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LOOP CONNECTIONS BETWEEN PRECAST CONCRETE COMPONENTS LOADED IN BENDING

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Preface

The present report is concerned with the strength of loop connections, i.e., structural joints formed by overlapping looped reinforcing bars which project from precast slabs and are embedded in in-situ concrete, designed to transmit flexural loading. This type of connection is already in widespread use in building construction. In the design of such joints it has hitherto been normal practice to apply a reduction in flexural load capacity as compared with that of a monolithic floor slab, this reduction being considered necessary because of uncertainty as to the behaviour of the connection. In this report, however, an (empirical) formula is given, by means of which the strength of such a connection can be calculated with greater accuracy. The requirements to be fulfilled by a loop connection in order to obtain the same flexural load capacity as in the case of continuous reinforcement likewise follow from this. The method of analysis presented here is valid for connections which are loaded (mainly) in bending.

The research leading to this report was carried out by the Institute TNO for Building Materials and Building Structures (IBBC). It had the financial backing of the Building Research Foundation (Stichting Bouwresearch). The investigations were conducted by Committee B7 of the same foundation. This committee was constituted as follows:

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ir. A. E. Christiaanse, secretary
ir. J. J. B. J. J. Bouvy, member
ing. A. Gerritse, member
ing. R. 't Hart, member
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The research work described in this report was carried out for the Committee by ir. M. Dragosavić, ir. A. van den Beukel and ir. F. B. J. Gijsbers, all of whom are on the staff of TNO-IBBC.

The results were published earlier in Dutch by "Stichting Bouwresearch" as report B 7-5 "Lusverbindingen tussen prefab-betonelementen op buiging belast" en B 7-6 "Beproeving lusverbindingen met "rechthoekige" lussen".

The present English translation is by ir. C. van Amerongen MICE.

In practice it is desired to use loop connections also in circumstances where bending is accompanied by a tensile force of substantial magnitude (inter alia, for establishing structural continuity of floors) or a relatively large shear force (e.g., for the attachment of cladding elements). Also, loop connections are constructed in which the amount of overlap (lap length) of the loops is less than the vertical distance between the top and the bottom reinforcement. The Committee is not yet in a position to give recommendations for the analysis of these cases, but does intended to undertake research on these aspects.

LOOP CONNECTIONS BETWEEN PRECAST CONCRETE COMPONENTS LOADED IN BENDING

Summary and conclusions

1. A flexurally rigid joint connecting precast concrete slabs by means of loops formed by the main reinforcement projecting from the slabs is often an attractive method of structural connection from the economic point of view (e.g., for floor-to-wall connections). The research described in this report was necessary in order to arrive at a structural design formula for this type of connection.
2. It appears from the investigations that the strength of a loop connection can be calculated with the aid of the following formula (see the accompanying list explaining the notation employed):

$$\sigma_{al} = 230 \cdot f_b \cdot \left(0{,}7 + 0{,}03 \frac{l_{dl}}{\phi}\right) \cdot \left(1 + 0{,}25 \frac{A_{ad}}{A_a}\right) \cdot \alpha \qquad (4)$$

where:

$$\alpha = \left(0{,}5 + 0{,}05 \frac{s_r}{\phi}\right) \leqslant 1{,}0$$

In order to obtain a fully effective connection, the condition $\sigma_{al} \geqslant f_a$ must be satisfied.
3. The above formula can be applied to joints in which the connecting loops extend through the full depth (thickness) of the slab (subject to providing the usual amount of concrete cover at top and bottom) and are bent to a semicircular shape or a shape comprising two quarter-circles. Also, the following conditions must be satisfied (see figure 11):

$$l_{dl} \geqslant 10\phi$$

$$l_{dl} \geqslant 2R$$

$$R \geqslant 2{,}5\phi$$

$$s_r \geqslant 5\phi$$

$$a \leqslant \tfrac{1}{3} l_{dl}$$

Notations

A_a	steel cross-sectional area in one loop $= \frac{1}{4}\pi\phi^2$
A_{ad}	total steel cross-sectional area of transverse reinforcement
a	distance between the loops in one pair
b	width of slab
c	concrete cover
f_a	design value of the steel stress in the stage of failure
f_e	0,2% proof stress of the steel used in the test specimens
f_b	design value of the tensile strength of the concrete
f_{bm}	$1+0{,}05\, f'_{bm}$ = average tensile strength of the concrete
f'_{bm}	average cube strength of the concrete
h	effective depth of the slab at the joint
h_t	total depth of the slab at the joint
M_{br}	failure moment measured on the test specimen
M_u	calculated failure moment of the slab in the case of continuous reinforcement (f_a is determinative)
M_l	calculated failure moment of the loop connection if failure of the in-situ concrete in the joint is determinative
n	number of loops in a slab
l_{dl}	lap length of loops, which is equal to the straight lap length of the bars plus the internal diameter of the loop
R	internal radius of curvature of the loop
p	$h_t-2c-2\phi$
s	centre-to-centre distance between two adjacent pairs of loops
s_r	distance from centre of outermost loop to lateral edge of slab
z	internal lever arm
σ_{al}	steel stress associated with M_l
ϕ	bar diameter
ω_0	reinforcement percentage

Loop connections between precast concrete components loaded in bending

1 Introduction

This report is concerned with an investigation of the strength and behaviour of connections formed between precast concrete floor slabs by means of looped reinforcing bars and in-situ concrete placed in the joints. This type of connection is shown schematically in figure 1.
A loop connection, i.e., a joint constructed in this way, may fail as a result of three possible causes:

a. yielding of the steel;
b. crushing of the compressive zone of the concrete;
c. cracking of the in-situ concrete in the joint at the overlapping loops.

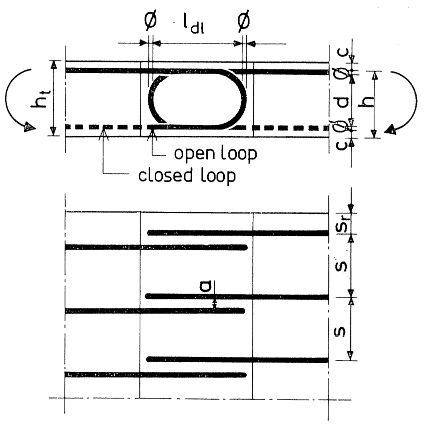


Fig. 1. The loop connection investigated (schematic).

The usually methods of analysis for flexurally loaded structural members are applicable to the failure modes (a) and (b). For failure to occur in accordance with (c) a number of factors are involved, the influence of which is difficult to quantify. The following possible factors can be mentioned (see also Fig. 1):

a. the quality of the in-situ concrete in the joint;
b. the lap length l_{dl} of the loop;
c. the bar diameter ϕ;
d. the quality of the loop steel;
e. the quantity of transverse reinforcement A_{ad} in the connection;
f. the concrete cover c;
g. the distance s between two adjacent pairs of loops;

h. the lateral cover s_r;
i. the loop diameter d;
j. the distance a between the overlapping loops in a pair;
k. the manner of loading applied to the connection.

With a view to arriving at a design formula the Committee had tests carried out by TNO-IBBC (Institute TNO for Building Materials and Building Structures). At about the same time, similar experimental research was undertaken in Germany, too, so that the results thereof were also available for the purpose of this report.

2 Tests performed

Details of the tests considered in the present report are given in the publications listed in Appendix 1. The most important data obtained from these sources are tabulated in Appendix 2.

2.1 *Tests conducted by Committee B7 of the SBR (Building Research Foundation)*

After some preliminary tests [1] had been carried out, the need was felt to have a scheme of experimental work which, by virtue of the larger number of tests it comprised, would permit a reliable conclusion with regard to the effects of the variables involved. For that reason 50 tests on scaled-down models were performed [2, 3].

The principal variables in these tests were the lap length of the loops, the edge distance, the bar diameter, the quantity of transverse reinforcement, and the quality of the concrete. Meanwhile the Committee had also obtained the results of tests on some loop connections which had been employed in actual practice [4, 5]. The experimental research was concluded with a series of tests with very low quality concrete in the joints and with different loop shapes [6].

2.2 *Tests by Kordina and Timm*

On considering the tests performed by Kordina [7] and Timm [8], in Germany, it appears that the variables under investigation likewise correspond to the influencing factors listed in the Introduction. Those investigators concluded that a loop connection must conform to the following requirements in order to attain the same strength as the comparable connection formed with continuous main reinforcement across the joint:

- maximum bar diameter: $\phi = 14$ mm
- maximum loop spacing: $a \approx 5\phi$
- maximum edge distance: $s_r \approx 4\phi$
- minimum internal diameter of loop: $d = 8\phi$
- minimum quality (strength class) of concrete: B 25
- for concrete B 25 the lap length l_{al} should be at least $10{,}5\phi$ according to Kordina and at least $15{,}5\phi$ according to Timm; according to the latter author the lap length

can permissibly be less for better quality concrete, but on no account less than 13ϕ;
- the joint should contain transverse reinforcement which, according to Timm, should consist of at least 3 bars of 6 mm diameter (ribbed bars);
- in side elevation a pair of loops should at least enclose a circular area.

This approach to a loop connection is unsatisfactory for the following reasons:

a. Such an enumeration of the limiting values of the various factors provides little insight into the actual effect of the factors individually.
b. It is quite conceivable that, for example, a combination of low concrete quality with a large lap length will give as good a result as a combination of high concrete quality with a small lap length.
c. A design rule that would allow various combinations of lap length, concrete quality and transverse reinforcement would give the designer greater freedom.
d. It is possible that the test results are too favourable because the tensile strength of the concrete was in fact higher than the design value thereof that should introduced into the calculations in actual practice. In this context it should be noted that in a subsequent version of DIN 1045, the German code of practice for reinforced concrete, more stringent requirements for loop connections were imposed.

3 Interpretation of the tests

3.1 *Failure load*

Experience gained in the course of the tests shows failure of a flexurally loaded loop connection to proceed as follows (see figure 2).

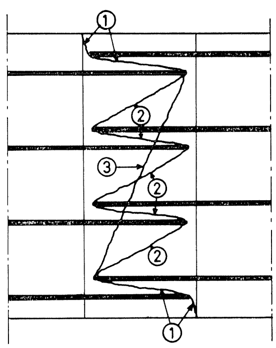


Fig. 2. Crack patterns at a loop connection.

At a relatively small value of the load, or bending moment, cracks already develop at the vertical contact surfaces (interfaces) between the in-situ concrete and the ends of the precast slabs. These interfaces are not actually part of the connection itself, and the cracks which occur there do indeed have little to do with the failure of the connection.

Failure is always initiated by cracks at the outermost pairs of loops (cracks 1 indicated in figure 2). Evidently, the cause of this cracking is that each pair of loops exerts outward-directed lateral forces which are more or less cancelled by the successive pairs of loops, except at the outermost ones, where these forces have to be resisted entirely by the concrete.

Next, the cracks 2 occur. These cracks do not necessarily always have to develop. Instead, an oblique crack 3 extending across a number of loops may be formed. If there is transverse reinforcement, more extensive cracking perpendicularly to the plane of the loop and less cracking of types 1 and 2 are found to occur. Naturally, this will be even more so if the strength of the loop connection is such that the in-situ concrete in the joint is not the determining factor with regard to failure. In that case the same failure moment will be attained as in the case where the reinforcement extends continuously across the joint, and cracking will accordingly be in a direction perpendicular to this reinforcement.

For clarification, the typical cracking patterns are indicated in figure 3. Figures 4 and 5 are photographs of two loop connections after failure.

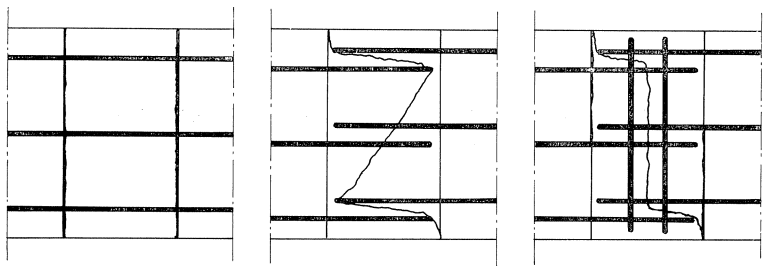


Fig. 3a.
Continuous bars.

Fig. 3b.
Loop connection without transverse reinforcement.

Fig. 3c.
Loop connection with transverse reinforcement

Fig. 3. Crack patterns.

From the foregoing it is already deducible that the following factors probably play an important part in determining the strength of a loop connection:

a. The tensile strength f_{bm} of the in-situ concrete in the joint, because the formation of the cracks 1 and 2 depends on this strength.
b. The lap length l_{dl} of the loops, because this determines how much of the in-situ concrete is available for transmitting the force from one loop to another.

c. The transverse reinforcement A_{ad}, because this can defer the formation of cracks and can, after cracking has taken place, partly and perhaps entirely act in lieu of the concrete stresses.
d. The distance s_r from the outermost loop to the edge of the slab, because the first cracks develop there.
e. The number of pairs of loops in the connection, because it will, after the outermost loops have failed, depend on the number and strength of the remaining ones whether there is still sufficient capacity to resist the load that is already acting.

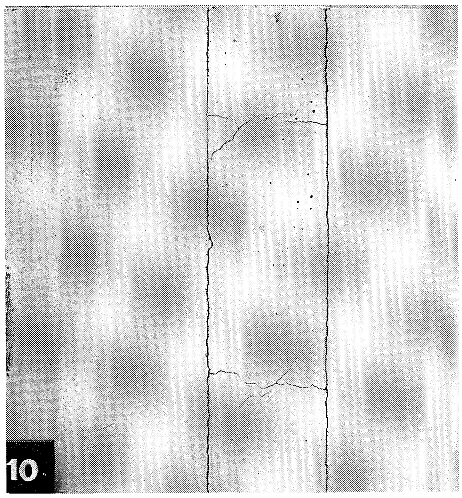


Fig. 4. Failure pattern of a loop connection without transverse reinforcement (No. 133 in Appendix 2).

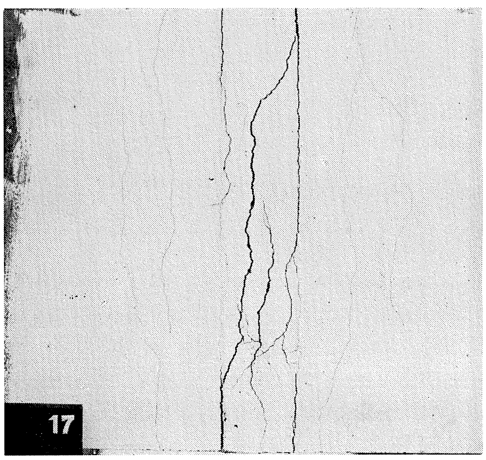


Fig. 5. Failure pattern of a loop connection with transverse reinforcement (No. 140 in Appendix 2).

The strength of a loop connection can be expressed in terms of the maximum steel stress σ_{al} that is attained in a loop before the in-situ concrete fails. If the loop connection is as strong as a connection with continuous reinforcement extending across the joint, then of course: $\sigma_{al} \geqslant f_e$. If $\sigma_{al} < f_e$, the value of σ_{al} will depend on the abovementioned factors. It is assumed that the following expression is valid:

$$\sigma_{al} = k \cdot f_1(f_{bm}) \cdot f_2\left(\frac{l_{dl}}{\phi}\right) \cdot f_3\left(\frac{A_{ad}}{A_d}\right) \cdot f_4\left(\frac{s_r}{\phi}\right)$$

By trial and error it has been established that in the range of behaviour investigated, namely, for $l_{dl} > 8\phi$ and $s_r > 1{,}5\phi$, a reasonably good approximation of the test results is obtained by adopting the following expressions for σ_{al}:

for an inner loop:

$$\sigma_{al} = 230 \cdot f_{bm} \cdot \left(0{,}7 + 0{,}03\frac{l_{dl}}{\phi}\right) \cdot \left(1 + 0{,}25\frac{A_{ad}}{A_a}\right) \qquad (1a)$$

for an outer loop with $s_r < 10\phi$:

$$\sigma_{al} = 230 \cdot f_{bm} \cdot \left(0{,}7 + 0{,}03\frac{l_{dl}}{\phi}\right) \cdot \left(1 + 0{,}25\frac{A_{ad}}{A_a}\right) \cdot \alpha \qquad (1b)$$

where:

$$\alpha = (0{,}5 + 0{,}05 s_r/\phi) \leqslant 1{,}0$$

The loop moment M_l of a connection comprising n pairs of loops is expressed by:

$$M_l = n \cdot A_a \cdot z \cdot \sigma_{al}$$

so that:

$$M_l = 230 \cdot n \cdot A_a \cdot z \cdot f_{bm} \cdot \left(0{,}7 + 0{,}03\frac{l_{dl}}{\phi}\right) \cdot \left(1 + 0{,}25\frac{A_{ad}}{A_a}\right) \cdot \alpha \qquad (2a)$$

where:

$$\alpha = (0{,}5 + 0{,}05 s_r/\phi) \leqslant 1{,}0$$

or:

$$M_l = 230 \cdot (n-2) \cdot A_a \cdot z \cdot f_{bm} \cdot \left(0{,}7 + 0{,}03\frac{l_{dl}}{\phi}\right) \cdot \left(1 + 0{,}25\frac{A_{ad}}{A_a}\right) \qquad (2b)$$

Formula (2b) expresses the fact that when the outer loops are ignored (it is at these loops that failure is initiated!), the strength of the inner loops, which are unaffected by the edge distance (the distance to the side face of the slab), can still be relied upon. Hence the larger of the two values obtained with (2a) and (2b) should be adopted.

(Of course, this is valid only if $s + s_r \geqslant 10\phi$, which is usually the case in slabs; for only on that condition the second pair of loops can permissibly be regarded as an "inner loop").

That the above loop formula is in reasonably good agreement with the test results is apparent from Fig. 6, in which, for all the tests, the values of M_{br}/M_u have been plotted against M_l/M_u, where:

M_{br} = measured failure moment;
M_u = theoretical failure moment for a corresponding monolithic connection which fails in the steel.

The determination of M_u is explained in Appendix 3.

For the case where $M_l < M_u$ we have theoretically $M_{br} = M_l$, and for $M_l > M_u$ we have theoretically $M_{br} = M_u$ (dotted lines in figure 6).

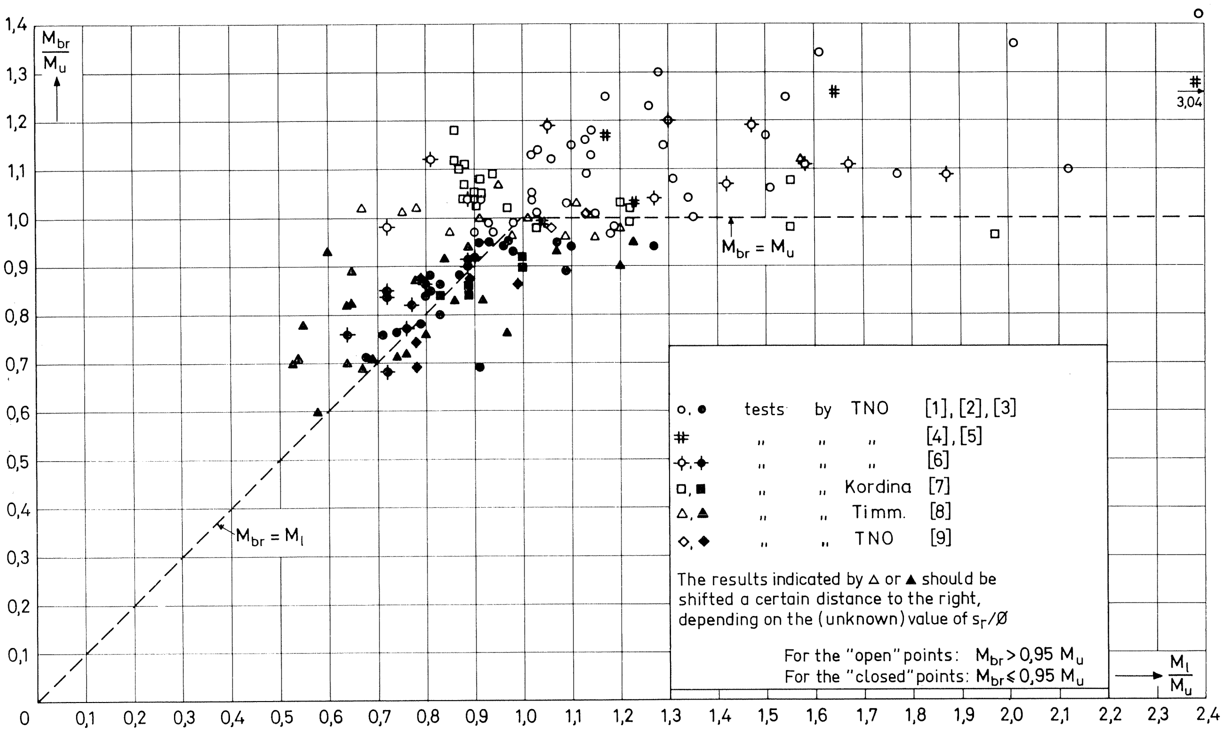


Fig. 6. Relations between M_{br}/M_u and M_l/M_u.

3.2 *Checking the influencing factors*

In justification of the formulas presented in 3.1, we shall here consider the influencing factors individually, lifting them out of the formula, as it were, and comparing them with the observed values (on the assumption that the effect of the other factors has been correctly represented). Figures 7, 8 and 9 may serve to elucidate this.

It should be noted that for this comparison only the results of those tests are applicable for which $M_{br} < M_u$, since the formula is representative only for $\sigma_{al} < f_e$.

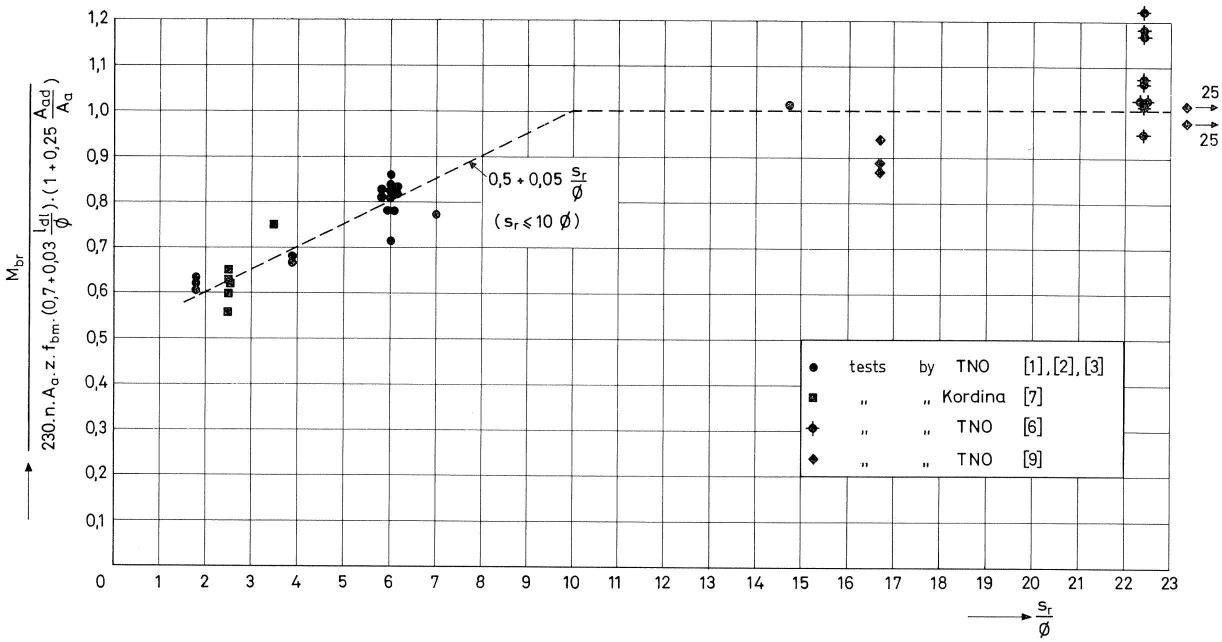


Fig. 7. Effect of edge distance s_r.

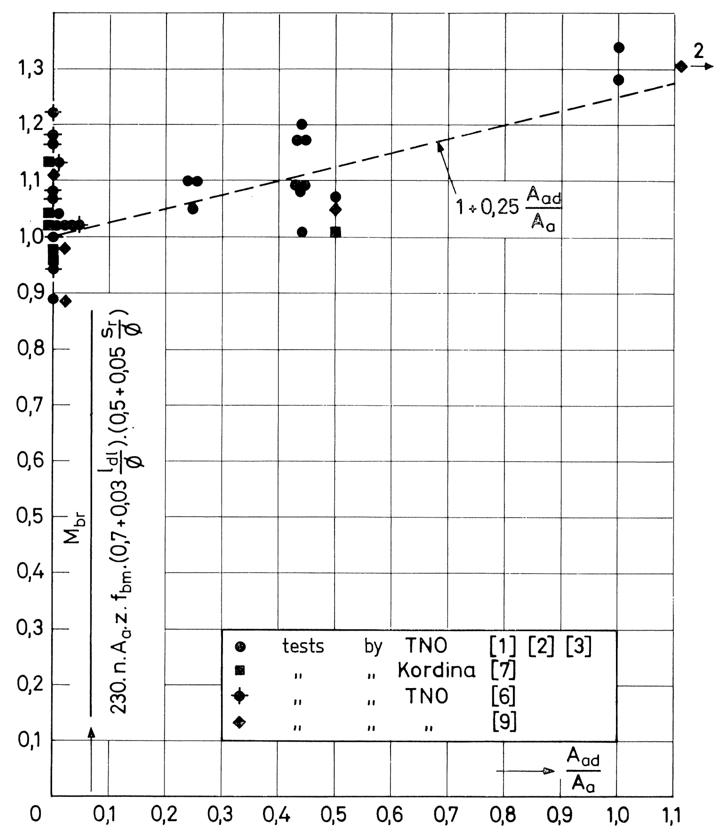


Fig. 8. Effect of transverse reinforcement A_{ad}.

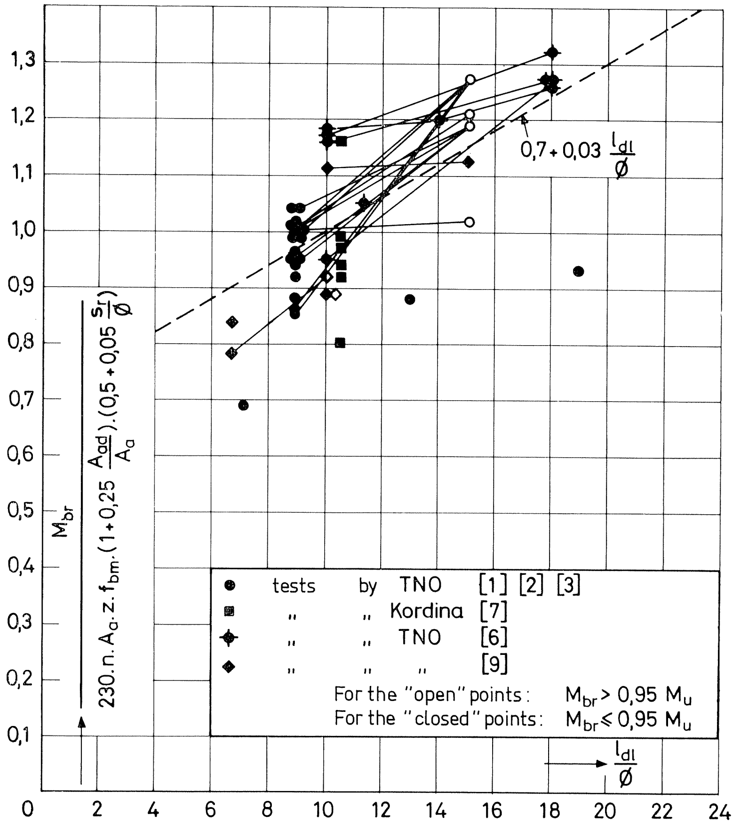


Fig. 9. Effect of lap length l_{dl}.

Because of the scatter displayed, only the results of those tests for which $M_{br} \leqslant 0{,}95 M_u$ will in fact be considered.

a. In figure 7 the values of s_r/ϕ have been plotted as abscissae. The ordinates indicate the measured failure moment divided by the reduced calculated failure moment, i.e., the moment M_l according to formula (2) without taking account of the effect of the edge cover:

$$M_{l_{\text{reduced}}} = M_l/(0{,}5 + 0{,}05 s_r/\phi)$$

The test results located on the extreme right-hand side of figure 7 indicate that when the edge distance exceeds approximately 10ϕ, this distance is no longer of influence, and the outer loop may then be assumed to be equivalent to an inner loop.

For $1{,}5\phi < s_r < 10\phi$ we have approximately:

$$f_4(s_r/\phi) = 0{,}5 + 0{,}05 s_r/\phi$$

b. A similar procedure has been followed in order to show the effect of transverse reinforcement in figure 8, where the values of A_{ad}/A_a have been plotted as abscissae, while the ordinates represent the values of $M_{br}/M_{l_{\mathrm{reduced}}}$:

$$M_{l_{\mathrm{reduced}}} = M_l/(1+0{,}25A_{ad}/A_a)$$

From the diagram it appears that the strength of the loop reinforcement increases with the increasing quantity of transverse reinforcement approximately in accordance with the following relationship:

$$f_3(A_{ad}/A_a) = 1+0{,}25A_{ad}/A_a$$

It should be noted, however, that if there is only a small amount of lateral cover s_r a transverse reinforcement for the outer loops may be less effective than would appear from f_3. To enable a transverse reinforcement to function effectively for the outer loops, this reinforcement should be bent round the outermost loop (in the form of hairpins).

c. In the same manner as described above, the values l_{dl}/ϕ and $M_{br}/M_{l_{\mathrm{reduced}}}$ have, respectively, been plotted as abscissae and ordinates in figure 9:

$$M_{l_{\mathrm{reduced}}} = M_l(0{,}7+0{,}03l_{dl}/\phi)$$

Those points for which only the lap factor l_{dl}/ϕ has been varied are joined to one another in the diagram. A few points for which $M_{br} > 0{,}95M_u$ were also used here, but the effect of the lap length was found to correspond to that for $M_{br} \leqslant 0{,}95M_u$. From the diagram it appears that for $l_{dl} > 8\phi$ a satisfactory approximation of the effect of the lap length l_{dl} upon the strength of the loop connection is provided by:

$$f_2(l_{dl}/\phi) = 0{,}7+0{,}03l_{dl}/\phi$$

d. In figure 10 the values of f_{bm} have been plotted against $M_{br}/M_{l_{\mathrm{reduced}}}$, where:

$$M_{l_{\mathrm{reduced}}} = M_l/f_{bm}$$

The results of the tests are found to be not entirely proportional to the tensile strength of the concrete (see the solid line in figure 10). However, this is more particularly true of the specimens for which the tensile strength of the in-situ concrete in the joint exceeded 2,5 N/mm^2. For practical use this is not a significant strength range, inasmuch as a characteristic tensile strength above 2,5 N/mm^2 requires a concrete whose quality (strength class) is above B 37,5 (see part A of the code of practice VB 1972), which is something that is generally not attainable with in-situ concrete. For a concrete tensile strength below 2,5 N/mm^2 the strength of the loop connection can be taken as proportional to the tensile strength (see dotted line in figure 10):

$$f_1(f_{bm}) = f_{bm}$$

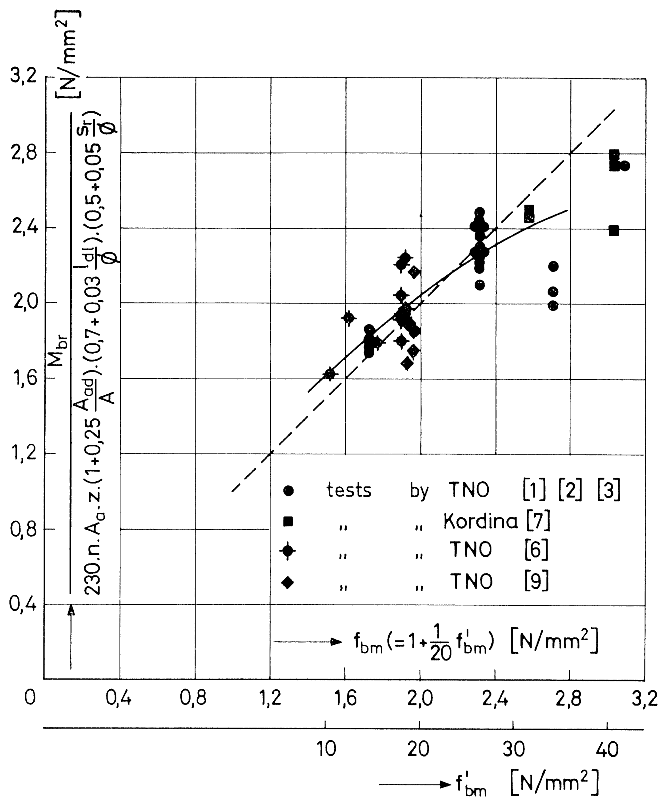


Fig. 10. Effect of concrete quality (strength class).

e. Besides the influences as reflected in f_1 to f_4, it was found that a constant $k = 230$ had to be introduced into the formula.
Evidently, the formulas for σ_{al} and for M_l have been arrived at empirically and that the component parts of those formulas (f_1, f_2, f_3 and f_4 respectively) cannot claim to be serviceable outside the range under investigation. For this reason the formulas presented here will have to be applied judiciously in any particular case.

3.3 *Other aspects*

Besides the effects of concrete quality (strength class), lap length, lateral concrete cover, quantity of transverse reinforcement and loop bar diameter there are other aspects concerning which the test results supply a certain amount of information.

a. In general, the test specimens were loaded either by a point load acting at the joint, i.e., by a combination of bending moment and shear force on each side of the loop connection, or were loaded by means of a four-point system to produce bending moment only. The results give no indication that the shear force could have an adverse effect on the strength of the connection. However, no tests were performed with an antimetric four-point flexural loading system in which the connection as a whole is itself subjected mainly to shear force, so that the formulas given here are not applicable to this last-mentioned case.

b. The effect, if any, of the concrete cover c over and under the loops and of the loop spacing a is not ascertainable on the basis of the available test results. It does appear likely, however, that some restriction will have to be imposed on the distance between the two loops in a pair, so as to limit this distance to something like $a < (0{,}3 \text{ to } 0{,}5)l_{dl}$.

c. Open or closed loops. A difference in behaviour between open and closed loops is ascertainable only in the test results reported in [6], where relatively low quality concrete was used in the joints. Those tests indicated that, with relatively small lap length ($l_{dl} = 10\phi$) and no transverse reinforcement, the connection formed with closed loops was about 20% stronger than with open loops.
In the investigations performed by Kordina and Timm the loops were, with one exception, all of the open type. Nevertheless their results are not found to be systematically lower than the others, which is something that may be attributable to the circumstance that in those tests the combination of low quality of the concrete with absence of transverse reinforcement hardly ever occurred. It is furthermore to be noted that the open loops in those tests were formed with a large bending radius, similar to that of the closed loops (i.e., not just ordinary U-hooks such as those commonly formed on reinforcing bars).

d. Different loop shapes. The foregoing considerations relate only to loop connections in which the loop was always shaped as a continuous semicircle (figure 11a). This shape, however, signifies a restriction upon the applicability of loops for forming connections between floor slabs such as are commonly installed in residential buildings, where the space available for producing the overlap of the reinforcement tends to be relatively small. With the semicircular loop shape a smaller lap length would result in a reduction in effective depth of the reinforced slab at the joint. Hence the question arose as to whether the formulas derived here are applicable also to connections in which the loops are bent to a shape comprising two quarter-circles of smaller diameter, so that the effective depth is maintained even if the lap length is made smaller than the vertical distance between the top and bottom bars (figure 11b).
With a view to assessing the validity of the formulas for such "rectangular" loops (so called because of their somewhat angular shape), the Committee had additional tests carried out [9]. The radius of bending of the bars was $R = 2{,}5\phi$, this being the minimum radius specified for normal U-hooks on the ends of reinforcing bars. In figures 6 to 10 the results have been plotted as a function of the respective variables, in so far as $M_{br} \leqslant 0{,}95 M_u$. These test results are in reasonably good agreement with the values calculated from formula (2b). The relevant data and results are listed in the table in Appendix 2 (Nos. 145 to 151).

e. Different forms of connection. In order to obtain some idea of the effect of forming connections with other than looped reinforcing bars, the Committee had a

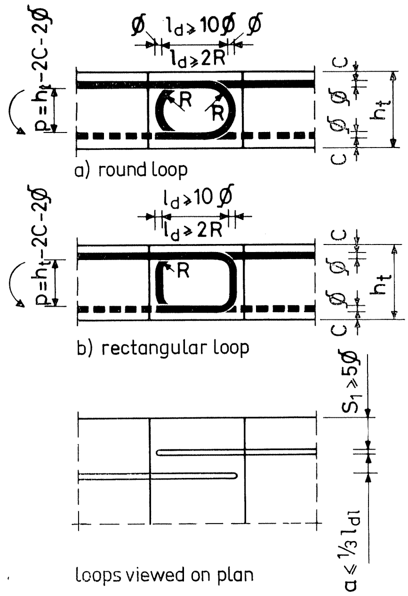


Fig. 11. Round and rectangular loops, with requirements to which the connection must conform.

comparative investigation carried out on four types of connection. The data and results of this series of tests are summarised in Appendix 4. It appears that a loop connection is considerably stronger than a connection formed with straight lap splices of the main reinforcement and than a connection in which U-hooks serve to transmit the force. The superiority of the loop connection over the ordinary U-hook as used in this latter instance is presumably due to the larger radius to which the loop is bent. However, in view of the generally limited lap length, as in these tests, the loop connection is distinctly less strong than the joint with bars extending continuously across it.

f. Rotational capacity. The total angular rotation between the supports has been deduced from the measured deflections of the test specimens envisaged in [6]. The rotation thus determined is found to correspond approximately to the rotational capacity of the connection. All the specimens whose measured failure moment *exceeded* 95% of the theoretical failure moment of a corresponding monolithic connection were found to have a rotational capacity of 0,07 radian, with a minimum observed value of 0,045 radian. A rotation of this magnitude is considered to be adequate to justify the assumption of a plastic hinge at the connection. As for the results of the tests with rectangular loops [9], the maximum rotational capacity at the instant of failure was between 0,025 and 0,06 radian.

4 Practical design

Equation (1) can serve as a starting point for establishing a suitable formula for the practical design calculations for a loop connection, provided that the conditions encountered in actual practice are duly taken into account in so far as they differ from those in the laboratory tests. This relates, on the one hand, to the quality of the materials and to the dimensioning and, on the other, to the required strength of the connection. The following considerations apply here:

a. Because of the scatter (variation) in the concrete quality and because of the long duration of the loading in actual practice, it is necessary to replace f_{bm} – this being the (average) tensile strength of the concrete in a test – by the design value f_b of the tensile strength of the concrete to be used in the connection concerned.
b. The dimensional accuracy with regard to the thickness of the slab, the concrete cover and therefore the effective depth at the loop connection need, generally speaking, not be any less than is elsewhere normally achieved with in-situ concrete. The same can be said with regard to the lateral cover s_r to the outermost loop. The lap length l_{dl} may, however, vary considerably as a result of an accepted wide tolerance. Hence the tolerance must be taken into account in the lap length l_{dl}:

   $(l_{dl} = \text{nominal } l_{dl} - \text{tolerance})$.

c. In Section 3.1 it has already been stated that formula (1) is not representative in cases where the values of l_{dl}/ϕ and s_r/ϕ are very small. The simple linear functions f_1 and f_2 can be maintained only when these extremes are excluded. Also, the behaviour of the loop may become different if the lap length is very small, while in that case the effect of the tolerances in the values l_{dl}, a and s_r increases disproportionately. The effect of a transverse reinforcement, if provided, likewise becomes doubtful for small values of s_r. For these reasons it is considered that a loop connection can permissibly be employed as a flexurally rigid connection and be designed with the aid of the formulas given here, if the following conditions are fulfilled (see figure 11):

   $$l_{dl} \geqslant 10\phi$$

   $$l_{dl} \geqslant 2R$$

   $$s_r \geqslant 5\phi$$

   $$a \leqslant \tfrac{1}{3} l_{dl}$$

   Furthermore, the loops should extend through the full thickness of the slab (subject to providing the usual amount of concrete cover):

   $$p = h_t - 2c - 2\phi$$

   (It should be noted that, as contrasted with the rule for the length of a lap splice given in the code of practice for reinforced concrete, the bar diameter is not included in the determination of the lap length l_{dl} of a pair of loops).

d. A precast concrete floor slab is usually supported at its two ends, without intermediate auxiliary supports, so that the slab carries its own weight even before the structural connections are established. For this reason the connection is generally designed without taking account of the dead weight of the slab itself in the calculations. As a result of subsequent creep, however, the dead weight may nevertheless give rise to bending moments acting upon the connection, so that there remains uncertainty as to the precise distribution of the bending moments at the supports and in the spans respectively. This problem is overcome by having recourse to the theorem of collapse load analysis stating that plastic hinges can permissibly develop, thus providing a considerable measure of freedom in distributing the reinforcement between the supports and the mid-span regions. An approach of this kind is acceptable, however, only if the assumed plastic hinges possess sufficient rotational capacity. In order to guarantee such rotational capacity at a loop connection, the condition $\sigma_{al} \geqslant f_a$ must be satisfied, for otherwise the in-situ concrete in the joint will fail when the deformation is still only relatively small, in which case the strength of the connection will be lost before the assumed redistribution of the moments can be achieved.

e. In the tests the steel employed for the main reinforcement (= the loops) was of grade FeB 400 or FeB 500, while in both cases the transverse reinforcement was FeB 400. These combinations are to be regarded as acceptable also in actual practice.

f. With due regard to the above conditions, the following design formula can be adopted:

$$\sigma_{al} = 230 \cdot f_b \cdot \left(0{,}7 + 0{,}03 \frac{l_{dl}}{\phi}\right) \cdot \left(1 + 0{,}25 \frac{A_{ad}}{A_a}\right) \cdot \alpha \geqslant f_a \qquad (3)$$

where:

$$\alpha = (0{,}5 + 0{,}05 s_r/\phi) \leqslant 1{,}0$$

With this formula the required quantity of transverse reinforcement can, for example, be calculated if the concrete and steel strengths, the lap length and the bar diameter are known. Then:

$$A_{ad} > A_a \left(\frac{f_a}{f_b} \cdot \frac{1}{\alpha(40{,}25 + 1{,}72 l_{dl})} - 4\right)$$

The results have been compiled in the following table for $\alpha = 1{,}0$ (i.e., for $s_r \geqslant 10\phi$) and $f_a = f_e$:

Table for the values A_{ad}/A_a

steel grade	strength class of concrete in joint	value l_{dl}/ϕ 10	15	20	
loop reinf. FeB 400 NR	B 12,5	3,0	2,1	1,4	A_{ad}/A_a
transv. reinf. FeB 400 NR	B 17,5	1,8	1,1	0,5	
	B 22,5	1,0	0,4	0	
loop reinf. FeB 500 NR	B 12,5	4,7	3,6	2,7	
transv. reinf. FeB 400 NR	B 17,5	3,3	2,3	1,6	
	B 22,5	2,2	1,4	0,8	

Example 1

With loop reinforcement FeB 400 NR, in-situ concrete in joint B 17,5, lap length $l_{dl} = 16\phi$ and $\phi = 8$mm, we obtain for the required transverse reinforcement: 2 bars ϕ6 mm (FeB 400 NR).

Example 2

With loop reinforcement FeB 500 NR, in-situ concrete in joint B 17,5, lap length $l_{dl} = 17\phi$ and $\phi = 8$ mm, we obtain for the required transverse reinforcement: 2 bars ϕ8 mm (FeB 400 NR).

As appears from these examples, the condition $\sigma_{al} \geqslant f_a$ can be satisfied by relatively little transverse reinforcement in the case of the frequently encountered type of loop connections.

g. It should be noted that only those bars qualify as transverse reinforcement which are *inside* the loops and in the *tensile zone* of the joint.
This means that the transverse bars cannot merely be laid on top of the loops, but must instead pass through them; and if the tensile zone is at the top (as is generally the case in floor-to-wall connections) those bars must tied to the top of the loops.
It is recommended to provide at least two transverse bars.
In a case where $\alpha < 1{,}0$ there should be additional transverse bars at the outer loops. The total quantity of transverse reinforcing steel to be provided there can also be calculated from equation (3).
It must be ensured that the transverse bars are well anchored at their ends. In general, these bars will have to be hairpin-shaped.
The requirement $\sigma_{al} \geqslant f_a$ is applicable also to an outer loop.

5 Scope for application

a. The proposed design calculation is, of course, valid only for those types of loop connection which are entirely or largely similar to the connections which have been the subject of tests, i.e., vertical loops which are (mainly) loaded in bending (see figure 12). It is not justifiable to apply this design procedure to loop connections which have to transmit relatively large tensile or shear forces (see figures

APPENDIX 1

References

[1] TNO-IBBC Report No. BI-66-55. Committee A3a. Some supplementary preliminary tests relating to the strength and rigidity of a structural joint.
Specimens Nos. 1 to 49 and 118 to 122 designated by ● or ○
[2] TNO-IBBC Report No. BI-67-37. Model tests on loop connections. Report 1.
Specimens Nos. 1 to 49 and 118 to 122 designated by ● or ○
[3] TNO-IBBC Report No. BI-67-43. Model tests on loop connections. Report 2.
Specimens Nos. 1 to 49 and 118 to 122 designated by ● or ○
[4] TNO-IBBC Report No. BI-70-194. Testing a loop connection formed between Datoss precast floor slabs.
Specimens Nos. 113 to 117 designated by #
[5] TNO-IBBC Report No. B-70-198. Testing a loop connection formed between Elementum precast floor slabs.
Specimens Nos. 113 to 117 designated by #
[6] This is a reference to tests which were carried out at the instance of SBR Committee B7 by TNO-IBBC during the course of 1972 and 1973. No TNO report was issued in respect of these tests.
Specimens Nos. 123 to 144 designated by ✦ or ✧
[7] TNO-IBBC. Summary of Professor Kordina's provisional report concerning joints formed with looped bars.
Specimens Nos. 50 to 75 designated by ■ or □
[8] A. TIMM. Untersuchung zur Verbindung von Stahlbetonplatten mit hakenförmig gebogenen Stäben (Investigation concerning the connection of reinforced concrete slabs with hook-shaped bent bars). Doctoral thesis. Karlsruhe, 1969.
Specimens Nos. 76 to 112 designated by ▲ or △
[9] TNO-IBBC Report No. BI-74-63. Results of the testing of loop connections with so-called "rectangular" loops.
Specimens Nos. 145 to 151 designated by ◆ or ◇

APPENDIX 2

Summary of data and test results (Explanatory notes are given on pages 32 and 33)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
no.	reference and specimen number	n	ω_0 [%]	f_e [N/mm²]	ϕ [mm]	A_a [mm²]	f'_{bm} [N/mm²]	f_{bm} [N/mm²]	z [mm]	a/ϕ	l_{dl}/ϕ	s_r/ϕ	A_{ad} [mm²]	$1+0{,}25\ A_{ad}/A_a$	$0{,}7+0{,}03\ l_{dl}/\phi$
1	I-1	3	0,608	451	2,4	4,52	26,3	2,32	19,7	2,1	14,97	6,0	0	1,00	1,15
2	-2	3	0,619	451	2,4	4,52	26,3	2,32	19,3	2,1	14,97	6,0	1,13	1,06	1,15
3	[2] -3	3	0,594	451	2,4	4,52	26,3	2,32	20,1	2,1	14,97	6,0	2,26	1,13	1,15
4	-4	3	0,618	451	2,4	4,52	26,3	2,32	19,4	2,1	14,97	6,0	2,01	1,11	1,15
5	-5	3	0,616	451	2,4	4,52	26,3	2,32	19,4	2,1	14,97	6,0	4,02	1,22	1,15
6	I-6	3	0,601	451	2,4	4,52	26,3	2,32	19,9	2,1	14,97	6,0	4,52	1,25	1,15
7	7	3	0,586	451	2,4	4,52	26,3	2,32	20,4	2,1	14,97	6,0	9,05	1,50	1,15
8	[2] II-10	3	0,589	451	2,4	4,52	26,3	2,32	20,2	2,1	8,96	6,0	0	1,00	0,97
9	-11	3	0,615	451	2,4	4,52	26,3	2,32	19,5	2,1	8,96	6,0	1,13	1,06	0,97
10	-12	3	0,615	451	2,4	4,52	26,3	2,32	19,5	2,1	8,96	6,0	2,26	1,13	0,97
11	-13a	3	0,604	451	2,4	4,52	26,3	2,32	19,8	2,1	8,96	6,0	2,01	1,11	0,97
12	-13b	3	0,618	451	2,4	4,52	26,3	2,32	19,8	2,1	8,96	6,0	2,01	1,11	0,97
13	[2] -14	3	0,612	451	2,4	4,52	26,3	2,32	19,6	2,1	8,96	6,0	4,02	1,22	0,97
14	-15	3	0,596	451	2,4	4,52	26,3	2,32	20,1	2,1	8,96	6,0	4,52	1,25	0,97
15	-16	3	0,599	451	2,4	4,52	26,3	2,32	20,0	2,1	8,96	6,0	9,05	1,50	0,97
16	II-18	3	0,602	451	2,4	4,52	26,3	2,32	19,9	0	8,96	7,0	1,13	1,06	0,97
17	-19	3	0,592	451	2,4	4,52	26,3	2,32	20,1	0	8,96	7,0	2,01	1,11	0,97
18	[2] -20	3	0,575	451	2,4	4,52	26,3	2,32	20,8	0	8,96	7,0	4,52	1,25	0,97
19	IV-21	3	0,602	451	2,4	4,52	26,3	2,32	19,9	2,1	8,96	1,8	1,13	1,06	0,97
20	-22	3	0,608	451	2,4	4,52	26,3	2,32	19,7	2,1	8,96	1,8	2,01	1,11	0,97
21	-23	3	0,590	451	2,4	4,52	26,3	2,32	20,2	2,1	8,96	1,8	4,52	1,25	0,97
22	-24	3	0,595	451	2,4	4,52	26,3	2,32	20,1	2,1	8,96	3,9	1,13	1,06	0,97
23	-25	3	0,623	451	2,4	4,52	26,3	2,32	19,2	2,1	8,96	3,9	2,01	1,11	0,97
24	[2] -26	3	0,620	451	2,4	4,52	26,3	2,32	19,3	2,1	8,96	3,9	4,52	1,25	0,97
25	[3] V-27	3	0,611	451	2,4	4,52	22,2	2,11	19,3	2,1	8,96	6,0	0	1,00	0,97
26	-28	3	0,605	451	2,4	4,52	22,2	2,11	19,5	2,1	8,84	6,0	2,01	1,11	0,97
27	-29	3	0,598	451	2,4	4,52	22,2	2,11	19,8	2,1	8,84	6,0	4,52	1,25	0,97
28	[3] -30	3	0,613	451	2,4	4,52	22,2	2,11	19,3	2,1	8,84	6,0	7,08	1,39	0,97
29	-31	3	0,625	451	2,4	4,52	22,2	2,11	18,9	2,1	8,84	6,0	2,01	1,11	0,97
30	-32	3	0,625	451	2,4	4,52	22,2	2,11	18,9	2,1	8,84	6,0	4,52	1,25	0,97
31	-33	3	0,622	451	2,4	4,52	22,2	2,11	19,0	2,1	8,84	6,0	7,08	1,39	0,97
32	VI-34	3	0,613	451	2,4	4,52	14,6	1,73	19,3	2,1	8,84	6,0	0	1,00	0,97
33	[3] -35	3	0,608	451	2,4	4,52	14,6	1,73	19,5	2,1	8,84	6,0	2,01	1,11	0,97
34	-36	3	0,616	451	2,4	4,52	14,6	1,73	19,2	2,1	8,84	6,0	4,52	1,25	0,97
35	-37	3	0,622	451	2,4	4,52	14,6	1,73	19,0	2,1	8,84	6,0	7,08	1,39	0,97
36	-38	3	0,628	451	2,4	4,52	14,6	1,73	18,9	2,1	8,84	6,0	2,01	1,11	0,97
37	-39	3	0,611	451	2,4	4,52	14,6	1,73	19,4	2,1	8,84	6,0	4,52	1,25	0,97
38	[3] -40	3	0,622	451	2,4	4,52	14,6	1,73	19,0	2,1	8,84	6,0	7,08	1,39	0,97
39	VII-41	3	0,628	451	2,4	4,52	41,8	3,09	18,9	2,1	8,84	6,0	0	1,00	0,97
40	-42	3	0,613	451	2,4	4,52	41,8	3,09	19,2	2,1	8,84	6,0	2,01	1,11	0,97

17	18	19	20	21	22	23	24	25	26	27	28	29
0,5+0,05 s_r/ϕ	σ_a [N/mm²]	σ_{al} [N/mm²]	M_u [N·m]	M_l [N·m]	M_{br} measured [N·m]	M_{br}/M_u	M_{br}/M_l	M_l/M_u	closed or open loop	3-point or 4-point bending test	remarks	symbol in dia-grams
0,80	485	491	127 *	131	144,5	1,14	1,10	1,03	closed	3-p		○
0,80	485	520,5	125 *	136	143,5	1,15	1,06	1,10	closed	3-p		○
0,80	485	554,5	130 *	147	150,5	1,16	1,02	1,13	closed	3-p		○
0,80	485	545	125 *	143	147,5	1,18	1,03	1,14	closed	3-p		○
0,80	485	599	125 *	157,5	153,5	1,23	0,98	1,26	closed	3-p		○
0,80	485	613,5	128,5*	165,5	147,5	1,15	0,89	1,29	closed	3-p		○
0,80	485	736,5	132,5*	204	165,5	1,25	0,81	1,54	closed	3-p		○
0,80	485	414	131	113,5*	115,5	0,88	1,02	0,87	closed	3-p		●
0,80	485	439	127	116 *	120,5	0,95	1,04	0,91	closed	3-p		●
0,80	485	468	126,5	123,5*	117,5	0,93	0,95	0,98	closed	3-p		●
0,80	485	459,5	127	123 *	120,5	0,95	0,98	0,97	closed	3-p		●
0,80	485	459,5	125	120 *	117,5	0,94	0,98	0,96	closed	3-p		●
0,80	485	505	126 *	134	141	1,12	1,05	1,06	closed	3-p		○
0,80	485	517,5	129 *	141	132,5	1,03	0,94	1,09	closed	3-p		○
0,80	485	621	128,5*	168,5	138,5	1,08	0,82	1,31	closed	3-p		○
0,85	485	466,5	128	126 *	126,5	0,99	1,00	0,98	closed	3-p		○
0,85	485	488,5	128,5*	133	120,5	0,94	0,91	1,10	closed	3-p		●
0,85	485	550	134,5*	155	135,5	1,01	0,87	1,15	closed	3-p		○
0,59	485	323,5	127,5	87 *	90,5	0,71	1,04	0,68	closed	3-p		●
0,59	485	339	127	90,5*	95	0,75	1,05	0,71	closed	3-p		●
0,59	485	381,5	131,5	104,5*	111,5	0,85	1,07	0,80	closed	3-p		●
0,69	485	378,5	130	102,5*	101,5	0,78	0,99	0,79	closed	3-p		●
0,69	485	396,5	124,5	103 *	99,5	0,80	0,97	0,83	closed	3-p		●
0,69	485	446,5	124,5	117 *	120,5	0,97	1,03	0,94	closed	3-p		○
0,80	485	378,5	119,5	98,5*	102,5	0,86	1,04	0,83	closed	3-p		●
0,80	485	418	122	109,5*	126,5	1,04	1,15	0,90	closed	3-p		○
0,80	475	470,5	124 *	126,5	140	1,13	1,11	1,02	closed	3-p		○
0,80	475	523,5	120 *	137	135,5	1,13	0,99	1,14	closed	3-p		○
0,80	475	418	118	106 *	114,5	0,97	1,08	0,90	closed	3-p		○
0,80	475	470,5	118 *	120,5	123,5	1,05	1,02	1,02	closed	3-p		○
0,80	475	523,5	119 *	134,5	129,5	1,09	0,96	1,13	closed	3-p		○
0,80	450	309	109	81 *	83	0,76	1,02	0,74	closed	3-p		●
0,80	450	342,5	110	89,5*	93,5	0,85	1,04	0,81	closed	3-p		●
0,80	450	386	108	100,5*	102,5	0,95	1,02	0,93	closed	3-p		●
0,80	450	429	107,5*	110,5	108,5	1,01	0,98	1,03	closed	3-p		○
0,80	450	342,5	106,5	87 *	93,5	0,88	1,07	0,81	closed	3-p		●
0,80	450	386	110	101,5*	108,5	1,99	1,07	0,93	closed	3-p		○
0,80	450	429	107,5*	110	111,5	1,04	1,01	1,02	closed	3-p		○
0,80	510	551,5	131,5*	141	125	0,95	0,89	1,07	closed	3-p		●
0,80	510	612	133 *	158	129,5	0,98	0,82	1,19	closed	3-p		○

Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
no.	reference and specimen number	n	ω_0 [%]	f_e [N/mm²]	ϕ [mm]	A_a [mm²]	f'_{bm} [N/mm²]	f_{bm} [N/mm²]	z [mm]	a/ϕ	l_{dl}/ϕ	s_r/ϕ	A_{ad} [mm²]	$1+0{,}25\ A_{ad}/A_a$	$0{,}7+0{,}03\ l_{dl}/\phi$
41	VII-43	3	0,613	451	2,4	4,52	41,8	3,09	19,2	2,1	8,84	6,0	4,52	1,25	0,97
42	-44	3	0,611	451	2,4	4,52	41,8	3,09	19,4	2,1	8,84	6,0	7,08	1,39	0,97
43	[3] -45	3	0,616	451	2,4	4,52	41,8	3,09	19,2	2,1	8,84	6,0	2,01	1,11	0,97
44	-46	3	0,618	451	2,4	4,52	41,8	3,09	19,2	2,1	8,84	6,0	4,52	1,25	0,97
45	-47	3	0,622	451	2,4	4,52	41,8	3,09	19,0	2,1	8,84	6,0	7,08	1,39	0,97
46	VIII-48	7	0,613	386	1,6	2,01	22,2	2,11	19,3	3,1	14,76	9,2	0	1,00	1,14
47	-49	7	0,608	386	1,6	2,01	22,2	2,11	19,4	3,1	14,76	9,2	2,01	1,25	1,14
48	[3] -50	7	0,608	386	1,6	2,01	22,2	2,11	19,5	3,1	14,76	9,2	4,52	1,56	1,14
49	-51	7	0,637	386	1,6	01	22,2	2,11	18,6	3,1	14,76	9,2	7,08	1,88	1,14
50	[7] I	6	0,781	⩾400	12	113	31,6	2,58	117,8	2,0	10,50	2,5	0	1,00	1,02
51	II	6	0,781	⩾400	12	113	31,6	2,58	117,8	2,0	10,50	2,5	0	1,00	1,02
52	III	6	0,781	⩾400	12	113	31,6	2,58	117,8	2,0	16,00	2,5	0	1,00	1,18
53	[7] 1A	6	0,781	⩾400	12	113	40,6	3,03	117,8	0,1	10,50	2,6	56,6	1,13	1,02
54	1B	6	0,781	⩾400	12	113	40,6	3,03	117,8	0,1	10,50	2,6	0	1,00	1,02
55	1C	6	0,781	⩾400	12	113	40,6	3,03	117,8	0,1	10,50	2,6	0	1,00	1,02
56	2A	6	0,781	⩾400	12	113	57,0	3,85	117,8	0,1	10,50	2,6	56,6	1,13	1,02
57	2B	6	0,781	⩾400	12	113	57,0	3,85	117,8	0,1	10,50	2,6	0	1,00	1,02
58	[7] 2C	6	0,781	⩾400	12	113	57,0	3,85	117,8	0,1	10,50	2,6	0	1,00	1,02
59	I/1	6	0,781	⩾400	12	113	44,6	3,23	117,8	2,0	10,50	3,5	56,6	1,13	1,02
60	I/2	6	0,781	⩾400	12	113	26,0	2,30	117,8	2,0	10,50	3,5	56,6	1,13	1,02
61	I/3	6	0,781	⩾400	12	113	26,0	2,30	117,8	2,0	10,50	3,5	0	1,00	1,02
62	I/4	6	0,781	⩾400	12	113	21,6	2,08	117,8	0	10,50	3,5	56,6	1,13	1,02
63	[7] I/5	6	0,781	⩾400	12	113	21,6	2,08	117,8	5,0	10,50	3,5	56,6	1,13	1,02
64	I/6	6	0,781	⩾400	12	113	21,6	2,08	117,8	5,0	10,50	3,5	56,6	1,13	1,02
65	I/7	6	0,781	⩾400	12	113	19,6	1,98	117,8	2,0	10,50	3,5	56,6	1,13	1,02
66	I/8	6	0,781	⩾400	12	113	21,9	2,10	117,8	5,0	10,50	3,5	56,6	1,13	1,02
67	I/9	6	0,781	⩾400	12	113	21,9	2,10	117,8	5,0	10,50	3,5	56,6	1,13	1,02
68	[7] I/10	6	0,525	⩾400	12	113	37,7	2,89	117,8	2,0	10,50	3,5	56,6	1,13	1,02
69	I/11	6	0,525	⩾400	12	113	59,6	3,98	117,8	2,0	10,50	3,5	56,6	1,13	1,02
70	I/14	6	0,781	⩾400	12	113	20,6	2,03	117,8	2,0	10,50	3,5	56,6	1,13	1,02
71	I/15	6	0,781	⩾400	12	113	20,6	2,03	117,8	2,0	10,50	3,5	56,6	1,13	1,02
72	I/16	6	0,781	⩾400	12	113	23,1	2,16	117,8	2,0	10,50	3,5	56,6	1,13	1,02
73	[7] I/17	6	0,781	⩾400	12	113	23,1	2,16	117,8	2,0	10,50	3,5	56,6	1,13	1,02
74	I/18	6	0,781	⩾400	12	113	23,1	2,16	117,8	2,0	10,50	3,5	56,6	1,13	1,02
75	I/19	6	0,781	⩾400	12	113	23,1	2,16	117,8	0	10,50	2,2	56,6	1,13	1,02
76	A.3	4	0,575	433	16	201	34,6	2,73	163,4	?	19,99	(1,25)	0	1,00	1,30
77	A.32	4	0,515	433	16	201	31,4	2,57	163,4	?	19,99	(1,25)	0	1,00	1,30
78	[8] A.3q	4	0,575	433	16	201	36,3	2,82	163,4	?	16,82	(1,25)	?	(1,00)	1,20
79	A.4	4	0,575	433	16	201	32,7	2,64	163,4	?	14,01	(1,25)	0	1,00	1,12
80	A.42	4	0,545	433	16	201	23,9	2,20	163,4	?	14,01	(1,25)	0	1,00	1,12

17	18	19	20	21	22	23	24	25	26	27	28	29
0,5+0,05 s_r/ϕ	σ_a [N/mm²]	σ_{al} [N/mm²]	M_u [N·m]	M_l [N·m]	M_{br} measured [N·m]	M_{br}/M_u	M_{br}/M_l	M_l/M_u	closed or open loop	3-point or 4-point bending test	remarks	symbol in diagrams
0,80	510	689,5	132,5*	179	132,5	1,00	0,74	1,35	closed	3-p		○
0,80	510	766,5	133,5*	201,5	141,5	1,06	0,70	1,51	closed	3-p		○
0,80	510	612	133,5*	158	129,5	0,97	0,82	1,18	closed	3-p		○
0,80	510	689,5	133,5*	179	138,5	1,04	0,77	1,34	closed	3-p		○
0,80	510	766,5	131,5*	197	153,5	1,17	0,78	1,50	closed	3-p		○
0,96	440	531	112 *	144	146	1,30	1,01	1,28	closed	3-p		○
0,96	440	664	112,5*	181	150,5	1,34	0,83	1,61	closed	3-p	load alter- nated	○
0,96	440	828,5	113 *	227	153,5	1,36	0,71	2,01	closed	3-p		○
0,96	440	998,5	108 *	258	153,5	1,42	0,59	2,39	closed	3-p		○
0,62	465	403,5*	36.250	32.200*	31.200	0,86	0,97	0,89	open	4-p		■
0,62	465	403,5*	36.250	32.200*	30.500	0,84	0,95	0,89	closed	4-p		■
0,62	465	467 *	36.100*	37.300	35.400	0,98	0,95	1,03	open	4-p		□
0,62	480	535,5*	38.200*	45.600	35.900	0,94	0,79	1,19	open	4-p		■
0,63	480	474 *	37.950	37.900*	34.300	0,90	0,90	1,00	open	4-p		■
0,63	480	474 *	37.950	37.900*	34.900	0,92	0,92	1,00	open	4-p		■
0,63	490	680 *	37.400*	58.000	40.000	1,07	0,69	1,55	open	3-p		□
0,63	490	602 *	39.500*	48.100	39.000	0,99	0,81	1,22	open	3-p		□
0,63	490	602 *	39.500*	48.100	40.800	1,03	0,85	1,22	open	3-p		□
0,67	480	574	38.150*	45.850	39.300	1,03	0,86	1,20	open	4-p		□
0,67	450	408,5	34.600	32.650*	37.700	1,09	1,15	0,94	open	4-p		□
0,67	450	361,5	34.800	28.850*	32.700	0,94	1,13	0,83	open	4-p		■
0,67	440	369,5	33.350	29.500*	36.900	1,11	1,25	0,88	open	4-p		□
0,67	440	369,5	33.350	29.500*	35.700	1,07	1,21	0,88	open	4-p		□
0,67	440	369,5	33.350	29.500*	34.700	1,04	1,18	0,88	open	4-p		□
0,67	435	351,5	32.600	28.100*	36.500	1,12	1,30	0,86	open	3-p		□
0,67	440	373	33.250	29.800*	34.600	1,04	1,16	0,90	open	3-p		□
0,67	440	373	33.150	29.800*	34.800	1,05	1,17	0,90	open	3-p		□
0,67	490	513,5	26.450*	41.000	25.900	0,98	0,63	1,55	open	4-p		□
0,67	510	707	28.650*	56.450	27.500	0,96	0,49	1,97	open	4-p		□
0,67	440	360,5	33.200	28.800*	36.500	1,10	1,22	0,87	open	4-p	100.000 alter- nations	□
0,67	440	360,5	33.300	28.800*	39.300	1,18	1,36	0,86	open	4-p	200.000	□
0,67	445	383,5	33.800	30.650*	36.500	1,08	1,19	0,91	open	4-p	alter-	□
0,67	445	383,5	34.000	30.650*	35.700	1,05	1,17	0,90	open	4-p	nations	□
0,67	445	383,5	34.000	30.650*	35.000	1,03	1,14	0,90	open	4-p		□
0,61	445	382 *	33.750	32.650*	34.400	1,02	1,05	0,97	open	4-p		□
(0,56)	485	457	62.300	60.050*	47.360	0,76	0,79	0,97	open	4-p		▲
(0,56)	485	430,5	55.750*	56.550	55.760	1,00	0,99	1,01	open	4-p		△
(0,56)	485	435,5	63.100	57.250*	63.110	1,00	1,10	0,91	open	4-p		△
(0,56)	480	381	62.300	50.000*	47.360	0,76	0,95	0,80	open	4-p		▲
(0,56)	470	317,5	56.700	41.700*	40.260	0,71	0,97	0,74	open	4-p		▲

Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
no.	reference and specimen number	n	ω_0 [%]	f_e [N/mm²]	ϕ [mm]	A_a [mm²]	f'_{bm} [N/mm²]	f_{bm} [N/mm²]	z [mm]	a/ϕ	l_{dl}/ϕ	s_r/ϕ	A_{ad} [mm²]	$1+0{,}25\ A_{ad}/A_a$	$0{,}7+0{,}03\ l_{dl}/\phi$
81	A.5	4	0,575	433	16	201	28,6	2,43	163,4	?	8	(1,25)	0	1,00	0,94
82	A.5q	4	0,575	433	16	201	30,8	2,54	163,4	?	8	(1,25)	?	(1,00)	0,94
83	[8] A.6	10	0,565	421	10	78,5	24,4	2,22	166,2	?	35	(2,00)	0	1,00	1,78
84	A.7	10	0,565	421	10	78,5	26,3	2,32	166,2	?	25	(2,00)	0	1,00	1,45
85	A.8	10	0,565	421	10	78,5	37,1	2,86	166,2	?	14	(2,00)	0	1,00	1,12
86	A.82	10	0,510	421	10	78,5	25,3	2,27	166,2	?	14	(2,00)	0	1,00	1,12
87	B.1	7	0,530	421	10	78,5	28,4	2,42	128,2	?	24	(2,00)	0	1,00	1,42
88	[8] B.2	8	0,583	421	10	78,5	23,3	2,17	128,2	?	17	(2,00)	0	1,00	1,21
89	B.3	7	0,530	421	10	78,5	34,1	2,71	128,2	?	10	(2,00)	0	1,00	1,00
90	B.32	8	0,583	421	10	78,5	30,0	2,50	128,2	?	10	(2,00)	0	1,00	1,00
91	B.4	7	0,600	421	10	78,5	33,9	2,70	109,2	?	18	(2,00)	0	1,00	1,24
92	B.5	7	0,443	421	10	78,5	33,7	2,69	147,2	?	12	(2,00)	0	1,00	1,06
93	[8] B.6	7	0,600	421	10	78,5	33,0	2,65	109,2	?	8	(2,00)	0	1,00	0,94
94	B.6q	7	0,600	421	10	78,5	26,6	2,33	109,2	?	8	(2,00)	?	(1,00)	0,94
95	B.7	6	0,575	433	16	201	33,4	2,67	249	?	12,5	(1,25)	0	1,00	1,08
96	B.8	3	0,780	433	16	201	29,5	2,48	249	?	13	(1,25)	0	1,00	1,09
97	B.8q	3	0,780	433	16	210	30,1	2,51	249	?	13	(1,25)	?	(1,00)	1,09
98	[8] C.1	8	0,521	423	8	50,3	30,1	2,51	91,2	?	8	(2,50)	0	1,00	0,94
99	C.2	7	0,410	423	8	50,3	26,2	2,31	110,2	?	11	(2,50)	0	1,00	1,03
100	C.3	12	0,530	423	8	50,3	33,8	2,69	128,2	?	14	(2,50)	0	1,00	1,12
101	C.4	4	0,502	432	14	154	30,6	2,53	145,3	?	8	(1,43)	0	1,00	0,94
102	C.4q	4	0,502	432	14	154	29,8	2,49	145,3	?	8	(1,43)	?	(1,00)	0,94
103	[8] C.5	4	0,485	432	14	154	26,1	2,31	164,3	?	11	(1,43)	0	1,00	1,03
104	C.6	5	0,530	441	12	113	31,5	2,58	127,3	?	8	(1,67)	0	1,00	0,94
105	C.6q	5	0,530	441	12	113	31,1	2,56	127,3	?	8	(1,67)	?	(1,00)	0,94
106	C.7	6	0,490	441	12	113	33,3	2,67	165,2	?	11	(1,67)	0	1,00	1,03
107	C.8	11	0,777	421	10	78,5	43,2	3,16	133,0	?	10	(2,00)	0	1,00	1,00
108	[8] D.1	4	0,675	520?	8,6	58,0	27,5	2,38	81,4	?	6,72	(1,75)	0	1,00	0,90
109	D.2	4	0,583	520	7,5	44,1	32,6	2,63	82,0	?	8	(2,00)	0	1,00	0,94
110	D.3	5	0,420	555	5,0	19,6	27,2	2,36	61,3	?	8,4	(3,00)	0	1,00	0,95
111	D.4	5	0,312	555	5,0	19,6	32,3	2,62	83,1	?	13	(3,00)	0	1,00	1,09
112	D.5	5	0,605	520	7,5	44,1	33,2	2,66	96,2	?	10	(2,00)	0	1,00	1,00
113	[4] A	5	0,181	⩾480	10	78,5	20,0	2,00	152	2,5	9	14	113	1,36	0,99
114	B	5	0,181	⩾480	10	78,5	22,6	2,13	152	5,0	9	14	113	1,36	0,99
115	C	5	0,181	⩾480	10	78,5	25,4	2,27	152	2,5	9	14	0	1,00	0,99
116	[5] I	10	0,215	⩾480	10	78,5	26,0	2,30	147,2	0	14	(5)	311	2,00	1,12
117	II	10	0,215	⩾480	10	78,5	22,3	3,12	147,2	0/6	14	(5)	157	1,50	1,12
118	A1	3	0,508	473	10	78,5	34,2	2,71	71,5	1,0	7	7,5	0	1,00	0,91
119	[3] A2	3	0,508	473	10	78,5	34,2	2,71	71,5	1,0	13	7,5	0	1,00	1,09
120	A3	3	0,508	473	10	78,5	34,2	2,71	71,5	1,0	19	7,5	0	1,00	1,27

17	18	19	20	21	22	23	24	25	26	27	28	29
0,5+0,05 s_r/ϕ	σ_a [N/mm²]	σ_{al} [N/mm²]	M_u [N·m]	M_l [N·m]	M_{br} measured [N·m]	M_{br}/M_u	M_{br}/M_l	M_l/M_u	closed or open loop	3-point or 4-point bending test	remarks	symbol in dia-grams
(0,56)	475	294	60.800	38.600*	42.550	0,70	1,10	0,64	open	4-p		▲
(0,56)	480	387,5	61.650	40.350*	54.900	0,89	1,36	0,65	open	4-p		▲
(0,60)	470	727 *	60.500*	94.800	67.750	1,12	0,71	1,57	open	4-p		△
(0,60)	470	619 *	61.250*	65.450	57.750	0,94	0,88	1,07	open	4-p		▲
(0,60)	485	589,5*	63.950*	76.900	57.750	0,90	0,75	1,20	open	4-p		▲
(0,60)	475	468 *	55.750*	61.000	53.500	0,96	0,88	1,09	open	4-p		△
(0,60)	480	564,5*	35.750*	39.800	36.800	1,03	0,92	1,11	open	4-p		△
(0,60)	465	453 *	37.300	36.450*	35.800	0,96	0,98	0,98	open	4-p		△
(0,60)	485	445 *	36.300	31.350*	33.750	0,93	1,08	0,86	open	4-p		▲
(0,60)	480	431 *	39.100	34.750*	36.750	0,94	1,06	0,89	open	4-p		▲
(0,60)	480	550 *	28.650*	33.000	27.500	0,96	0,83	1,15	open	4-p		△
(0,60)	490	468,5*	40.100	37.900*	42.900	1,07	1,13	0,95	open	4-p		△
(0,60)	480	413,5*	28.950	24.800*	24.000	0,83	0,97	0,86	open	4-p		▲
(0,60)	470	360 *	27.950	21.650*	28.500	1,02	1,32	0,78	open	4-p		△
(0,56)	480	442 *	143.750	132.650*	119.300	0,83	0,90	0,92	open	4-p		▲
(0,56)	460	348	68.300	52.200*	49.150	0,72	0,94	0,76	open	4-p	beam	▲
(0,56)	460	352,5	68.000	52.850*	59.150	0,87	1,12	0,78	open	4-p	beam	▲
(0,62)	480	407 *	17.600	14.950*	17.050	0,97	1,14	0,85	open	4-p		△
(0,62)	485	391 *	20.300	15.150*	20.500	1,01	1,35	0,75	open	4-p		△
(0,62)	485	577,5*	37.500*	44.900	36.750	0,98	0,82	1,20	open	4-p		△
(0,57)	485	312	43.450	27.900*	30.000	0,69	1,08	0,67	open	4-p		▲
(0,57)	480	307	42.650	27.450	35.400	0,83	1,29	0,65	open	4-p		▲
(0,57)	480	312	52.800	31.550*	49.100	0,93	1,56	0,60	open	4-p		▲
(0,58)	495	334,5*	35.550	24.050*	25.250	0,71	1,05	0,68	open	4-p		▲
(0,58)	495	332 *	35.950	23.900*	36.650	1,02	1,53	0,67	open	4-p		△
(0,58)	500	421,5*	56.400	47.150*	51.300	0,91	1,09	0,84	open	4-p		▲
(0,60)	480	594,5*	55.550*	68.300	52.750	0,95	0,77	1,23	open	4-p		▲
(0,59)	545	290,5	19.800	11.000*	15.450	0,78	1,40	0,55	open	4-p		▲
(0,60)	560	341	18.250	9.850*	12.950	0,71	1,31	0,54	open	4-p		▲
(0,65)	585	335	7.690	4.040*	5.380	0,70	1,33	0,53	open	4-p		▲
(0,65)	595	427	10.930	6.970*	8.960	0,82	1,29	0,64	open	4-p		▲
(0,60)	580	367	21.900	15.550*	16.150	0,60	1,04	0,58	open	4-p		▲
1,00	520	743	30.600*	36.900	37.000	1,17	1,03	1,17	closed	3-p		#
1,00	520	791,5	32.000*	39.400	33.000	1,03	0,84	1,23	closed	3-p		#
1,00	520	620,5	32.400*	33.700	32.000	0,99	0,95	1,04	closed	3-p		#
(0,75)	575	948 *	65.600*	205.400	84.000	1,28	0,41	3,04	closed	3-p		#
(0,75)	575	655,5*	65.100*	106.500	82.000	1,26	0,77	1,64	closed	3-p		#
0,875	510	496	9.180	8.350*	6.340	0,69	0,76	0,91	closed	3-p		●
0,875	510	594,5	9.180*	10.020	8.130	0,89	0,81	1,09	closed	3-p		●
0,875	510	693	9.180*	11.670	8.590	0,94	0,74	1,27	closed	3-p		●

Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
no.	reference and specimen number	n	ω_0 [%]	f_e [N/mm²]	ϕ [mm]	A_a [mm²]	f'_{bm} [N/mm²]	f_{bm} [N/mm²]	z [mm]	a/ϕ	l_{dl}/ϕ	s_r/ϕ	A_{ad} [mm]	$1+0{,}25\ A_{ad}/A_a$	$0{,}7+0{,}03\ l_{dl}/\phi$
121	[1] B1	3	0,508	473	10	78,5	32,9	2,65	71,5	1,0	7	7,5	308	1,99	0,91
122	B2	3	0,508	473	10	78,5	32,9	2,65	71,5	1,0	13	7,5	308	1,99	1,09
123	4	3	0,245	510	6	28,3	15,3	1,77	82,7	1,0	11,33	14,7	0	1,00	1,04
124	[6] 1	4	0,223	596	5	19,5	18,0	1,90	69,5	1,4	10	22,4	0	1,00	1,00
125	2	4	0,223	596	5	19,5	18,4	1,92	69,5	1,4	10	22,4	0	1,00	1,00
126	3	4	0,223	596	5	19,5	20,2	2,01	69,5	1,4	10	22,4	53,4	1,69	1,00
127	4	4	0,223	596	5	19,5	18,4	1,92	69,5	1,4	10	22,4	100,8	2,30	1,00
128	[6] 5	4	0,223	596	5	19,5	18,0	1,90	69,5	1,4	14	22,4	0	1,00	1,12
129	6	4	0,223	596	5	19,5	18,4	1,92	69,5	1,4	14	22,4	0	1,00	1,12
130	7	4	0,223	596	5	19,5	20,2	2,01	69,5	1,4	14	22,4	53,4	1,69	1,12
131	8	4	0,223	596	5	19,5	18,4	1,92	69,5	1,4	14	22,4	100,8	2,30	1,12
132	9	4	0,223	596	5	19,5	18,0	1,90	69,5	1,4	18	22,4	0	1,00	1,24
133	[6] 10	4	0,223	596	5	19,5	18,4	1,92	69,5	1,4	18	22,4	0	1,00	1,24
134	11	4	0,223	596	5	19,5	28,2	2,01	69,5	1,4	18	22,4	53,4	1,69	1,24
135	12	4	0,223	596	5	19,5	18,0	1,90	69,5	1,4	10	22,4	0	1,00	1,00
136	13	4	0,223	596	5	19,5	18,4	1,92	69,5	1,4	10	22,4	0	1,00	1,00
137	14	4	0,223	596	5	19,5	18,0	1,90	69,5	1,4	18	22,4	0	1,00	1,24
138	[6] 15	4	0,223	596	5	19,5	18,4	1,92	69,5	1,4	18	22,4	0	1,00	1,24
139	16	4	0,223	596	5	19,5	12,4	1,62	69,5	1,4	10	22,4	0	1,00	1,00
140	17	4	0,223	596	5	19,5	10,6	1,53	69,5	1,4	10	22,4	53,4	1,69	1,00
141	18	4	0,223	596	5	19,5	12,4	1,62	69,5	1,4	10	22,4	100,8	2,30	1,00
142	[6] 19	4	0,223	596	5	19,5	10,4	1,52	69,5	1,4	14	22,4	53,4	1,69	1,12
143	20	4	0,223	596	5	19,5	10,4	1,52	69,5	1,4	18	22,4	0	1,00	1,24
144	21	4	0,223	596	5	19,5	10,6	1,53	69,5	1,4	18	22,4	53,4	1,69	1,24
145	1	4	0,121	572	8	50	19,1	1,96	161	2,75	10	25	0	1	1
146	2	4	0,121	617	8	50	20,5	2,03	161	2,75	10	25	100	1,5	1
147	3	4	0,121	572	8	50	18,6	1,93	161	2,75	15	25	0	1	1,15
148	[9] 4	4	0,276	589	12	113	19,1	1,96	153	1,5	6,7	16,7	560	1,12	0,901
149	5	4	0,276	606	12	113	18,6	1,93	152	1,5	6,7	16,7	226	1	0,901
150	6	4	0,276	589	12	113	19,1	1,96	153	1,5	10	16,7	0	1	1
151	7	4	0,276	606	12	113	17,4	1,87	151	1,5	10	16,7	226	1,5	1

Explanatory notes to the table:

Column 7: the value of A_a relates to one loop bar.
Column 8: the cube strength f'_{bm} is based on 150 mm cubes.
Column 9: the tensile strength f_{bm} of the concrete has been determined from: $f_{bm} = 1 + 0{,}05 f'_{bm}$.
Column 10: for the internal lever arm the value $\chi = 0{,}95\ h$ has been adopted.
Column 13: the values in parentheses are minimum values based on the concrete cover; the correct values are not known in those cases.
Column 14: A_{ad} is based on the total cross-sectional area of the transverse reinforcement located inside the loop and in the tensile zone.

17	18	19	20	21	22	23	24	25	26	27	28	29
$0{,}5+0{,}05\ s_r/\phi$	σ_a [N/mm²]	σ_{al} [N/mm²]	M_u [N·m]	M_l [N·m]	M_{br} measured [N·m]	M_{br}/M_u	M_{br}/M_l	M_l/M_u	closed or open loop	3-point or 4-point bending test	remarks	symbol in diagrams
0,875	510	966	9.180	16.280	10.040	1,09	0,62	1,77	closed	3-p		○
0,875	510	1157	9.180*	19.480	10.090	1,10	0,52	2,12	closed	3-p		○
1,00	560	521	3.890	2.970*	3.000	0,77	1,01	0,76	closed	4-p		✦
1,00	645	437	3.300	2.370*	2.760	0,84	1,16	0,72	closed	4-p		✦
1,00	645	441	3.300	2.390*	3.240	0,98	1,36	0,72	closed	3-p		✧
1,00	650	781	3.330	4.240	3.470	1,04	0,82	1,27	closed	4-p		✧
1,00	645	1016	3.300*	5.510	3.650	1,11	0,66	1,67	closed	4-p		✧
1,00	645	489	3.300	2.650*	2.850	0,86	1,07	0,80	closed	4-p		✦
1,00	645	495	3.300	2.680*	3.700	1,12	1,38	0,81	closed	3-p		✦
1,00	650	875	3.330*	4.740	3.550	1,07	0,75	1,42	closed	4-p		✧
1,00	645	1137	3.300*	6.170	3.590	1,09	0,58	1,87	closed	4-p		✧
1,00	645	542	3.300	2.940*	3.000	0,91	1,02	0,89	closed	4-p		✦
1,00	645	548	3.300	2.970*	3.440	1,04	1,16	0,90	closed	3-p		✧
1,00	650	969	3.330*	5.250	3.710	1,11	0,71	1,58	closed	4-p		✧
1,00	645	437	3.300	2.370*	2.240	0,68	0,95	0,72	open	4-p		✦
1,00	645	441	3.300	2.390*	2.790	0,85	1,17	0,72	open	3-p		✦
1,00	645	542	3.300	2.940*	2.980	0,90	1,01	0,89	open	4-p		✦
1,00	645	548	3.300	2.970*	3.030	0,92	1,02	0,90	open	3-p		✦
1,00	630	373	3.160	2.020*	2.390	0,76	1,18	0,64	closed	4-p		✦
1,00	620	595	3.070*	3.220	3.640	1,19	1,13	1,05	closed	4-p		✧
1,00	630	857	3.160*	4.650	3.750	1,19	0,81	1,47	closed	4-p		✧
1,00	620	662	3.070*	3.590	3.850	1,25	1,07	1,17	closed	4-p		✧
1,00	620	434	3.070	2.350*	2.510	0,82	1,07	0,77	closed	4-p		✦
1,00	620	737	3.070*	4.000	3.690	1,20	0,92	1,30	closed	4-p		✧
1,75	572	450	18.640	14.760	16.270	0,87	1,1	0,79	closed	4-p		◆
1,75	617	699	20.100	22.750	20.310	1,01	0,89	1,13	closed	4-p		◇
1,75	572	510	18.630	16.670	16.290	0,87	0,98	0,89	closed	4-p		◆
1,335	589	455	41.400	32.490	30.610	0,74	0,94	0,78	closed	4-p		◆
1,335	606	599	42.460	42.010	36.560	0,86	0,87	0.99	closed	4-p		◆
1,336	589	450	41.400	32.100	28.820	0,69	0,89	0,78	closed	4-p		◆
1,335	606	645	42.280	44.830	41.450	0,98	0,92	1,06	closed	4-p		◇

Column 17: see explanatory not to column 13; furthermore, for $s_r \approx 10\phi$ the following expression has been adopted: $0{,}5+0{,}05 s_r/\phi = 1{,}00$.

Column 18: the steel stress σ_a associated with the theoretical failure moment M_u has been determined in accordance with the method described in CUR Report 9; see also Appendix 3.

Column 19: the steel stress σ_{al} associated with the loop moment M_l is equal to the larger of the values obtained from $\sigma_{al} = 230 f_{bm}(1+0{,}25 A_{ad}/A_a)(0{,}7+0{,}03 l_{dl}/\phi)(0{,}5+0{,}05 s_r/\phi)$ and $\sigma_{al} = (n-2)/n \cdot 230 f_{bm} \cdot (1+0{,}25 A_{ad}/A_a)(0{,}7+0{,}03 l_{dl}/\phi)$. The latter case is indicated by *.

Column 20: M_u has been calculated from: $M_u = \sigma_a \cdot \omega_0/100 \cdot bh^2(1-0{,}5\sigma_r/0{,}8 f'_{bm} \cdot \omega_0/100)$.

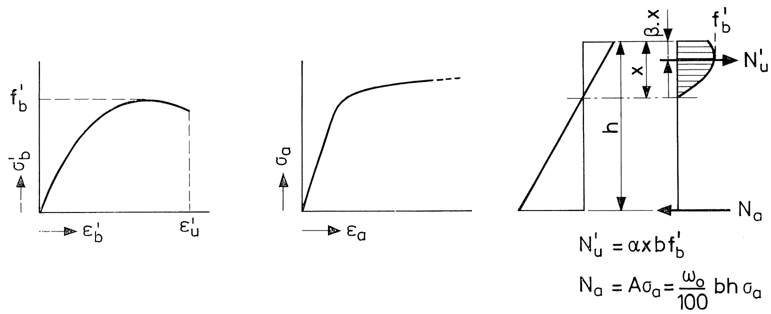
Column 21: M_l is obtained from: $M_l = n \cdot A_a \cdot z \cdot \sigma_{al}$.

The lowest, determinative, value of M_l or M_u is indicated by * in columns 20 and 21.

APPENDIX 3

Determination of the theoretical failure moment M_u

Basic assumptions:



Conditions:

$$x = h \cdot \frac{\varepsilon'_u}{\varepsilon_a + \varepsilon'_u} \qquad \text{(a)}$$

$$N'_u = N_a \rightarrow x = h \cdot \frac{\omega_0}{100} \cdot \frac{1}{\alpha} \cdot \frac{\sigma_a}{0{,}8 f'_{bm}} \qquad \text{(b)}$$

From the conditions (a) and (b) it follows that:

$$\sigma_a = \frac{100}{\omega_0} \cdot \alpha \cdot 0{,}8 f'_{bm} \cdot \frac{\varepsilon'_u}{\varepsilon_a + \varepsilon'_u}$$

The values of σ_a can be read from figure 6 in CUR Report 9 as a function of $0{,}8 f'_{bm} \cdot 100/\omega_0$ and the given stress-strain diagram (σ_a against ε_a). It has been assumed that $\alpha = 0{,}8$ and $\varepsilon'_u = 0{,}2\%$.

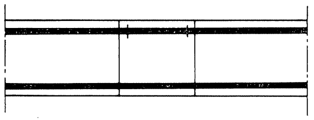
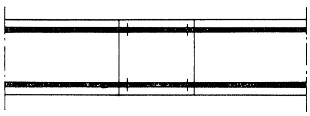
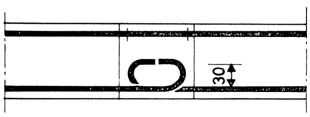
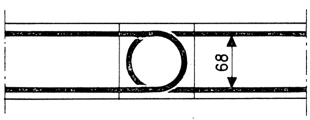
The failure moment M_u is now obtained from:

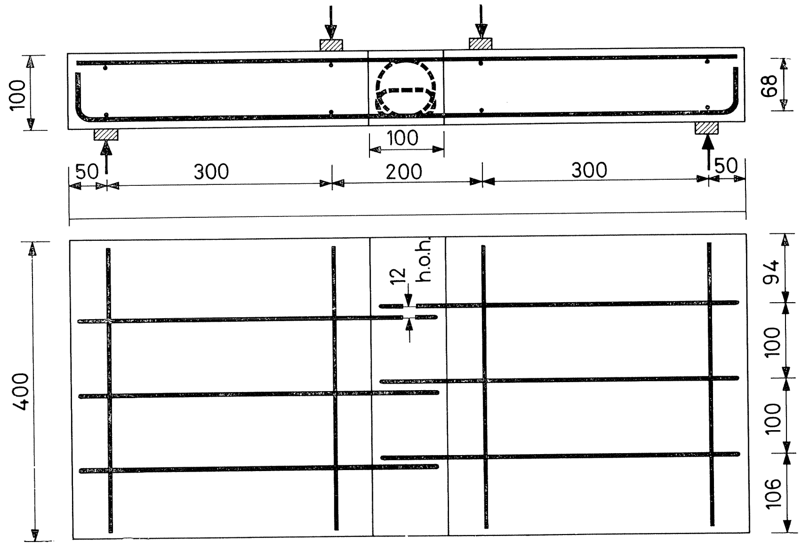
$$M_u = \sigma_a \cdot \frac{\omega_0}{100} \cdot bh^2 \cdot \left(1 - \frac{\beta}{\alpha} \cdot \frac{\sigma_a}{0{,}8 f'_{bm}} \cdot \frac{\omega_0}{100}\right)$$

where $\beta/\alpha = 0{,}5$ has been adopted.

APPENDIX 4

Results of tests on four types of connection

no.	type of connection	failure load P_{br} [kN]	deflection at $0{,}9 \times P_{br}$ [mm]	remarks
1′	 continuous reinforcement	28,4	2,9	failure due to fracture of steel ($\sigma_a \approx 600$ N/mm²)
2′	 reinforcement with straight lap splices (80 mm)	7,9	0,5	bars pulled out ($\sigma_a \approx 178$ N/mm²)
3′	 reinforcement with U-hooks	14,8	1,9	failure due to splitting between the three pairs of hooks ($\sigma_a \approx 333$ N/mm²)
4′	 reinforcement with loop (circular)	20,0	2,6	failure due to splitting between the outer pairs of loops ($\sigma_a \approx 450$ N/mm²); concrete beside the outermost loops spalled off



quality of concrete in the joint: $f'_{bm} = 15{,}3$ N/mm²
quality of concrete in the slab: $f'_{bm} = 42{,}3$ N/mm²
steel grade: FeB 40 HK NR with $f_e = 510$ N/mm²
$f_{ar} = 570$ N/mm²

bar diameter: ϕ 6 mm
concrete cover: 10 mm