INSTITUTE OF BUILDING DESIGN

Report no. **106**

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RIGID JOINTED CONCRETE FRAME

Den polytekniske Læreanstalt, Danmarks tekniske Højskole

Technical University of Denmark. DK-2800 Lyngby 1974

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Report No. 106.

ERRATA:

It should be observed that the following numbers should be divided by 10:

Table I, pag. 9:

The values of M_c and M_T

Table II, pag. 15:

The values of σ_b', σ_c', M_c and M_T

Figure 9, pag. 11, and Figure 16, pag. 18:

The values of M.

Pag. 12, line 8:

(40 - 80 kNm)

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Preface

The contents of this report is a contribution to the 6th Congress of CIB in Budapest, 3rd - 10th October, 1974.

Denne rapport indeholder et indlæg til CIB's 6. kongres i Budapest, 3-10. oktober 1974.

Resumé

I rapporten gennemgås hovedresultaterne af nogle pilotforsøg med samlinger, som har været udført på Instituttet for Husbygning.

De afprøvede samlinger er samlinger mellem to bjælker og samlinger mellem bjælker og søjler. Samlingerne har været udsat for momentpåvirkning, og ønsket var at opnå et plastisk brud uden for samlingen.

For samlingen mellem to bjælker (figur 1) er forskellige forholds indflydelse på styrken belyst ved forsøgene. Anvendes i samlingen hårnålebøjler af R16, og er samlingsbetonens styrke ca. 30 MN/m^2, er det tilstrækkeligt som låsejern at anvende 2 stk. K20 (figur 7) eller en ring af K14 (figur 8). For den afprøvede søjle-bjælkesamling med bøjler af R16 (figur 12) er låsejern unødvendige, (men af andre grunde ønskelige) når samlingsbetonens styrke er ca. 35 MN/m^2.

Hovedkonklusionen er, at det vil være muligt at udvikle simple samlinger med god momentbæreevne mellem præfabrikerede søjle- og bjælkeelementer.

ABSTRACT

The development of rational, rigid joints for use in the construction of frame systems from precast columns and beams is of great importance because such systems open the way for buildings with a high utility value using elements that are rod-shaped and therefore easy to manufacture and transport.

The present paper presents a joint between two beams and a joint between a beam and column. The joints are easy to execute and have a high rotational capacity.

The tests are pilot tests for a series of research assignments on the subject: "Rigid Joints between Precast Beams and Columns", which are at present in progress at the Institute of Building Design of the Technical University of Denmark in Copenhagen, under the direction of Professor Johs. F. Munch-Petersen.

NOTATION

- b : lap length (figure 1)
- E : modulus of elasticity
- F_ℓ : area of lateral reinforcement
- I : moment of inertia
- M : moment
- M_C : calculated yield moment
- M_T : measured yield moment
- S : sudden split failure
- Y : failure following formation of plastic hinge
- σ'_b : compressive cylinder strength of beam and column concrete
- σ'_c : compressive cylinder strength of joint concrete
- σ_y : tensile yield strength of reinforcement
- σ_u : ultimate tensile strength of reinforcement

κ : curvature

R : plain round bars

K : deformed bars with guaranteed $\sigma_y = 420$ MN/m^2

T : deformed bars with guaranteed $\sigma_y = 560$ MN/m^2

R16: type R reinforcement with diameter 16 mm.

Unless otherwise specified, all measurements in the figures are in mm.

INTRODUCTION

Normal prefabricated diaphragm construction is characterized by a simple production and erection process. However, in recent years, this method of construction has been criticized for lack of flexibility because the load-bearing walls restrict the choice of plans, in addition to which it is difficult to meet new requirements in the event of conversion and modernization.

The demand for flexibility can be met by partially or wholly replacing the load-bearing walls by columns and beams.

In precast construction, force-transmitting joints have to be executed on site between columns and beams and between columns and foundation and sometimes also between two beams. Up to the present time it has not been normal practice to design these joints for the transmission of moment as well, even though this entails a number of obvious advantages.

By using moment-transmitting joints it is possible to restrict production to rod-shaped elements (columns and beams). Such elements are easier to manufacture, transport and assemble than, say, frames and L-, T-, and X-shaped components. In low-level structures this solution would also obviate the need for the difficult restraint of the columns at the foundation. Yet, another advantage is that the degree of statical indeterminateness could be increased, thereby augmenting the safety against progressive collapse.

However, this statical indeterminateness also presents a number of problems, i.e. constraint due to alterations in temperature, differential settlements, etc. Furthermore, rigid joints will probably make greater requirements to tolerances and execution.

Because of the advantages offered by rigid joints, the Institute of Building Design of the Technical University of Denmark has started a test programme to develop joints that can be used for the construction of frame structures from rod-shaped elements.

The joints aimed at should, as far as possible, fulfil the following requirements:

The joints must be able to:

1. transmit the applied loads with a known degree of safety;
2. resist the forces without significant displacements and rotations, and in such a way as to avoid high local stresses;
3. be executed with reasonable tolerances on elements and assembly;
4. be executed in a few, simple work operations;
5. permit effective control of the execution;
6. be executed without regard to weather conditions (rain and frost).

The following results are from pilot tests in which the strength properties and deformations of a number of possible joints were investigated.

In their present form, the joints are not yet suitable for contracting purposes, but we are still working on this problem and looking into a number of other possible jointing methods.

BEAM-BEAM JOINT

TEST PROGRAMME

The tests were carried out on two beams with a length of 145 cm, which were cast together with a 200 mm joint. The cross-section was 200 x 400 mm throughout. Two projecting hairpin stirrups were placed on end in the tensile zone of the beam, overlapping each other in the joint. Various types of lateral reinforcement were placed in the opening of the stirrups for jointing purposes. The principle of the joint is shown in figure 1.

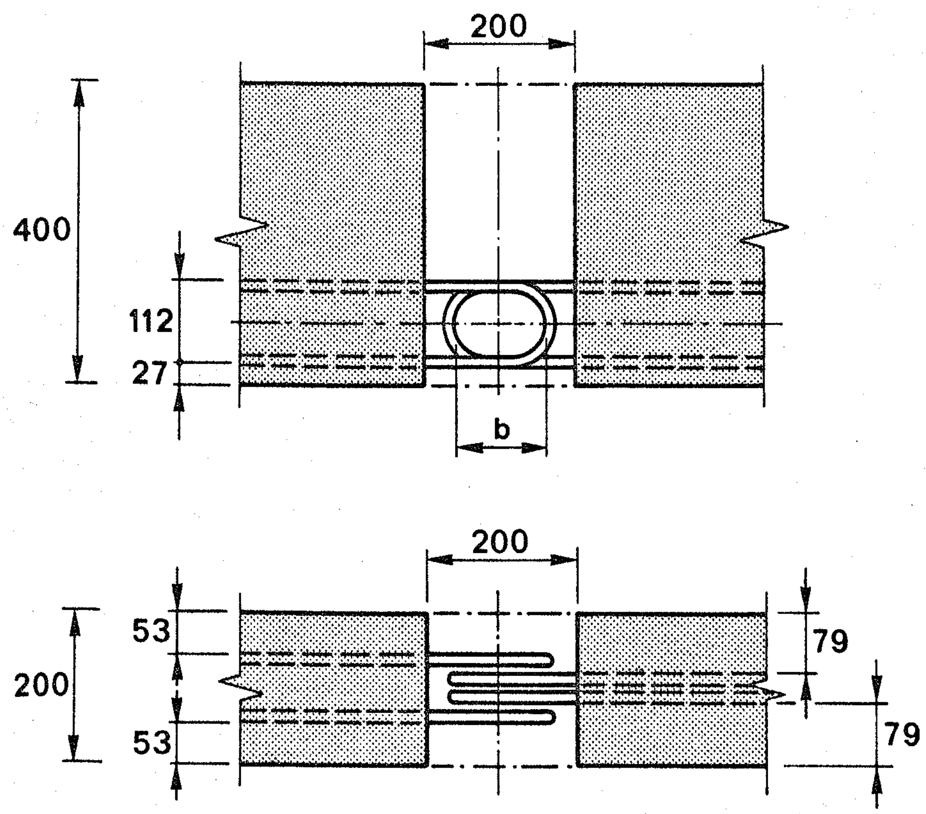


Figure 1: Joint Principle

The hairpin stirrups were of R16 steel, with $\sigma_y = 291\ MN/m^2$ and $\sigma_u = 391\ MN/m^2$.

The lateral reinforcement was type K or T steel.

The purpose of the lateral reinforcement was to prevent the lateral elongation of the concrete between the stirrups from giving rise to split failure before yielding of the stirrups. For this reason profiled steel was used. And for the same reason, the strength of the lateral reinforcement is not of prime importance.

The beams themselves were reinforced in such a way that they were stronger than the sections with four reinforcing bars at the joint.

The testing was carried out in an arrangement ensuring pure moment over the middle 800 mm, as shown in figure 2.

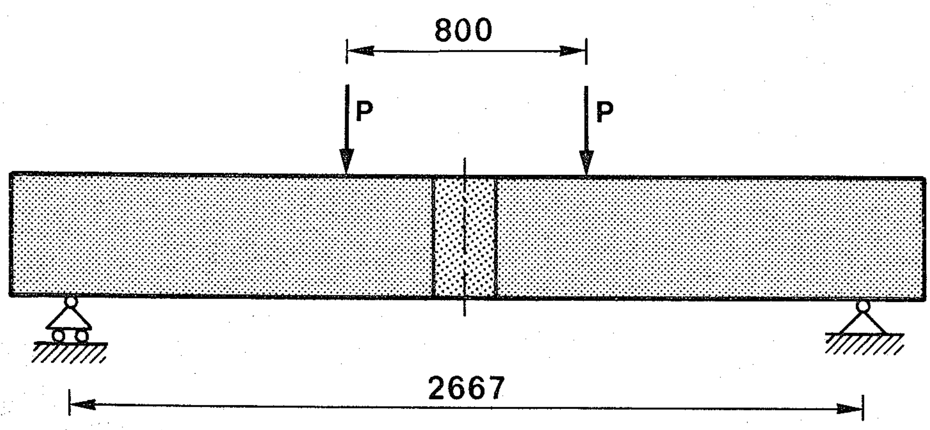


Figure 2: Loading Principle

For control purposes, two tests were carried out in which the four reinforcing bars in the joint were continuous, from which an upper bound was obtained for the carrying capacity of the joints.

The compression was measured 35 mm from the top edge and the expansion, 35 mm from the bottom edge, both measurements being taken over a length of 260 mm symmetrically about the middle of the joint. From these measurements, a mean curvature over the joint was found.

The entire test programme and the results obtained are shown in table I. The joints tested are shown in figures 3 - 8.

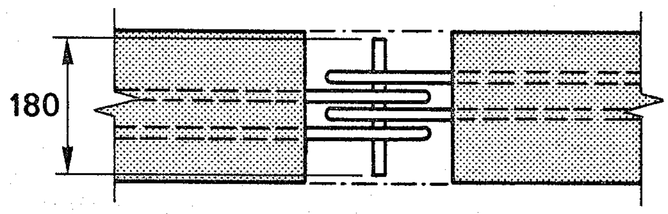


Figure 3: Type I. Lateral Reinforcement: T16

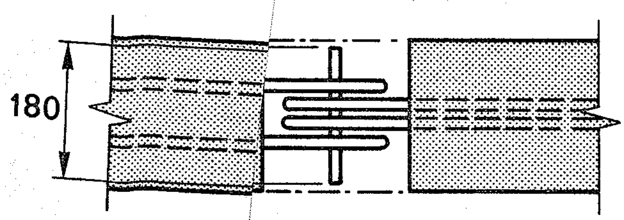


Figure 4: Type II. Lateral Reinforcement: T16
Type III.Lateral Reinforcement: K14

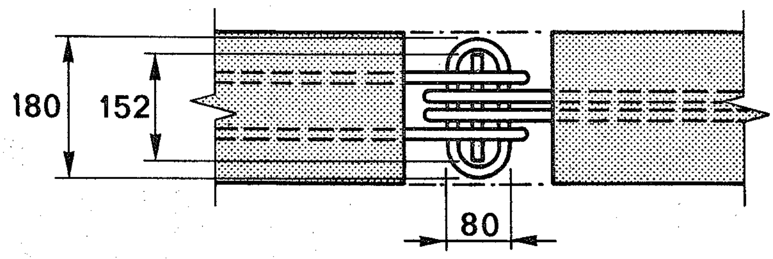


Figure 5: Type IV. Lateral Reinforcement:
2 K14 rings.

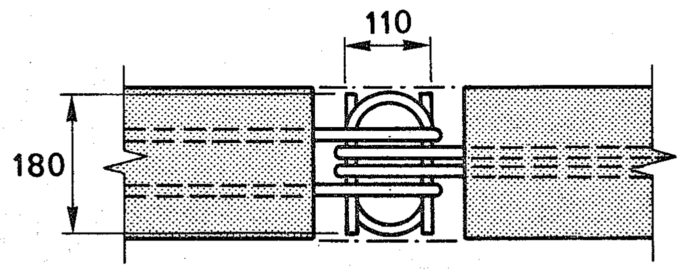


Figure 6: Type V. Lateral Reinforcement:
2 K14 hairpin stirrups

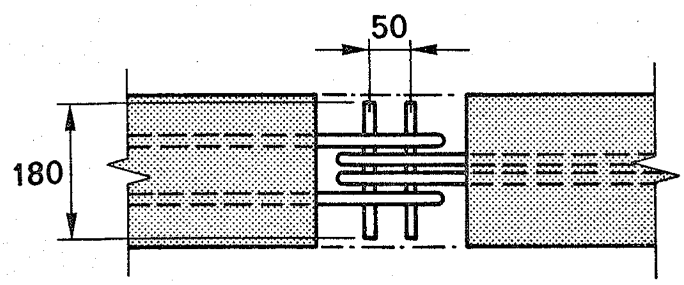


Figure 7: Type VI. Lateral Reinforcement: 2 K20

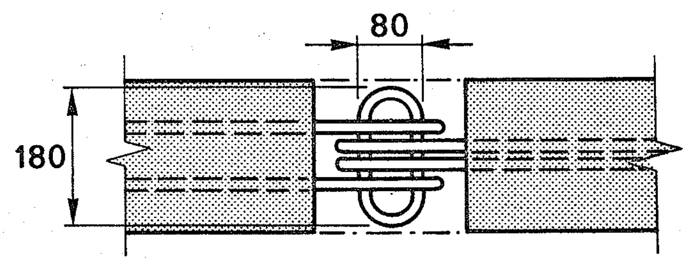


Figure 8: Type VII. Lateral Reinforcement:
K14 ring

Test No.	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21
Type No.	Reference	Reference	I	I	I	I	I	I	II	II	II	II	II	II	III	III	III	IV	V	VI	VII
b mm			80	80	110	110	140	140	80	80	110	110	140	140	80	80	80	140	140	110	110
F_{ℓ} mm^2			201	201	201	201	201	201	201	201	201	201	201	201	154	154	154	616	616	628	308
σ'_b MN/m^2	39,2	37,3	40,3	41,7	40,7	38,3	39,7	38,3	40,3	41,7	40,7	38,3	39,7	38,3	40,3	40,3	41,7	39,7	38,3	40,7	38,3
σ'_c MN/m^2	28,9	28,9	31,1	31,1	31,1	33,7	33,7	33,7	34,9	34,9	31,5	31,5	32,2	32,2	20,7	34,1	42,4	29,1	29,1	32,6	32,6
Type of failure	Y	Y	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	Y	Y	Y	Y
M_c kNm	690	690	690	690	690	700	700	700	700	700	690	690	700	700	670	700	710	690	690	700	700
M_T kNm	652	660	466	479	454	454	454	458	417	371	475	413	475	454	306	437	482	582	610	568	578
$E \cdot I$ MNm^2	3,59	2,79	2,20	2,66	2,60	2,57	2,42	2,42	2,56	2,79	2,63	2,88	2,79	2,68	3,05	3,00	3,00	3,09	3,24	3,22	2,68

Table I: Beam - beam joints.

TEST RESULTS

Two types of failure occurred in the tests, i.e. sudden split failure in the concrete due to the concentrated load from the stirrups and compression failure of the concrete at the top of the beam after yielding of the reinforcement on the tensile side. The types of failure are denoted S and Y, respectively, in table I.

In order to achieve the desired yielding, the lock must be able to transmit sufficiently heavy forces. The influence of different parameters was investigated in these tests, and on the background of table I, the results are discussed in the following:

Symmetrical or Asymmetrical Joint

In tests 03-08, the joints were asymmetrical (type I, figure 3), while in tests 09-14, they were symmetrical (type II, figure 4). In all cases, failure occurred as sudden split failure at a moment of about 70 per cent of that of the reference beams. (Tests 01 and 02.) The results show no significant difference between a symmetrical and an asymmetrical arrangement of the hairpin stirrups.

Lap-length of Hairpin Stirrups

In both the symmetrical and the asymmetrical joints, the lap-length of the hairpin stirrups was varied (b in figure 1). The test results show that the lap-lengths used have no significant influence of the bearing capacity.

Strength of Concrete

The strength of the concrete in the joint was varied in tests 15, 16, and 17, and as expected, the bearing capacity increased with increasing strength of concrete, i.e. weaker concrete requires more lateral reinforcement in order for yielding to occur in the hairpin stirrups.

Lateral Reinforcement

The purpose of this reinforcement is to prevent lateral expansion of the concrete in order to avoid tensile cracking and thus split failure. In order to obtain good adhesion between concrete and lateral reinforcement, profile steel was used. In tests 18, 19, 21, the adhesion was further improved by using ring-shaped lateral reinforcement or hairpin stirrups.

Tests 18-21 all resulted in yielding in the tensile reinforcement prior to failure. The bearing capacity was about 90 per cent of that of the reference beams.

In order to achieve the desired plastic failure, a K14 steel ring (F_ℓ = 308 mm^2) or 2 K20 steel (F_ℓ = 628 mm^2) will thus suffice when the concrete has a compressive strength of about 30 MN/m^2.

A lower bound for the lateral reinforcement, which just gives the desired type of failure, was not found.

Relationship between Load and Deformation

The relationship between moment and curvature for three typical tests is shown in figure 9. There

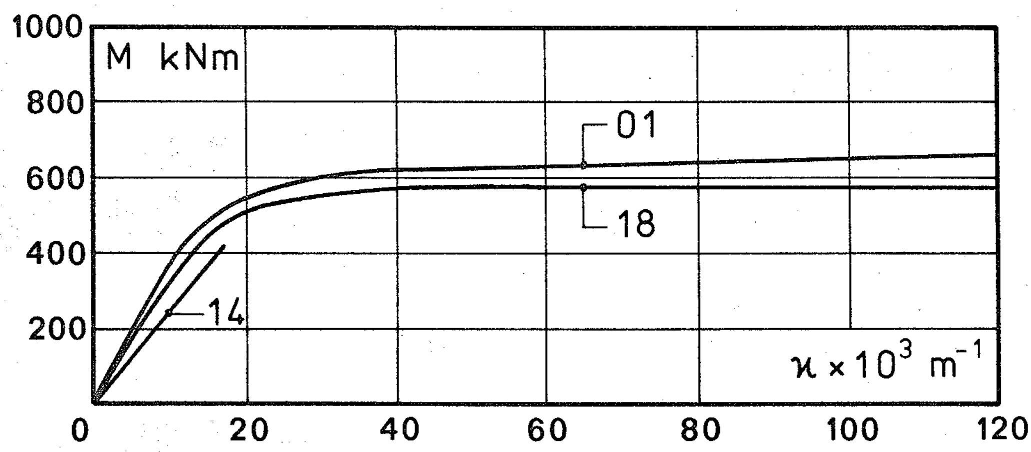


Figure 9: Relationship between Moment and Curvature

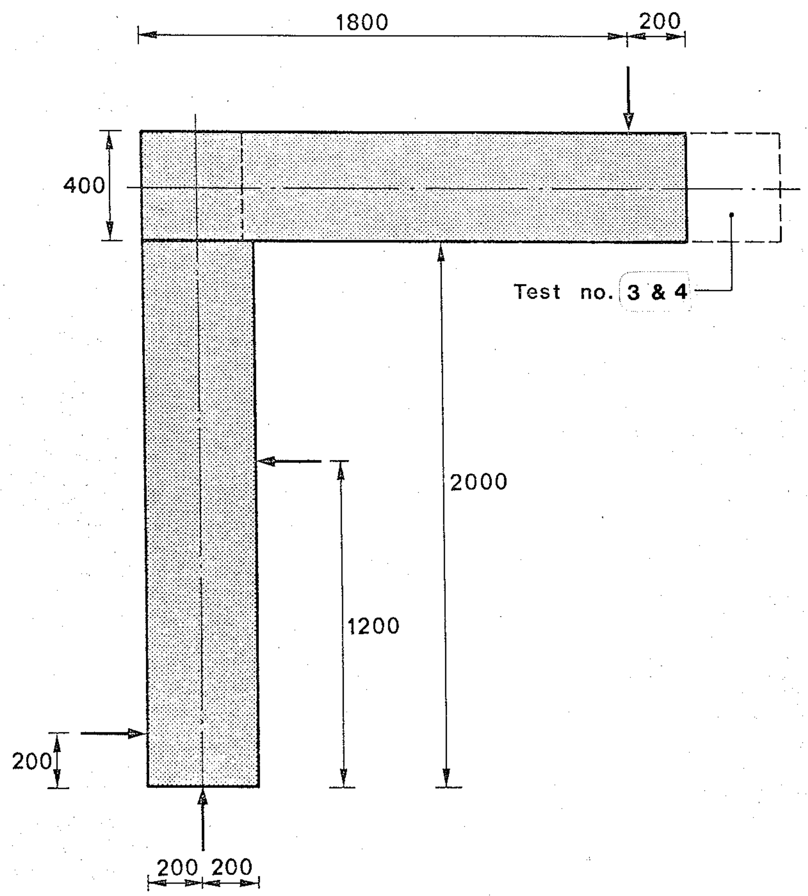
was a linear relationship between moment and curvature in all the tests at the beginning, and on this basis, the elastic bending stiffness was found to be $E \cdot I = M : \kappa$.

Like the reference beams, the joints resulting in yielding in the tensile reinforcement had a high rotational capacity.

At an early stage of the tests (40-80 kNm), cracks were observed at the transition between beam concrete and joint concrete. The cracks were small during the elastic stage, but at yielding in the tensile reinforcement, they opened up.

COLUMN-BEAM JOINT

4 preliminary tests were carried out in a vertical test arrangement with a loading principle as shown in figure 10. Columns and beams with a cross-section of 200 x 400 mm were used in the tests.



Figur 10: Loading Principle

In the first two tests, the column and the beam were joined by means of two bolts from the column projecting up through two recesses in the beam (figure 11). The beam was underpacked with mortar,

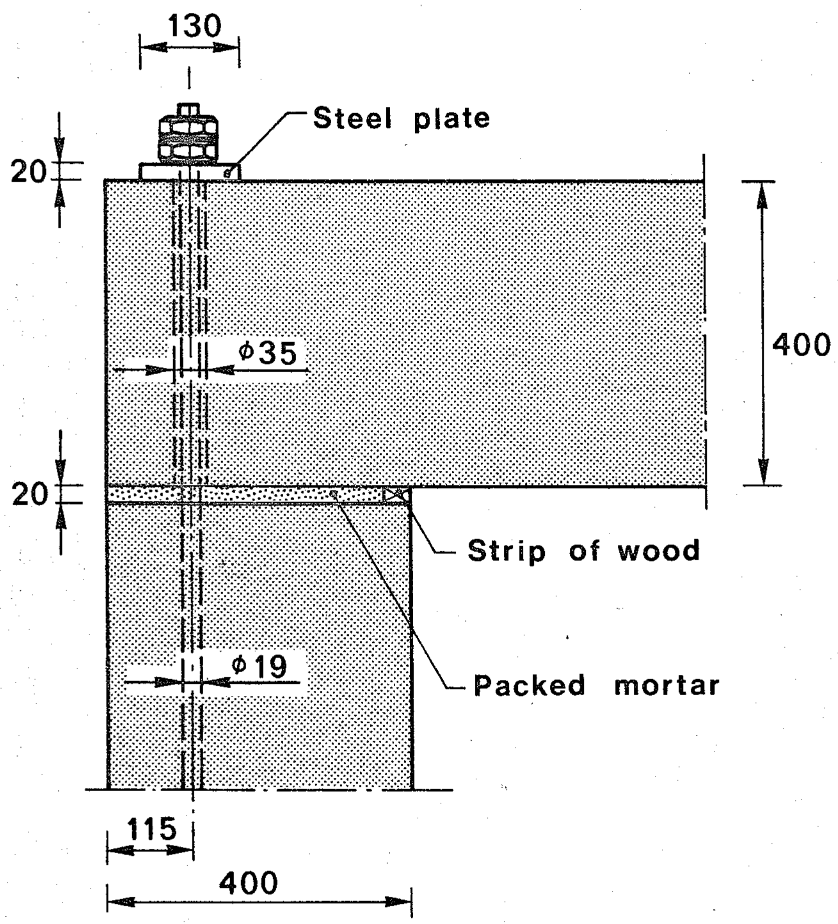


Figure 11: Type I

and the bolts were tightened the day before the test. The bolts were of mild steel with σ_y = 246 MN/m^2 and σ_u = 357 MN/m^2.

The other two tests were carried out with a type of hairpin stirrup joint, as shown in figure 12. The lateral reinforcement was 2 K20, placed as shown in figure 13. The stirrups were of R16 steel with σ_y = 276 MN/m^2 and σ_u = 410 MN/m^2.

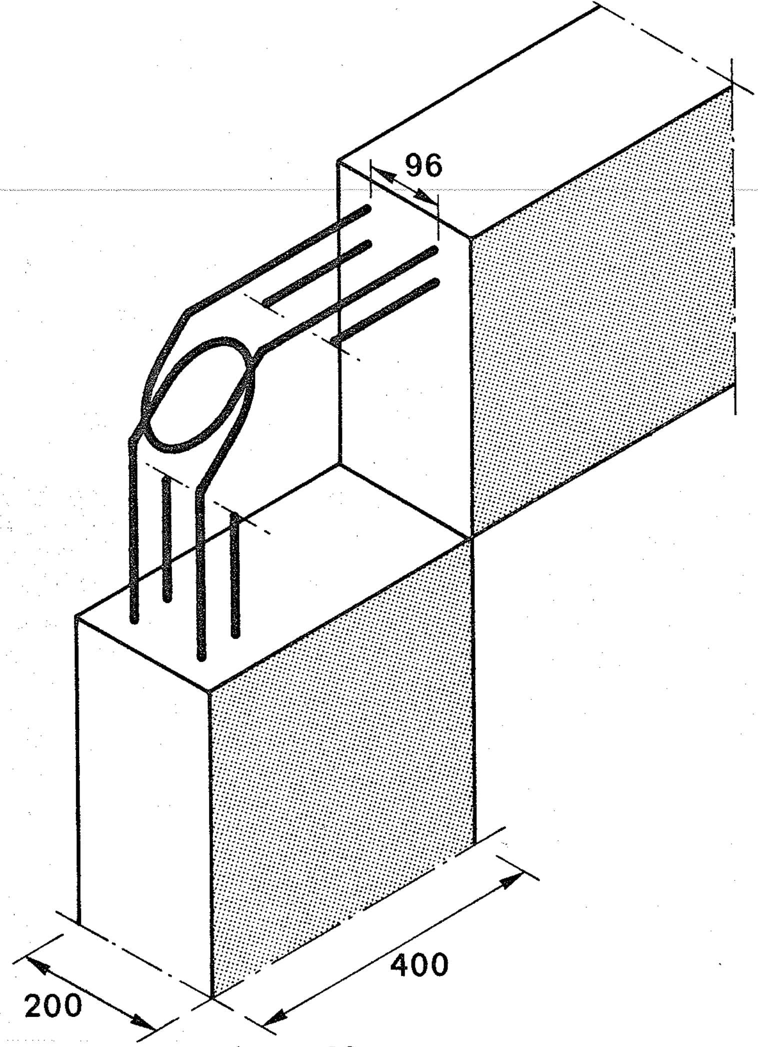


Figure 12: Type II-V

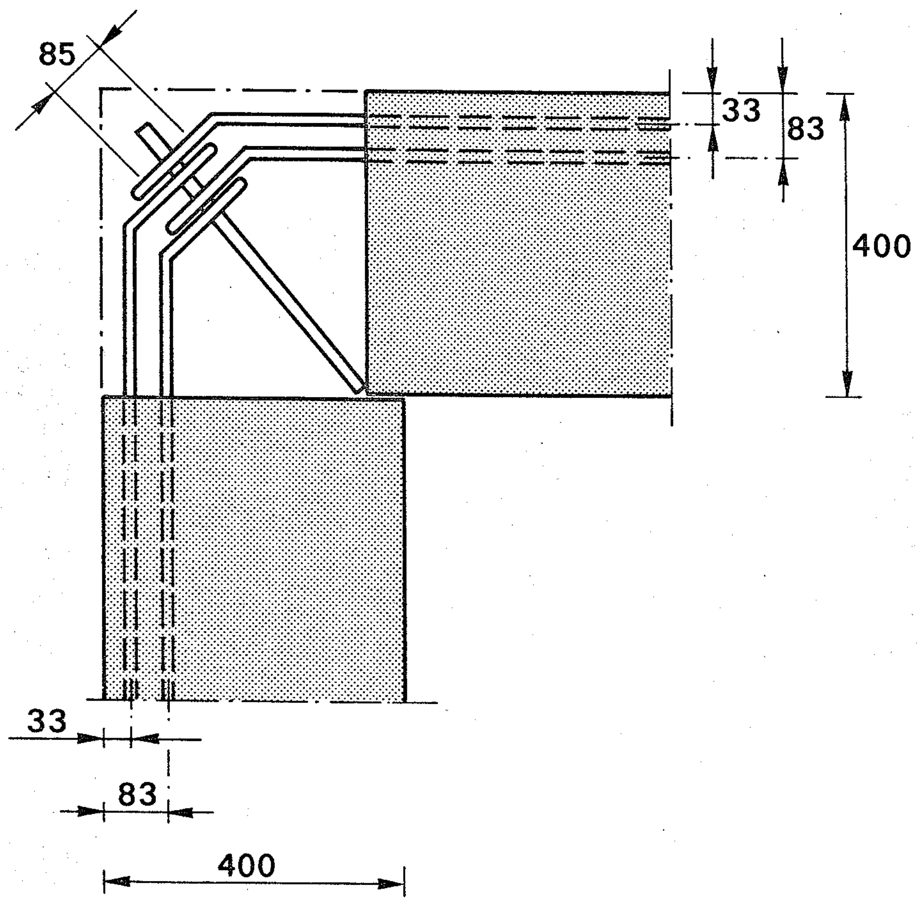


Figure 13: Type II-Lateral Reinforcement: 2 K20

Plastic failure occurred in all four tests.

In tests 1 and 2, the plastic hinge formed in the section between column and beam, which is theoretically the weakest section in the joint.

In tests 3 and 4, the plastic hinge also formed in the section over the column against the joint despite the fact that, in this section, there is a normal force which should, theoretically, make the bearing capacity of the section greater than that between beam and joint.

Test No.	1	2	3	4	5	6	7	8	9	10	11	12
Type No.	I	I	II	II	III	III	III	III	III	IV	IV	V
F_{ℓ} mm^2			628	628	226	226	100	100	0	100	0	0
σ'_b MN/m^2	348	299	388	361	365	413	418	400	436	369	394	417
σ'_c MN/m^2	409	421	181	277	339	294	318	373	343	312	351	344
Type of failure	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	S
M_c kNm	460	450	670	700	870	850	860	870	870	860	870	870
M_T kNm	360	410	730	740	780	810	780	790	800	790	752	780
$E \cdot I$ MNm^2	4,08	5,00	8,44	6,90	7,60	8,79	8,75	8,77	7,36	6,81	6,35	5,79

Table II: Column - beam joints.

The results are shown in table II, in connexion with which it should be noted that the bearing capacity in tests 1 and 2 was slightly lower than calculated, while in tests 3 and 4, it was slightly higher.

The subsequent tests were carried out in a horizontal loading arrangement, the loading principle of which is shown in figure 14. The

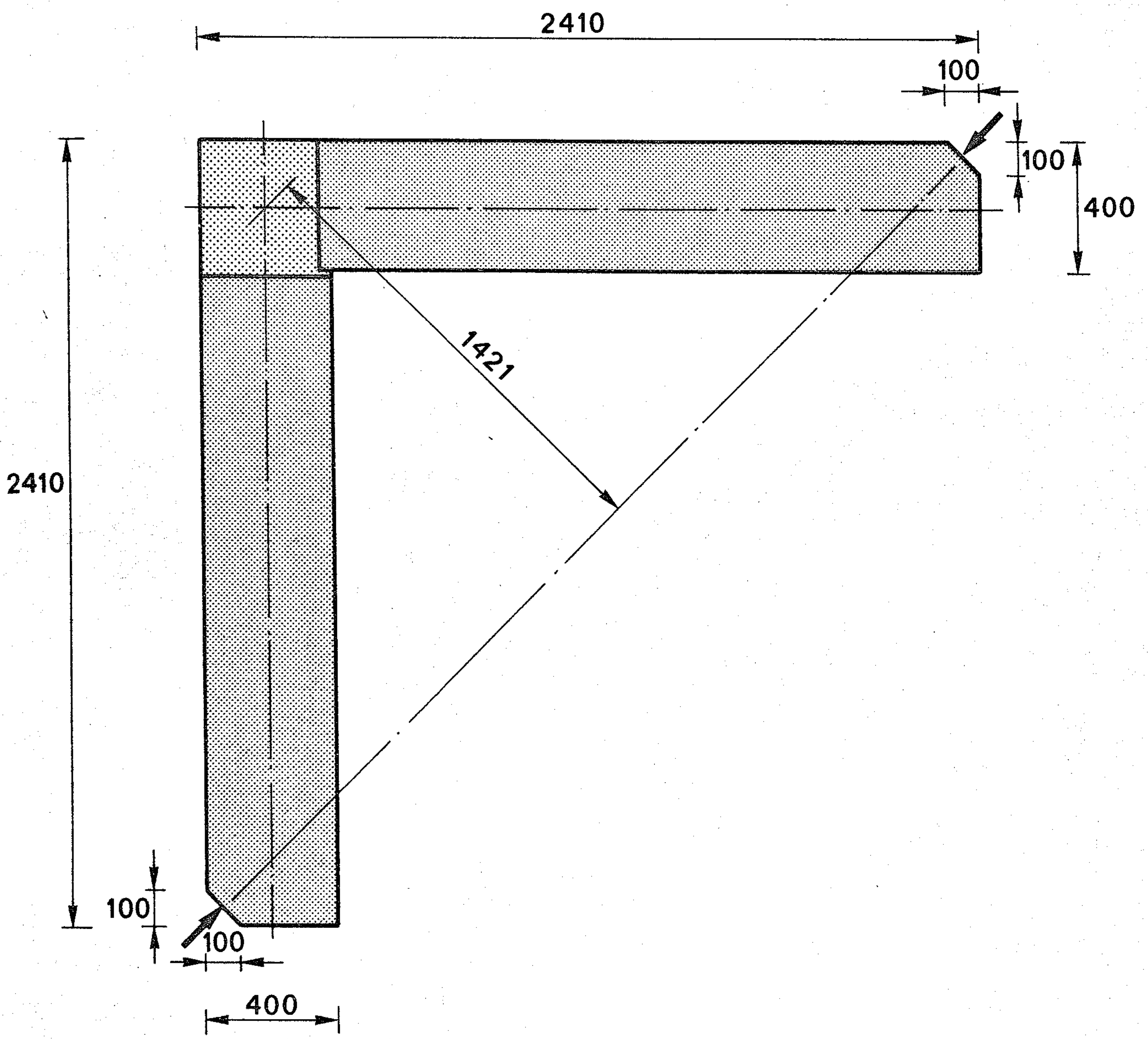


Figure 14: Loading Principle

joints were of the same type as in tests 3 and 4, except that the lateral reinforcement was placed as shown in figure 15. The hairpin stirrups used in the tests were of R16 steel with $\sigma_y = 281$ MN/m^2 and $\sigma_u = 405$ MN/m^2.

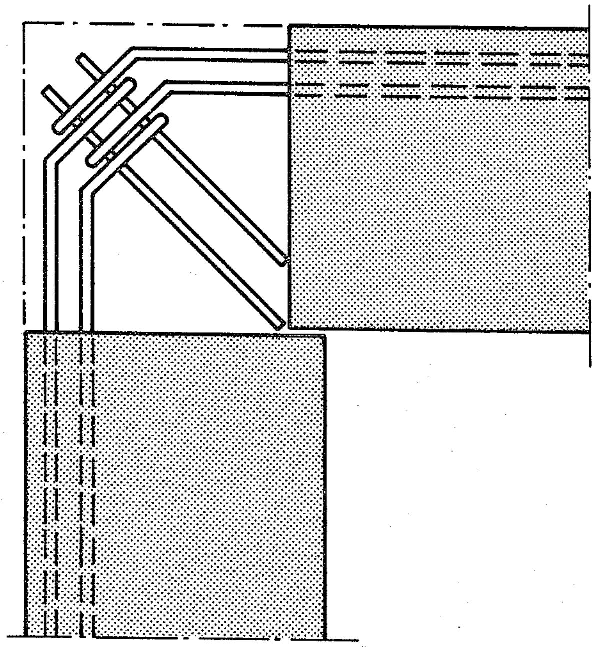


Figure 15: Type III (IV and V).
Lateral Reinforcement: Variable

In tests 5 to 9, efforts were made to find the lateral reinforcement that would just result in yielding in the hairpin stirrups. As will be seen from table II, lateral reinforcement is not necessary to the achievement of plastic failure.

In order to avoid friction forces from the straight legs of the hairpin stirrups, these were enclosed in plastic tubing in tests 10 and 11. Lateral reinforcement was also unnecessary here.

In the last tests, plastic tubing was used in the same way as in tests 10 and 11, and the remainder of the stirrups was greased so that friction was greatly reduced all over the stirrups.

In the tests, split failure occurred just as the yield load was reached. The failure consisted of the concrete over the outermost hairpin stirrup in the joint being lifted up, leaving this stirrup partly free. The considerable residual bearing capacity was due, inter alia, to the fact that the other hairpin stirrup was still active.

In practice, a hairpin stirrup joint of this type should always be executed with lateral reinforcement in order to increase safety in case of faulty execution or progressive collapse.

The mutual angular rotation between the two sections on either side of the joint was measured in all 12 tests. This angular rotation was then converted to a mean curvature along the centreline.

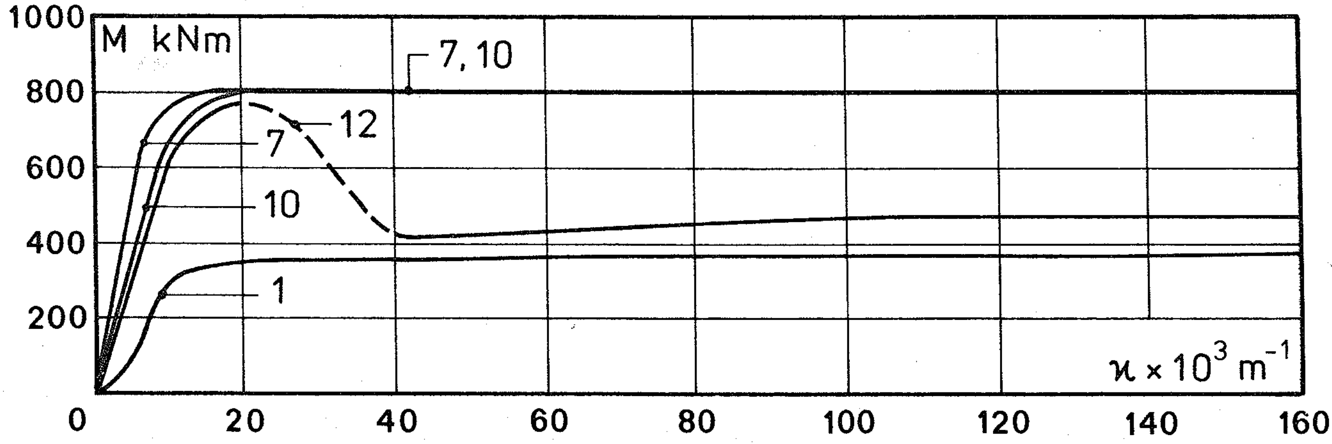


Figure 16: Relationship between Moment and Curvature

The relationship between moment and curvature for a single test is shown in figure 16. The elastic bending stiffness $E \cdot I = M : \kappa$ is included in table II. Amongst other things, it will be seen that in the tests with reduced friction (10, 11, and 12), the bending stiffness was also reduced.

There was good agreement between the measured and the calculated bearing capacity in all 12 tests. The calculation takes into account the effect of the normal force, except in tests 3 and 4, where a plastic hinge is assumed between beam and joint. Thus, in tests 5 to 12, the bearing capacity is about 90 per cent of the calculated value.

CONCLUDING REMARKS

On the basis of the tests described above, it seems likely that it will be possible to develop theoretically simple joints between precast columns and beams and between two beams in such a way that failure occurs as plastic failure and in such a way that their bearing capacity can be determined on the basis of "normal" calculations of the bearing capacity of the concrete cross-section.

The hairpin stirrup joints fulfil most of the requirements to joints listed in the introduction, but they cannot be executed independently of weather conditions (point 6) and they cannot be immediately executed in a few, simple work operations (point 4).

The Institute of Building Design is continuing its work on the development of rigid joints, with the aim of making the joints more suitable for ordinary contracting work, for example, by making the joints self-shuttering.

Besides the joints discussed here, we will also work on T- and X-joints, and will carry out tests with other loading combinations than those used in the tests mentioned. The bolted joints described will be made the subject of further investigations, inter alia on prestressed bolts. The column-beam joints all have negative bending moments. Tests with positive moments have been initiated.

In connexion with the formulation of rational design rules for joints, we have started a test series with rupture criteria for concentrated loads, for example, from hairpin stirrups.

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