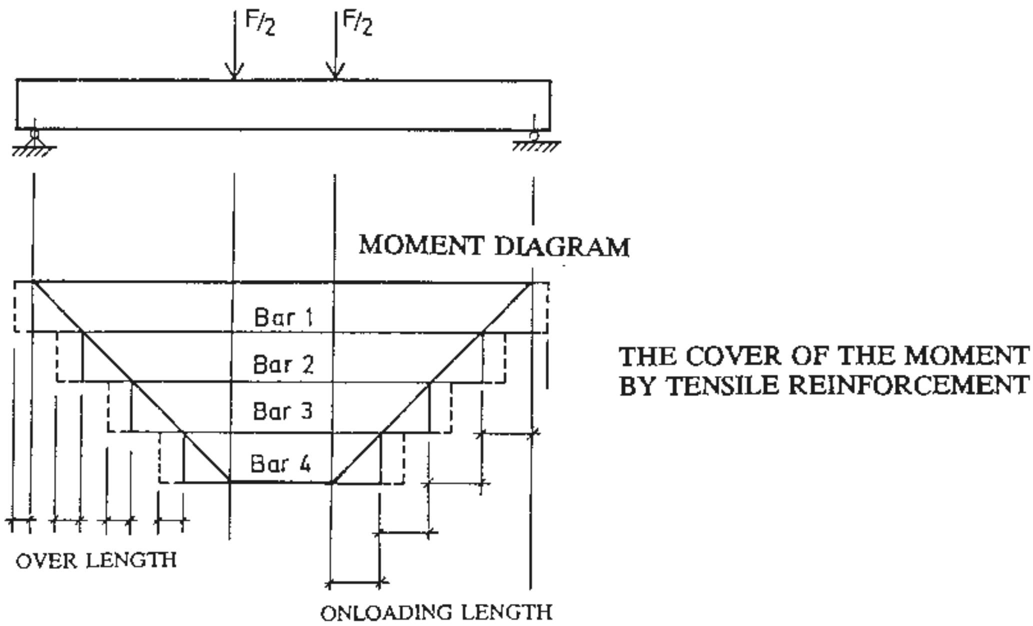


FIGURE 1. Definition of onloading length and overlength.

TEST PROGRAM

Two series of tests were performed with isostatic reinforced concrete beams loaded with 2 symmetric point loads.

SERIES A. /1/.

In the first series, SERIES A, 10 beams with staggered and bundled reinforcing bars in groups of two and three were tested. The design of the beams is shown in FIG. 2 and 3. The stirrups were designed to take full shear force according to the truss analogy. The bars were staggered according to the following presentation. No attention was paid to the "shift-rule" at staggering of the bars. The inclination of the shear reinforcement is also given.

The tensile reinforcement in the beams A1 to A5 was 3 bundles of 3 Ø 8 mm bars. The outer two bars went through to the supports. The rest of the bars were:

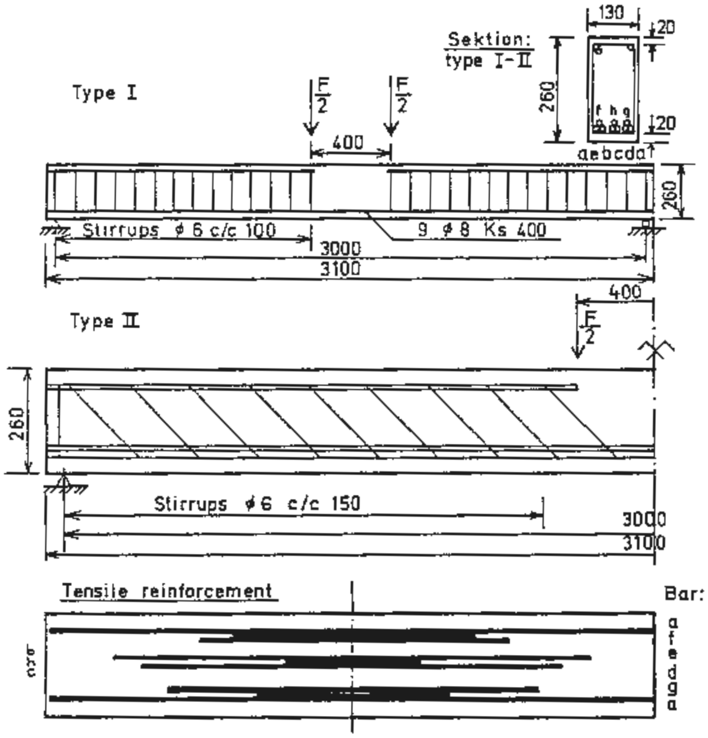


FIGURE 2. Design of the beams in Series A, beams A1 to A5.

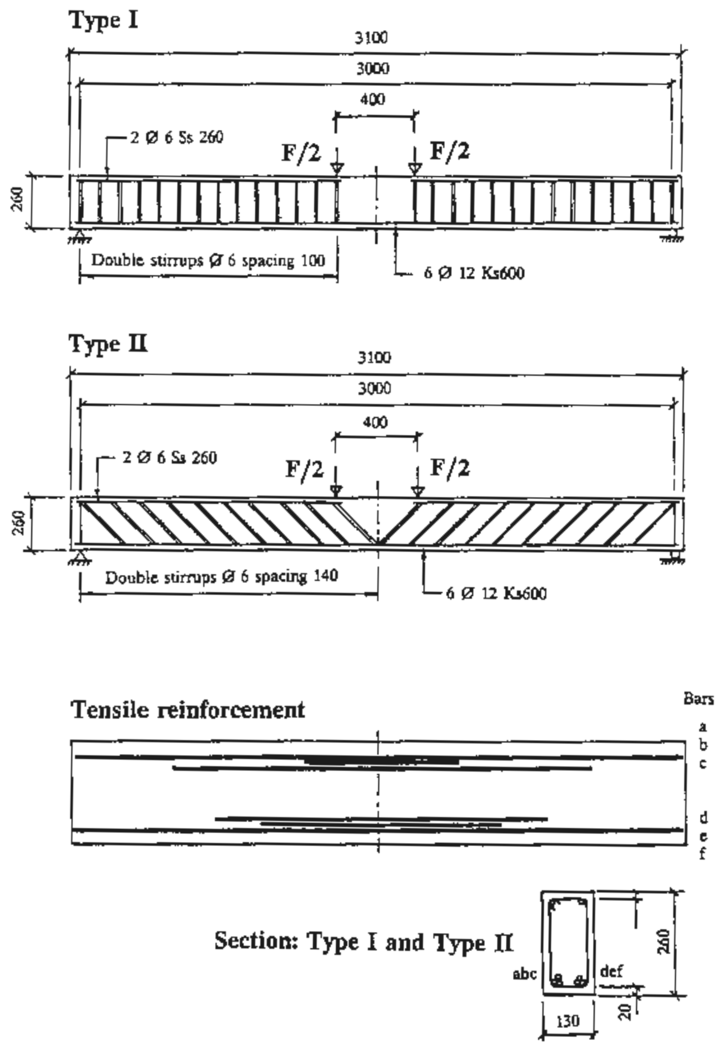


FIGURE 3. Design of the beams in Series A, beams A6 to A10.

BEAM A1
Staggered according to the moment diagram. Vertical stirrups.

BEAM A2
Staggered with 100 mm overlength. Vertical stirrups.

BEAM A3
All bars going from support to support. Vertical stirrups.

BEAM A4
Staggered according to the moment diagram. Inclined (45°) stirrups.

BEAM A5
Staggered with overlength 100 mm. Inclined (45°) stirrups.

The tensile reinforcement in the beam A6 to A10 was 2 bundles of 3 Ø 12 mm bars. The outer two bars went through to the supports. The rest of the bars were:

Beam A6

Staggered according to the moment diagram. Vertical stirrups.

BEAM A7
Staggered with 100 mm overlength. Vertical stirrups.

BEAM A8
All bars going from support to support. Vertical stirrups.

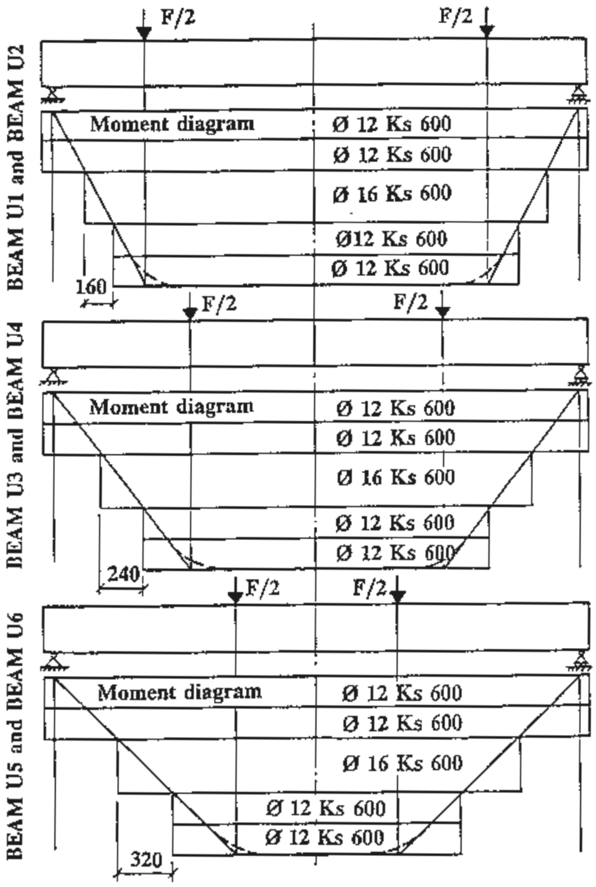
BEAM A9
Staggered according to the moment diagram. Inclined (45°) stirrups.

BEAM A10
Staggered with 100 mm overlength. Inclined (45°) stirrups.

SERIES U. /2/.

In this series the intension was to investigate the anchoring capacity of the onloading length of a staggered bar, when there is no overlength. The design of the isostatic beams was based on the results from the SERIES A. The investigated staggered bar of Ø 16 Ks600 was placed single with a distance of 17 mm to the neighbouring Ø 12 Ks600 bars placed in groups of two. The concrete cover in vertical direction was 20 mm. The staggering of the bars was made according to FIG. 4. The design of the bars and the arrangement of the load is shown in FIG. 5, 6 and 7. The two outer 12 mm:s bars reached between the supports. The two inner 12 mm bars were staggered at the same place. This meant that one of them had an overlength and they together had better bond properties than the investigated 16 mm bar. By this arrangement the eventual bond failure should be located to the 16 mm bar.

The tests were made with three different moment diagram slopes. One beam with vertical stirrups and one with inclined (45°) were tested for each slope. The stirrups were designed to take full shear force according the truss analogy. No attention was paid to the "shift rule" at staggering of the 16 mm bar.



<u>FIGURE 4.</u> Staggering of the tensile reinforcement in Series U.

<u>BEAM U1</u>
Onloading length of the 16 mm bar 160 mm. Vertical stirrups ϕ 6 mm in groups of three with centroid distance 60 mm. Every second group of stirrups open on top.

<u>BEAM 2U</u>
Onloading length of the 16 mm bar 160 mm. Inclined (45°) stirrups ϕ 6 mm in groups of three with centroid distance 80 mm. Every second group of stirrups open on top.

<u>BEAM U3</u>
Onloading length of the 16 mm bar 240 mm. Vertical stirrups ϕ 6 mm in groups of three with centroid distance 90 mm. Every second group of stirrups open on top.

<u>BEAM U4</u>
Onloading length of the 16 mm bar 240 mm. Inclined (45°) stirrups ϕ 6 in groups of three with centroid distance 120 mm. Every second group of stirrups open on top.

<u>BEAM U5</u>
Onloading length of the 16 mm bar 320 mm. Vertical stirrups ϕ 6 mm in groups of two with centroid distance 80 mm. Every second group of stirrups open on top.

<u>BEAM U6</u>
Onloading length of the 16 mm bar 320 mm. Inclined (45°) stirrups ϕ 6 mm in groups of two with centroid distance 110 mm. Every second group of stirrups open on top.

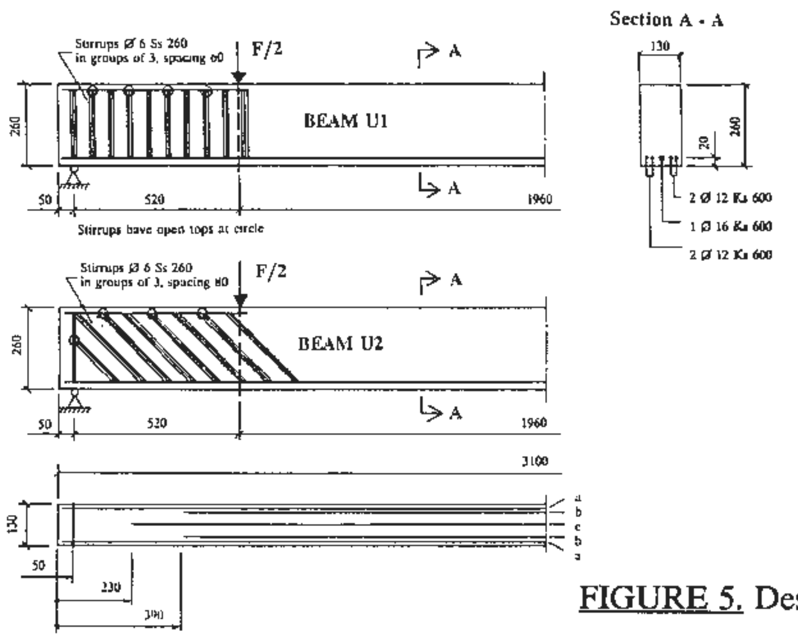


FIGURE 5. Design of the beams U1 and U2.

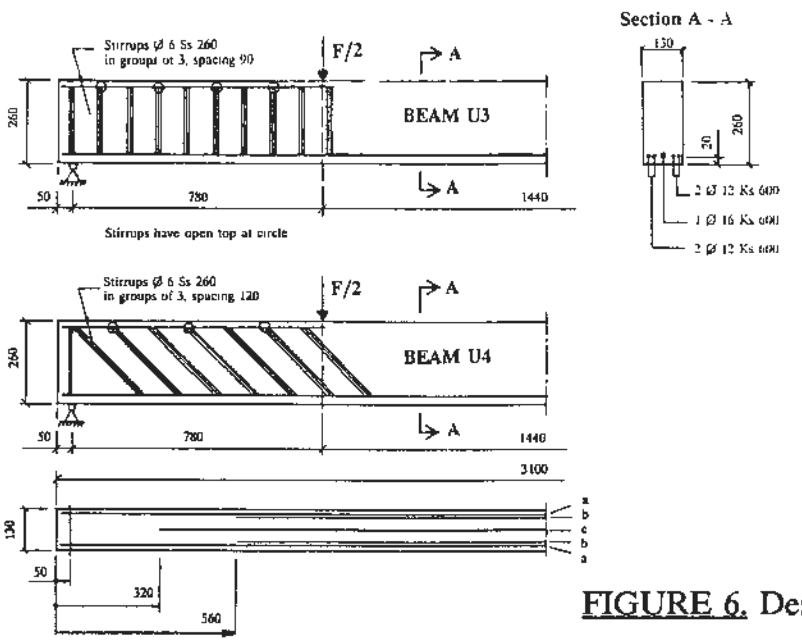


FIGURE 6. Design of the beams U3 and U4.

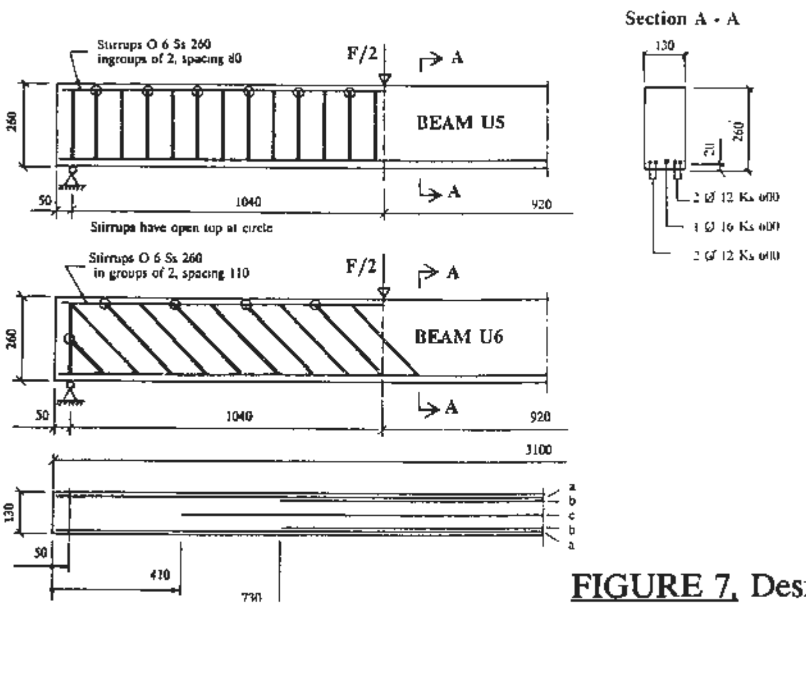


FIGURE 7. Design of the beams U5 and U6.

CONCRETE

The concrete was made of standard portland cement mixed with granite sand and gravel of maximum size 22 mm. Water cement ratio was 0.60.

At testing of the beams the mean compressive strength of the concrete was determined by crushing 3 cubes with a side length of 200 mm. Also the mean tensile strengtb was determined by splitting 3 cubes of the same size. The mean strengths are given in TABLE 1. There is also given the compressive cylinder strength of the concrete calculated from the cube strength using relations given in diagrams in Swedish Concrete Code B5 /3/ and KB5 /4/.

TABLE 1.
Compressive strength of the concrete for Series A and U.

BEAM	Cube, side 200 mm		Cylinder
	Compressive strength fc,cube MPa	Splitting tensile strength fct MPa	Compressive strength fcc MPa
A1	31.4	2.67	27.8
A2	25.8	2.34	22.8
A3	31.2	2.80	27.6
A4	30.6	2.67	27.1
A5	35.2	2.70	31.2
A6	32.5	2.69	28.8
A7	38.9	2.99	34.4
A8	36.9	2.91	32.7
A9	42.1	2.95	37.3
A10	51.5	3.10	45.6
U1	39.5	2.64	35.0
U2	42.5	2.76	37.6
U3	41.9	2.88	37.1
U4	49.9	2.73	44.2
U5	48.3	2.99	42.7
U6	46.6	2.93	41.2

REINFORCEMENT

The tensile reinforcement in the Series A was of Swedish quality Ks 400 with relative rib area 0.05 for 8 mm bars and 0.06 for 12 mm bars and appearance according to FIG. 8. The determined yield strength for each beam is given in TABLE 2. The stirrups were made of plain 6 mm bars with nominal yield strength 260 MPa.

The tensile reinforcement in the Series U was of Swedisb quality Ks 600 with relative rib area 0.13 and appearance according to FIG. 8. The determined yield strength for each beam is given in TABLE 3. The stirrups were made of plain 6 mm bars with nominal yield strength 260 MPa.

Ks 400 Ks 600

08 012 012 016

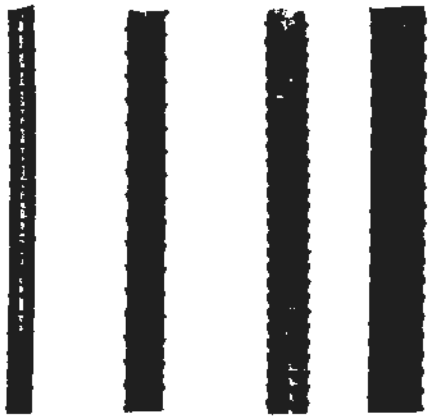


FIGURE 8. Swedish Ks 400 and Ks 600 high bond reinforcement.

TEST RESULTS

SERIES A.

The stress in the tensile reinforcement was measured at centre of the beam using equipment for determination of the beam curvature and the concrete strain at a certain level in the compressive zone. The measured tensile reinforcement stresses are compared with the determined yield stresses of the reinforcement in each beam in TABLE 2.

TABLE 2.

Comparison of the tensile reinforcement stress fsu at failure of the beam with the yield stress fsy and the cause of beam failure.

Beam	fsu MPa	fsy MPa	fsu/fsy	Cause of failure
A1	380	461	0.82	Anchorage failure.
A2	460	459	1.00	Anchorage failure.
A3	465	460	1.01	Moment failure. Yielding.
A4	465	458	1.01	Moment failure. Yielding.
A5	467	467	1.00	Moment failure. Yielding.
A6	621	633	0.98	Anchorage failure.
A7	630	630	1.00	Moment failure. Yielding.
A8	635	636	1.00	Moment failure. Yielding.
A9	630	633	1.00	Moment failure. Yielding.
A10	620	620	1.00	Moment failure. Yielding.

The three beams A1, A2 and A6, which failed by anchorage failure, had vertical stirrups. The moment shift due to inclined cracks is the cause of failure, because the curtailment of the bars was done without taking this fact into account. The beam A2 had an overlength of 100 mm. This is not enough because the beam is 260 mm high and the moment shift in that case is estimated to require 130mm overlength. However the anchorage failure appeared at the level when the moment yielding in tensile reinforcement was just to start. It can be noted, that the anchorage of the tensile reinforcement did not fail for beam A7.

The beams A3 and A8 had full tensile reinforcement all way through between the supports and consequently these beams failed due to yielding of tensile reinforcement caused by moment.

The beams with inclined (45°) stirrups covering full shear force have no shift of moment. Consequently these beams all failed by moment failure with yielding tensile reinforcement. In spite of the fact that the curtailed reinforcement had no overlengths, beams A4 and A9, no anchorage failures appeared. The onloading length was 145 mm (8 mm bar) and 215 mm (12 mm bar) for respective beam.

At failure the reinforcement had reached the yield stress at each point of curtailment. Thus the bond stress evenly distrihuted along the onloading length can be calculated and is for:

BEAM A4 fcb = Ø*fsy / 4*l = 0.008*458 / 4*0.145 = 6.31 MPa

BEAM A9 fch = Ø*fsy / 4*l = 0.012*633 / 4*0.215 = 8.83 MPa

The ultimate bond stress at splitting off the concrete cover is calculated according to /5/. The calculation is done for the bar with the weakest (closest to the concrete surface) onloading length under the assumption of cover cracks along the onloading length. Evenly distributed bond stresses can therefore be assumed.

Vertical projection according to FIG. 9 gives:

fcb*Ø = 2(c + Ø/2)*fct + 2Ast/a* εcu*Es; ....(1)

εcu*Es = 0.15/1000 * 200,000 = 30 MPa at ultimate tensile strain in the concrete.

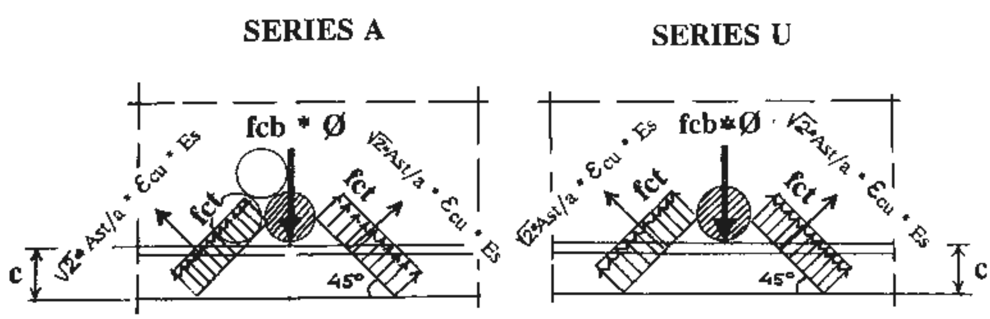


FIGURE 9. Ultimate splitting failure patterns with transverse reinforcement and stress diagrams.

The following bond resistances are obtained:

BEAM A4
fcb = 2*fct*(c + Ø/2)/Ø + 60*Ast / a*Ø = 2*2.67*(0.02+0.008/2) / 0.008 + 60*(0.006)*π / 4*0.15*0.008 = 17.4 MPa > 6.31 MPa

BEAM A9
fcb = 2*fct*(c + Ø/2)/Ø + 60*Ast / a*Ø = 2*2.95*(0.02+0.012/2) / 0.012 + 60*2*(.006)*π/ 4*0.14*0.012 = 14.8 MPa > 8.83 MPa

The calculated bond stresses are lower than ultimate pull-out stresses according to /6/.

These calculated resistances exceed the existing bond stresses at the yielding of the tensile reinforcement in each of the beams. Consequently there should not be anchorage failure, and there were not.

SERIES U.

The stress in the tensile reinforcement was measured at centre of the beam using equipment for determination of the curvature and the concrete strain at a certain level in the compressive zone. This stress exists at each curtailment of the reinforcement for beams with inclined (45°) stirrups. For beams with vertical stirrups these stresses at staggering points must be increased with stress caused by the "shift rule". When the stirrups are designed to take full shear force, this increase in stress is half shear force devided by the actual reinforcing area at the section assuming inclined (45°) struts.

In TABLE 3 and FIG. 10 the measured stresses (without "shift rule" correction) are compared with the determined yield streses of the reinforcement for each beam.

TABLE 3.

Comparison of the tensile reinforcement stress fsu at failure of the beam with the yield stress fsy and the cause of beam failure.

Beam	fsu MPa	fsy MPa	fsu/fsy	Cause of failure
U1	420	628	0.67	Anchorage failure
U2	550	615	0.89	Anchorage failure
U3	475	626	0.76	Anchorage failure
U4	625	614	1.02	Yielding and anchorage failure
U5	545	622	0.88	Anchorage failure
U6	626	628	1.00	Yielding and moment failure

The three beams with vertical stirrups failed by anchorage failure of the staggered 16 mm bar. The failure was due to moment shift caused by inclined cracks. The tree beams with inclined (45°) stirrups did not have moment shift. The beam U2 with the shortest onloading length failed by anchorage failure of the 16 mm bar. The reinforcement in beam U4 started to yield and an anchorage failure followed immediately. The test results from this beam give an indication of that the necessary onloading length is > 240 mm for anchoring the yielding force of a 16 mm bar in concrete with a compressive (cylinder) strength of fcc = 44 MPa and a cover of 20 mm. The transverse reinforcement in the cover must correspond to that of stirrups designed to cover the full shear fôrce. The stirrups should have dense spacing. The reinforcement in beam U6 yielded and the beam failed by moment failure without any indication of weakening anchorages.

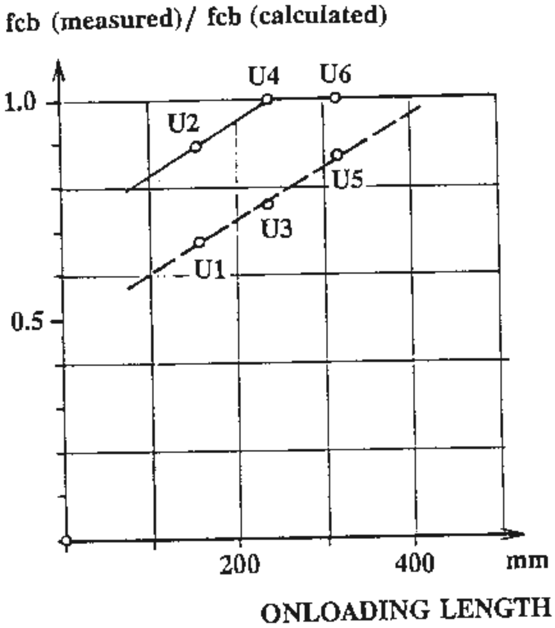


FIGURE 10. The relation between the measured stress fsu in tensile reinforcement at beam failure and the yield stress fsy of reinforcement as function of the onloading length l.

The vertical difference between the lines for beams U2, U4, U6 and U1, U3, U5 in FIG. 10 represents the influence of the moment shift.

The ultimate bond resistance fcb (calculated) at splitting off the concrete cover along the onloading length of the 16 mm bar is in the following calculated according to Eq. (1) under assumption of evenly distributed bond stresses due to cover cracks along the onloading length.

The measured bond stress fcb (measured) along the onloading length is determined under assumption that the measured tensile reinforcement stress in the middle of the beam also exists at the staggering points. The onloading length has to anchor this stress in the 16 mm bar under assumption of evenly distributed bond stress.

By comparing fcb (measured) with fcb (calculated), TABLE 4, it can be concluded, that the beams U2 and U4, without moment shift, have measured bond stresses in level of the calculated. For beam U4 there is a balanced situation between yielding of all reinforcement at middle point of the beam and at staggering points and a following bond failure. For beam U6 the measured bond stress falls below the calculated, because there was no bond failure.

TABLE 4.
Comparison of measured and calculated evenly distributed bond stresses along the onloading length for the staggered 16 mm bar.

Beam	Onloading length m	fcb measured MPa	fcb calculated MPa	Moment shift exists
U1	0.160	10.5	14.5	Yes
U2	0.160	13.75	13.6	No
U3	0.240	7.91	13.6	Yes
U4	0.240	10.41	12.2	No
U5	0.320	6.81	13.1	Yes
U6	0.320	7.81	12.1	No

For beams U1, U3 and U5 the measured bond stresses are lower than the calculated, because these are determined without paying attention to the moment "shift rule".

For the tested beams the applied cover splitting bond theory is obviously useful for determination of the bond resistance of the onloading lengths for staggered reinforcement.

CONCLUSIONS

The high bond bars are effective in taking force by bond. The bars take force by bond immediately from the curtailed end. The force can be loaded on a 16 mm Swedish Ks 600 bar up to yield force with an onloading length of 300 mm when the concrete has a compressive strength fcc = 44 MPa, the cover is 20 mm and there is transverse reinforcement in the cover corresponding to that of stirrups designed for the full shear force.

These test results have contributed to the development of the rules in the Swedish Code BBK79, which allows to use the onloading lengths to cover up the moment load. These experiences have also promoted the, for the time being, existing proposal in the CEB Model Code 90.

ACKNOWLEDGMENT

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