SPLICING OF REINFORCEMENT IN FRAME CORNERS: Experimental Studies

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ABSTRACT

To study the alternative of splicing reinforcement in a frame corner, a research project is currently being carried out at Chalmers University of Technology. Three test series have been performed, so far, in which specimens with reinforcement splices within the frame corners were compared with corresponding specimens without splices. If the reinforcement in frame corners could be spliced, this would considerably simplify the production of structures such as slab frame bridges and shelters for civil defence. Two of the test series employed reinforcement detailing suitable for slab frame bridges. Results from these tests did not uncover any drawbacks relating to spliced reinforcement in the frame corners. The first of the test series consisted of frames loaded statically to failure, while the second consisted of frames loaded cyclically to fatigue failure. In the third test series a new reinforcement detailing in civil defence shelters was tested. This test series did not show any major disadvantages for the new reinforcement detailing. Altogether, the test results support the idea that it should be feasible to splice the reinforcement within the corner area of a frame.

Key-words: Reinforcement splices, frame corners, concrete bridges, shelters for civil defence, load carrying capacity, static tests, fatigue tests.

1 INTRODUCTION

1.1 Background

According to present Swedish concrete codes BBK 79, Statens betongkommitté /1/, splicing of reinforcement shall be avoided within the corner of a frame. In the connection between a wall and a slab, this often means that the corner reinforcement extends far into the slab, which requires reinforcement of the slab before the wall can be cast. This is a problem for slab frame bridges with long spans, which have very dense reinforcement in the frame corners, with long reinforcing bars extending into the bridge deck slabs. In shelters for civil defence, the corner reinforcement, generally, is also very dense with long corner bars, and the reinforcement detailing is complicated to carry out correctly according to the Swedish Shelter Regulations, Räddningsverket /2/. To simplify the production of these kinds of structures, it is desirable to splice all reinforcement within the frame corners.

1.2 Aim and Scope

The objective of this study was to investigate whether all reinforcement within the corner area of a frame could be spliced. Three test series, intended to examine the behaviour of frame corners under different load conditions up to failure, were carried out. In the test series, specimens with all reinforcement spliced within the frame corners were compared with specimens having conventional reinforcement detailing, without splices in the frame corners.

The specimens in the first two test series were designed with reinforcement detailing suitable for slab frame bridges. The first test series consisted of three frames, two of which had all reinforcement spliced within the frame corners. The frames were loaded with gradually increasing loads up to failure in the corner area. In this test series, the failure mechanisms, the failure loads and the strain distributions along the corner reinforcement were studied.

The second test series comprised seven specimens, each of which consisted of a frame corner connecting a column and a beam. The frame corner was loaded with a cyclic load until fatigue failure occured, in order to achieve a more complete view of the influence of reinforcement splices. In this test series, the influences of cyclic load, reinforcement bends and construction joints were studied, in addition to the failure mechanisms and strain distributions in the corner reinforcement.

Specimens reinforced according to the Shelter Regulations were tested in the third test series. A new reinforcement detailing, with all reinforcement spliced within the corner area, was compared with the conventional detailing. The specimens were loaded with a gradually increased load up to failure. Besides failure mechanisms and failure loads, the rotational capacities and failure energies were studied for different reinforcement ratios.

The aim of this study was to gain a better understanding of the behaviour of frame corners under loading up to failure and of the response in the reinforcement. The test series were intended to show whether it is possible for reinforcement to be spliced in frame corners, with respect to the structural behaviour, and also to serve as a basis for further research.

2 CORNERS IN SLAB FRAME BRIDGES - STATIC TESTS

2.1 Test Specimen

The static tests were performed as a pilot series with three test specimens, see Vo Minh and Plos /3/. The test specimens were designed as frames with two frame corners, according to Figure 1. Two of the frames had the same geometry and reinforcement detailing outside the corner areas. One of these frames had conventional, unspliced reinforcement, while the other had all reinforcement spliced within the corners. The third specimen had spliced corner reinforcement but a shorter span length. The results from this specimen are not mentioned further here, since it obtained a shear failure outside the corner areas.

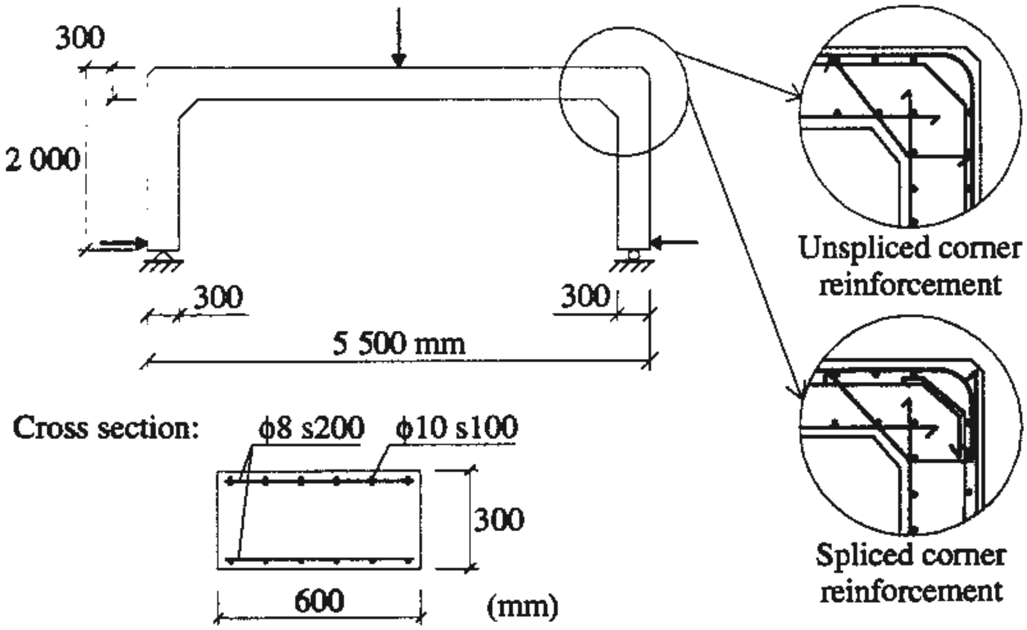

Fig. 1. Frames loaded in static tests

The frames were cast horizontally, without any construction joints, but were tested in an upright position, see Figure 2. The frames had two layers of tension reinforcement on the outside of the frame corners. The outer of these reinforcement layers had a 90° bend with a radius of 125 mm in the frame corners, while the inner layer had two 45° bends with a smaller radius. The frame corners were provided with haunches. The concrete quality was K40 according to the Swedish code, BBK 79. The main reinforcement was of quality Ks60s, with a diameter of 10 mm, and the secondary reinforcement of quality Ks40s, with diameter 8 mm.

2.2 Test Performance

The frames were loaded both vertically at mid-span of the frame beams and horizontally at the bottom of the frame columns to induce moment failures in the corner areas. The relation between the vertical and horizontal loads was kept constant at a relation that ensured the occurrence of the failure in the corner area. During the tests the frames were loaded with gradually increasing loads up to failure.

The loads were applied by hydraulic jacks. The magnitudes of the loads were measured by load gauges placed between the jacks and the specimen. Deflections of the specimen were measured, at several locations along the frame beam and frame columns, by electronic position gauges. Strain gauges were used to measure the strain in some of the outer corner reinforcement bars and the concrete compression strain at the inside of the frame corner. The crack growth was continuously registered. The concrete and reinforcement strengths were determined according to Swedish standard /4/.

2.3 Test Results

The failure loads were almost identical for the unspliced frame and the frame with spliced corner reinforcement, see Table 1. Both frames obtained moment failure in the frame columns close to the corners after considerable plastic rotation in the corner areas, as well as at mid span of the frame beams, see Figure 2.

The stress variation along the outer corner reinforcement was almost equal for both frames, see Figure 3. The stresses were calculated from the measured strains, using a stress-strain relation obtained from tension tests of the reinforcement used. For the specimen with spliced corner reinforcement, the stresses along the overlapping bars were added. The sums of the stresses were, in some places, even larger than the yield stress, showing that the forces transmitted by the tensile reinforcement were greater than the maximum tensile capacity for a single bar.

Tab. 1. Loads at failure for the pilot frame specimens

Specimen	Loads at failure [kN]	
	Vertical load	Horizontal load
A1 (unspliced)	293	127
A2 (spliced)	309	130

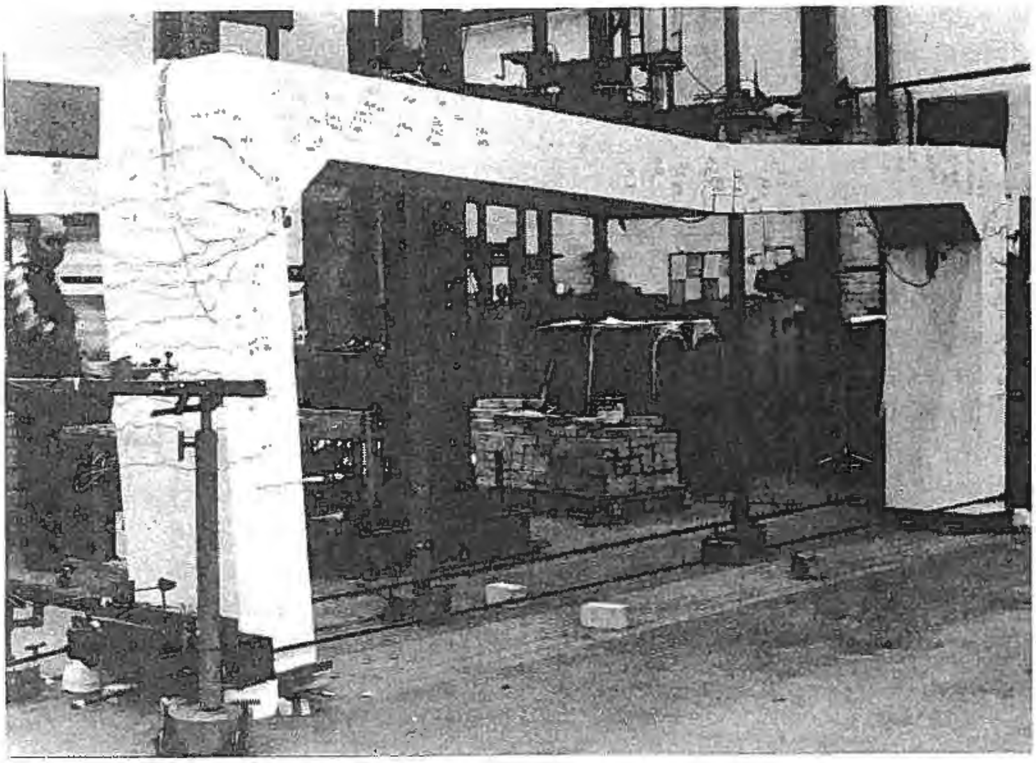

Fig. 2. Deformed frame during the test, after development of plastic hinges, both under the frame corners and at mid-span of the bridge beam

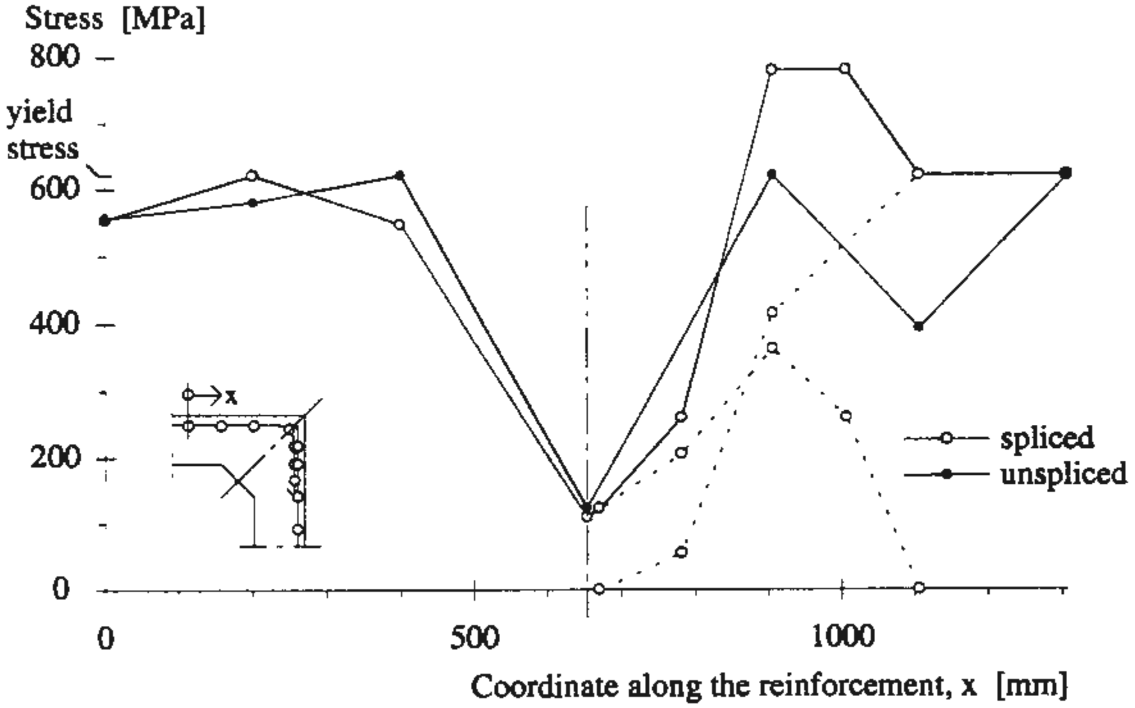

Fig. 2. Distribution of stress along the outer corner reinforcement just before failure in the static pilot tests. For the spliced corner reinforcement, the dotted lines (- - -O- - -) show the stress in the two overlapping bars, while the continuous line (—O—) shows the sum of the strains along the lap length.

2.4 Concluding Remarks

The pilot tests did not reveal any disadvantages for the spliced corner reinforcement. The two frames had almost equal capacity and strain distribution in the corner reinforcement. As this test series was limited, more tests are needed in order to draw more definite conclusions. Since the frame corners are intended for use in bridges, it was of special interest to extend the test basis with fatigue tests.

The stresses at the reinforcement in the mid-section of the corner were considerably smaller than in the cross-sections adjoining the corner. The haunch in the corner had a very positive influence on the stress distribution in the corner, allowing the stresses to become considerably reduced in the splice. Accordingly, the design for the following tests excluded haunches, as it was our aim to avoid performing tests limited to the more favourable design.

3 CORNERS IN SLAB FRAME BRIDGES - FATIGUE TESTS

3.1 Test Specimens

The second test series consisted of seven test specimens that were subjected to cyclically varying loads until fatigue failure was reached, see Plos /5/. The test specimens had frame corner regions of the same dimensions as the corners in the previously tested frames, see Figure 4. The length of the frame columns and the frame beams was chosen to obtain the

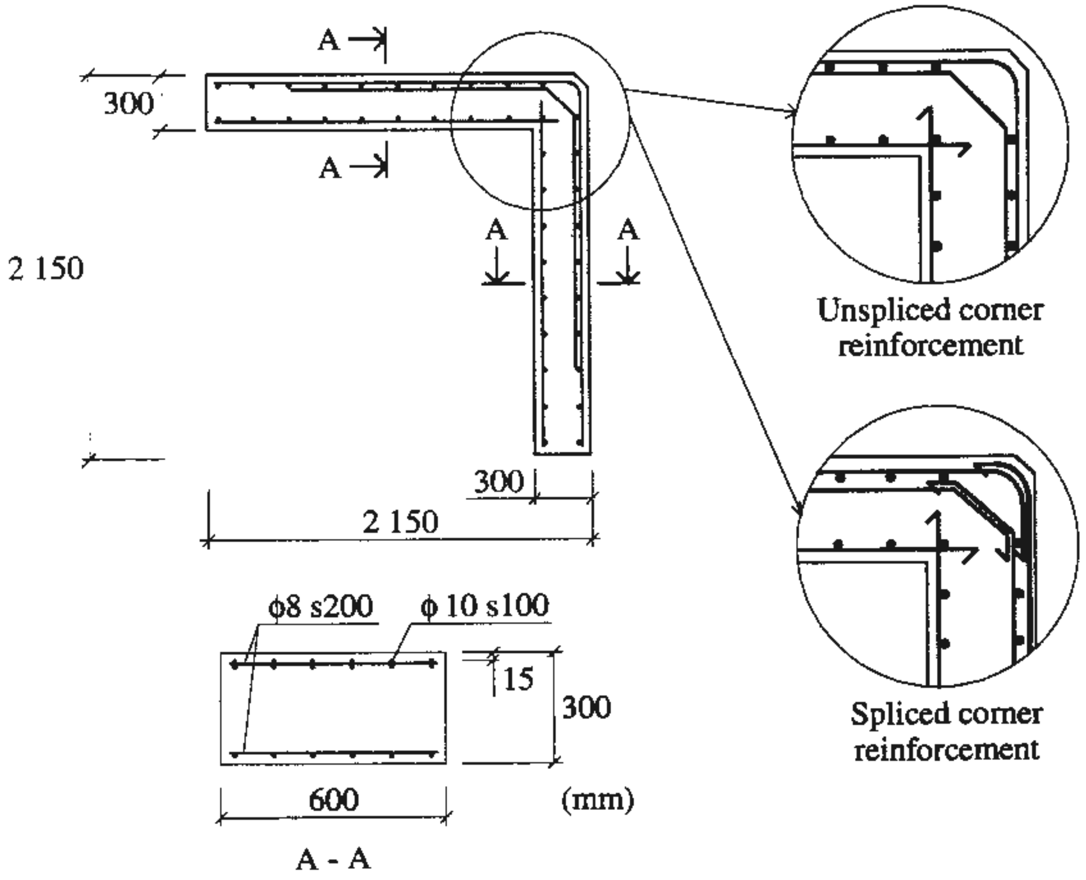

Fig. 4. Dimensions and detailing for the first five specimens in the fatigue tests (no. B0 - B4).

same relations between the moment, the normal force and the shear force as in the pilot tests. In contrast to the pilot tests, none of the specimens had a haunch in the corner.

Three of the specimens had unspliced reinforcement and the remaining four had all reinforcement spliced in the frame corner. One of the specimens was used in a pilot test of the projected test set-up and loading arrangements. The other six specimens were manufactured and tested in

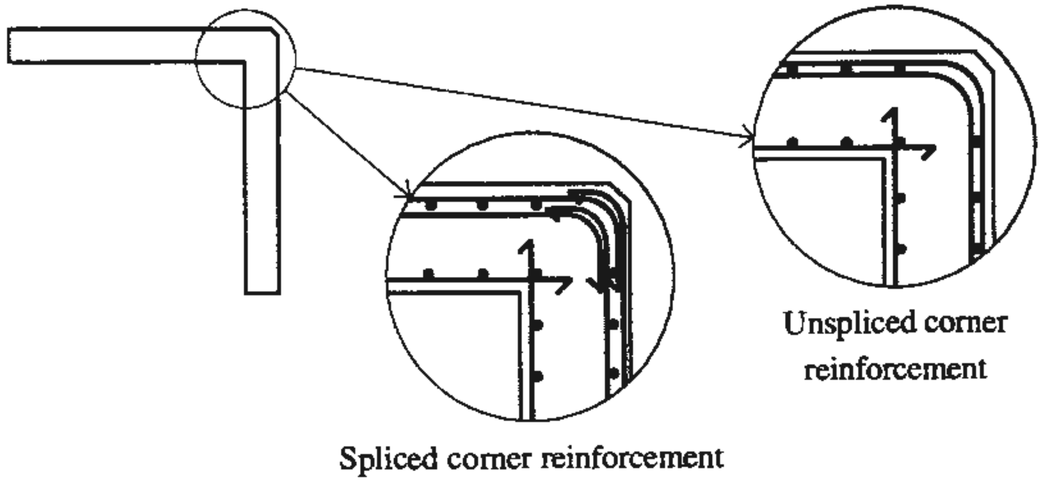

Fig. 5. Dimensions and detailing for the last two specimens in the fatigue tests (no. B5 and B6).

pairs consisting of one specimen with spliced and one with unspliced reinforcement. Except for the reinforcement splice, the dimensions and detailing were the same for the pairs of specimens, and they were subjected to the same cyclic loading history.

The first two pairs of specimens had, in principle, the same reinforcement detailing as the specimens in the first test series, as shown in Figure 4. The 45° reinforcement bends for the inner tension reinforcement were made with the smallest radius permitted according to the codes, that is, in this case, 38 mm. The last pair of specimens had somewhat different detailing in the frame corner, where both tension reinforcement layers had 90° bends with a larger radius of 125 mm, see Figure 5. The pilot specimen had the same detailing as the first two pairs of specimens, but with a considerably smaller bending radius for the inner reinforcement layer.

The specimens were cast with the columns in a vertical position. To have construction joints at the top of the frame columns, the casting was interrupted. The quality of concrete and reinforcement was the same as in the pilot tests, that is K40 for the concrete, ϕ10 Ks60s for the main reinforcement and ϕ8 Ks40s for the secondary reinforcement (according to the Swedish codes).

3.2 Test Set-up

The test specimens were tested in a vertical test rig, see Figure 6. The pulsating load was applied by a hydraulic pulsator with the load acting along the diagonal line between the loading and support points. The specimens were braced in the horizontal direction at the loading and support points, allowing displacements only along the loading line. Free rotation at the loading and support points was provided by hinges.

The loads were measured using a load gauge placed between the pulsator and the specimens.

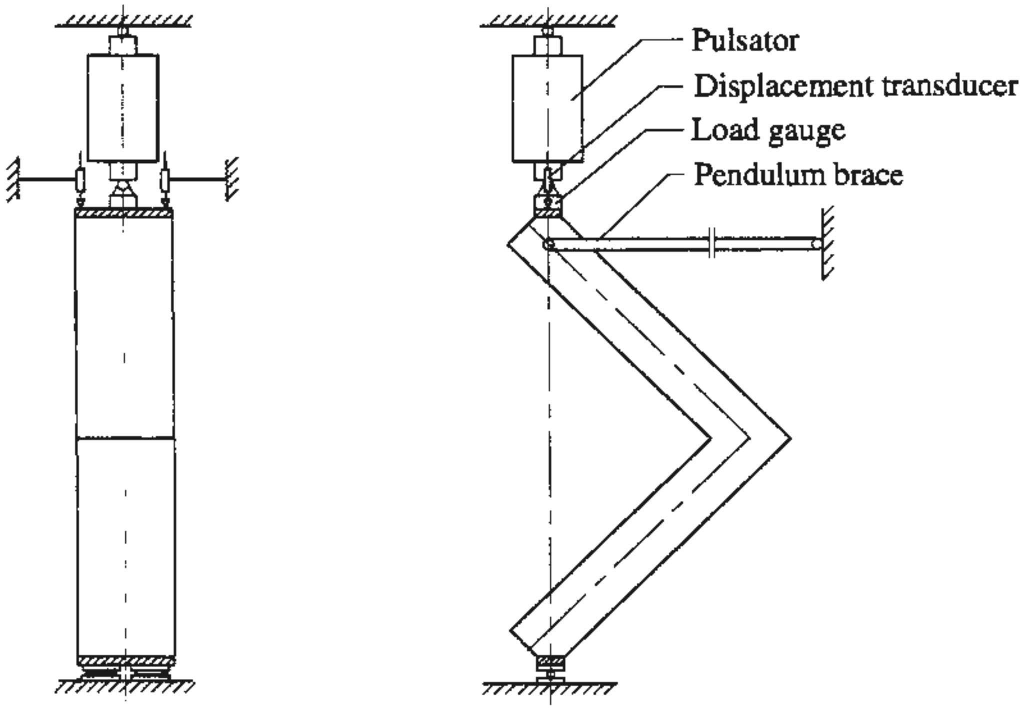

Fig. 6. Test set-up for fatigue tests

The total deflection of the specimens was measured by electronic displacement transducers. As in the static tests, the strain in the outer corner reinforcement and the concrete strain at the inside of the frame corners were measured by strain gauges. The crack growth was registered, and the material strengths were determined according to the Swedish Standard, in the same way as in the static tests.

3.3 Test Performance

The specimens were first loaded with a gradually increasing load until the intended maximum load level was reached. The load varied thereafter between a maximum and a minimum compressive load level. The load variation was approximately sinus-formed and slow enough to make the dynamic effects negligible.

Load, deformation and strains were measured at every load step during the initial loading and at maximum and minimum load levels during cyclic loading. To enable the latter measurements, the pulsator was stopped while the specimens were loaded statically to the maximum and minimum load levels.

3.4 Test Results

The cracking in all of the specimens occurred symmetrically around the frame corner, but the deformations became concentrated during the cyclic loading to a major crack, immediately above the corner, see Figure 7. For all of the specimens, the failure was determined by fatigue failure in the tension reinforcement where it crossed the major crack. For the specimens with smaller bending radius of the inner reinforcement layer, the fatigue failure occurred in the reinforcement bend, see Figure 8. In the last two specimens, where both reinforcement layers had the same, larger, bending radius, the failure occurred in the more heavily stressed outer layer instead.

In the specimen with unspliced reinforcement and the larger bending radius for both reinforcement layers (specimen no. B5), spalling of the side cover determined the failure after only about 400 load cycles, see Figure 9. The uncovered bars were therefore cut, and the cyclic loading was continued at the same stress range as before in the remaining reinforcement. The final failure was, as in the corresponding spliced specimen, determined by fatigue in the outer reinforcement layer.

The load values and number of load cycles to failure are shown in Table 2. For all the pairs of test specimens, the specimen with spliced reinforcement could withstand a greater number of load cycles before fatigue failure in the reinforcement. However, the numbers of load cycles were of the same magnitude and no determinant differences in capacity between spliced and unspliced reinforcement detailing were apparent from the test results.

The fatigue failures occurred, for all of the specimens, in one of the reinforcement bends that had the smallest radius. The radius of the bend had a clear influence on the number of load cycles to failure. This is especially obvious if the pilot test specimen (no. B0) is compared with the last pair of specimens (nos. B5 and B6), since these specimens had almost the same load

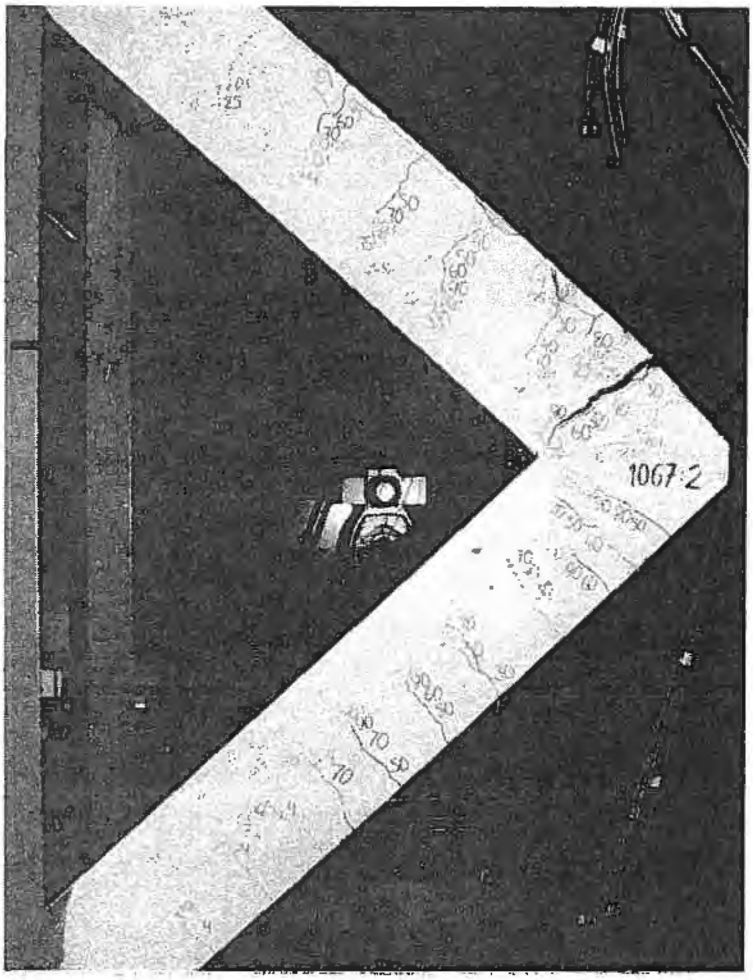

Fig. 7. Fatigue failure in a spliced frame corner

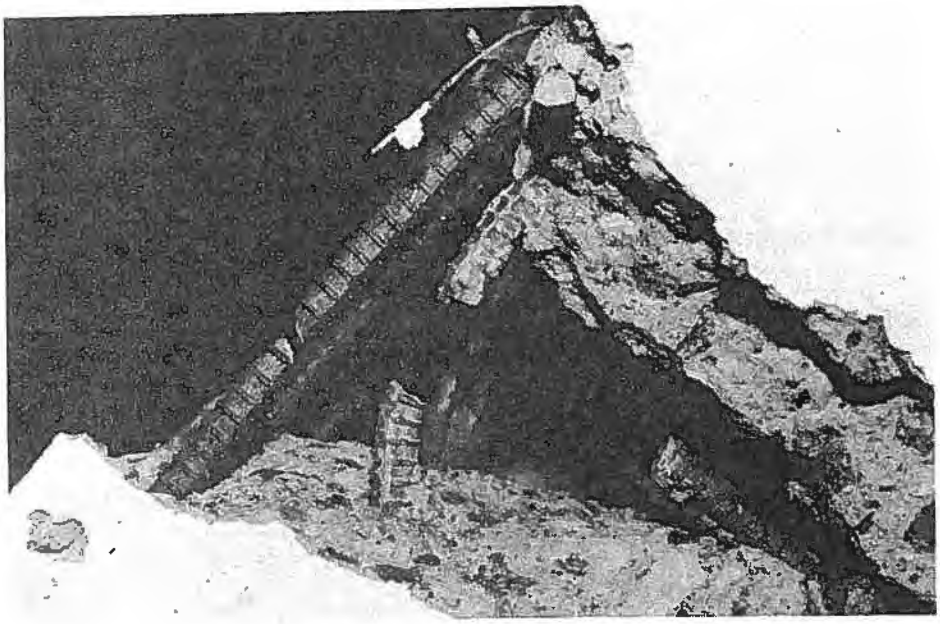

Fig. 8. Fatigue failure in the 45° bend in the inner reinforcement. The failure in the outer reinforcement occurred after yielding, when the test specimen was subjected to additional loading following the fatigue failure. Unattached concrete pieces have been removed.

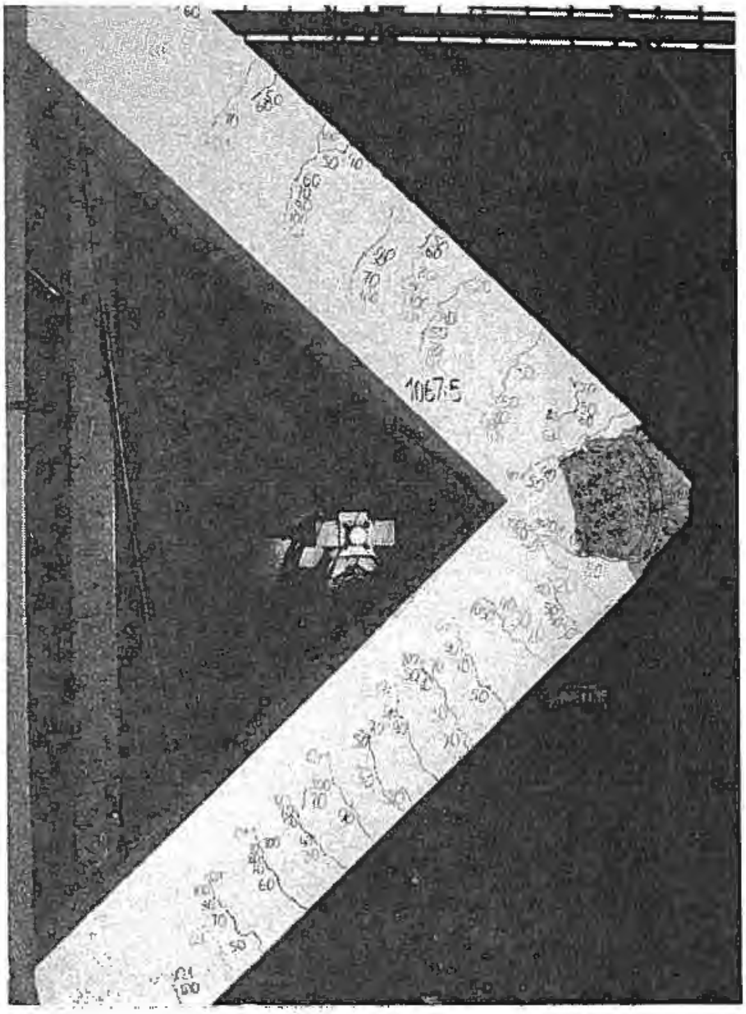

Fig. 9. For the specimen with unspliced reinforcement and both tension reinforcement layers bent 90°, i.e. the same bending radius, spalling of the side concrete cover occurred after only about 400 load cycles. This failure could not be predicted with the current design model in the Swedish concrete codes, BBK 79.

range. The test result for specimen number B5 is not directly comparable to the other test results, since yielding was reached in the reinforcement when the spalling of the concrete cover occurred. The yielding caused shorter fatigue lifetime for the reinforcement in this specimen.

Tab. 2. Load levels, load ranges and number of load cycles to failure

Specimen	B0	B1	B2	B3	B4	B5	B6
Spliced(s)/Unspliced(u)	u	u	s	u	s	u	s
Min. bend. radius [mm]	12	38		38		125	
Maximum load [kN]	100	90		83		100/77	100
Minimum load [kN]	10	20		20		15/20	15
Load range [kN]	90	70		63		85/57	85
Cycles to failure [10^3]	6	56	79	44	81	0,4+30	61

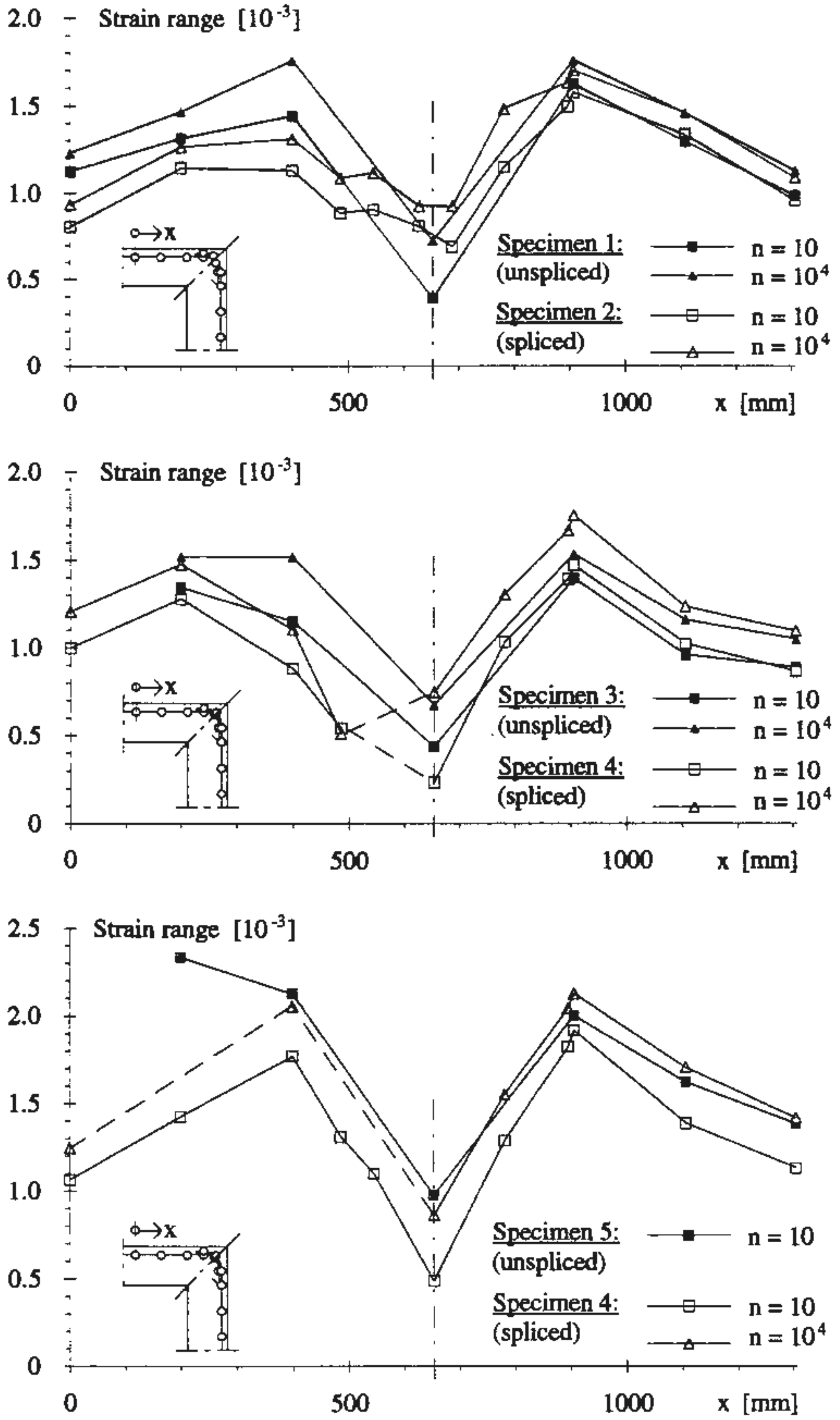

Fig. 10. Distribution of strain range (strain difference between maximum and minimum loads) along the outer corner reinforcements after 10 and 10 000 load cycles. For the spliced corner reinforcements, the sums of the strains along the overlapping bars are shown.

The strain in the outer reinforcement layer during the initial loading varied in the same general way as in the static tests, with a considerably smaller reinforcement strain in the middle of the 90° bend in the frame corner. The strain ranges (strain differences between maximum and minimum loads) in the corner reinforcement, after 10 and 10 000 load cycles, are shown in the diagrams in Figure 10. For the spliced corner reinforcements, the sum of the strain ranges in the two overlapping bars are displayed.

The strain ranges in the reinforcement were, for all of the specimens, notably smaller in the middle of the frame corners than in the cross sections immediately adjacent to the corners. The strain ranges in the corners increased, however, in relation to the strain ranges in the adjacent sections, as the number of load cycles became greater. With the exception of test specimen number B2 (where the minimum stress range in the corner was 60 to 70 % of the stress ranges in adjacent sections) the minimum stress ranges in the corner varied from 10 to 35 %, after 10 load cycles, to 20 to 45 %, after 10 000 cycles, in comparison with the adjacent sections.

3.5 Concluding Remarks

The fatigue tests did not show any major difference between frame corners without any reinforcement splices and corners where all reinforcement was spliced within the corner. The test series supports, together with the static tests, the idea that it should be permitted to splice the reinforcement in a frame corner. Fatigue failure in the reinforcement in a cross section adjacent to the frame corner determined the capacity in all of the tests, and no indication of anchorage failure was found.

Although none of the frame corners had haunches, the stress ranges in the tension reinforcement decreased considerably towards the middle of the frame corner. The construction joints were not found to be disadvantageous, and the fatigue failures never occurred in the same section as the construction joint. The presence of reinforcement bends had, as expected, a great influence on the fatigue strength of the reinforcement. A smaller bending radius had a negative influence on the fatigue strength.

The regulations regarding spalling of the side cover in the case of bent reinforcement (found in the Swedish codes BBK 79) do not seem to be applicable when more than one parallel reinforcement layer is bent with the same radius.

4 FRAME CORNERS IN SHELTERS FOR CIVIL DEFENCE

4.1 Test Specimens

The test series consisted of four specimens used to compare a new reinforcement detailing with conventional reinforcement in shelters for civil defence, see Plos /6/. The specimens had the same dimensions as those in the fatigue tests, and reinforcement detailing according to Figure 11. Two of the specimens had a large amount of reinforcement, approximately equal to the maximum allowed reinforcement ratio according to the Swedish Shelter Regulations, Räddningsverket /2/. This meant 6 ϕ16 as longitudinal reinforcement on the outside, as well as on the inside of the frame corner. The other two specimens had a longitudinal reinforcement of

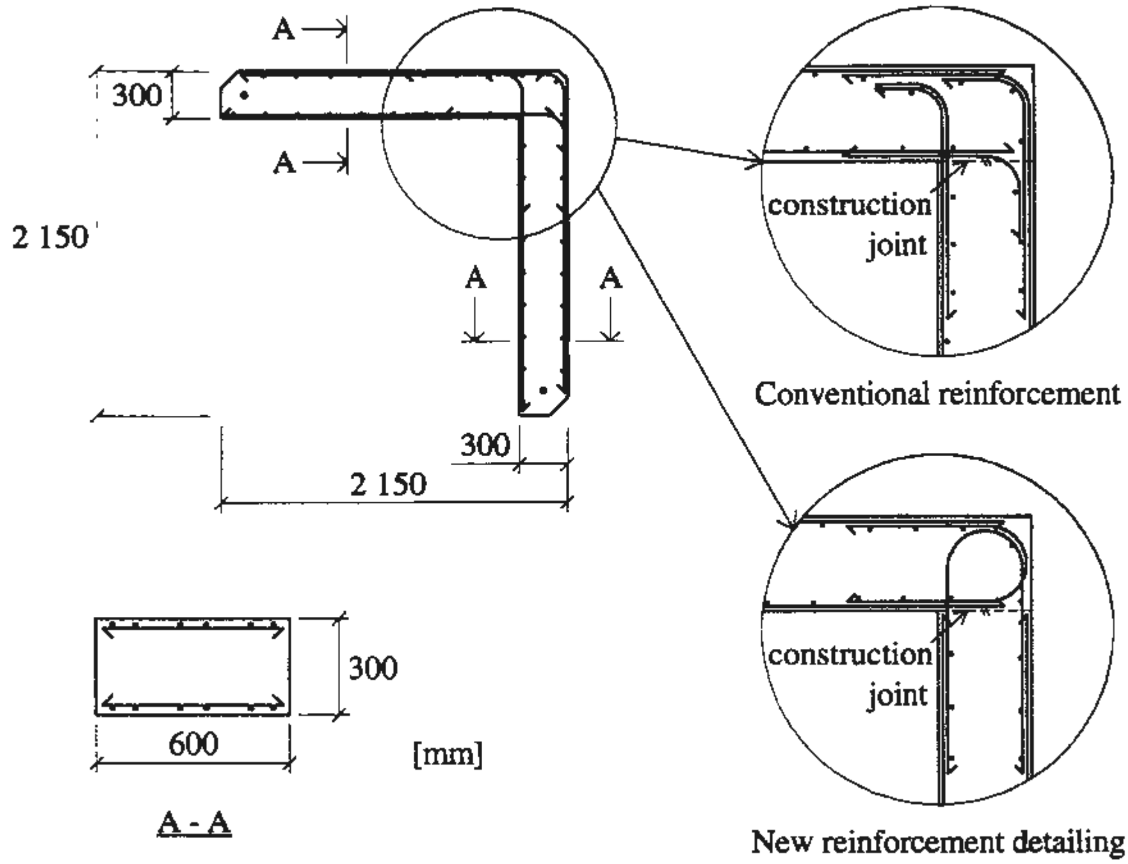

Fig. 11. Dimensions and detailing for specimens with reinforcement suitable for shelter design.

4 ϕ10 on both sides, approximately equal to the corresponding minimum reinforcement ratio.

For each reinforcement ratio, one specimen was provided with the new reinforcement detailing, while the other had conventional reinforcement according to the Swedish Shelter Regulations. The two specimens had the same detailing apart from the corner regions. Conventional reinforcement detailing means that the reinforcement was spliced in the horizontal parts of the frame beam, close to the frame corner, and that the reinforcement ratio was increased 25 % where it crossed the construction joint. With this reinforcement detailing, the extra reinforcement contributed to the capacity of both cross sections adjoining the corner. In the new reinforcement detailing, the reinforcement was completely spliced within the frame corner by reinforcement loops, formed as hairpins. The legs of the loops were then spliced to the main reinforcement in both the column and the beam. With this reinforcement detailing, the capacity was higher in the cross section immediately below the frame corner, than in the cross section immediately above.

The specimens were cast and tested in pairs that consisted of specimens with the same reinforcement ratio. Concrete from the same batch was used for both specimens of each pair, and they were cast in the same way as the fatigue test specimens, with the columns in vertical position and with a construction joint below the frame corner. The concrete quality chosen was K30 and the reinforcement quality was Ks40s, according to the Swedish code BBK 79.

4.2 Test Set-up

The specimens were tested in the same test rig as the fatigue tests, see Figure 6. The load was applied by a hydraulic jack and the magnitude of the load was measured by a load gauge. The total deflection along the loading line was measured by electronic displacement transducers. The concrete and reinforcement strength were determined according to Swedish standard /4/.

4.3 Test Performance

The load was applied in load steps of 5 kN for the specimens with the low reinforcement ratio, and 10 kN for those with the high reinforcement ratio. When large time dependent deformations started to occur, the magnitude of the load steps was decreased and the load was kept constant until the deformation increase was less than 0.01 mm/s.

4.4 Test Results

During the initial loading, the cracking was well distributed and symmetrical with respect to the frame corner. When yielding was reached in the reinforcement, the deformations were concentrated to the frame corner region. The specimens with the conventional reinforcement detailing exhibited plastic hinges on both sides of the frame corner, while the specimens with the new detailing showed only one plastic hinge above the corner, see Figures 12 and 13. This difference is due to the uneven capacities of the sections adjacent to the frame corner with the new

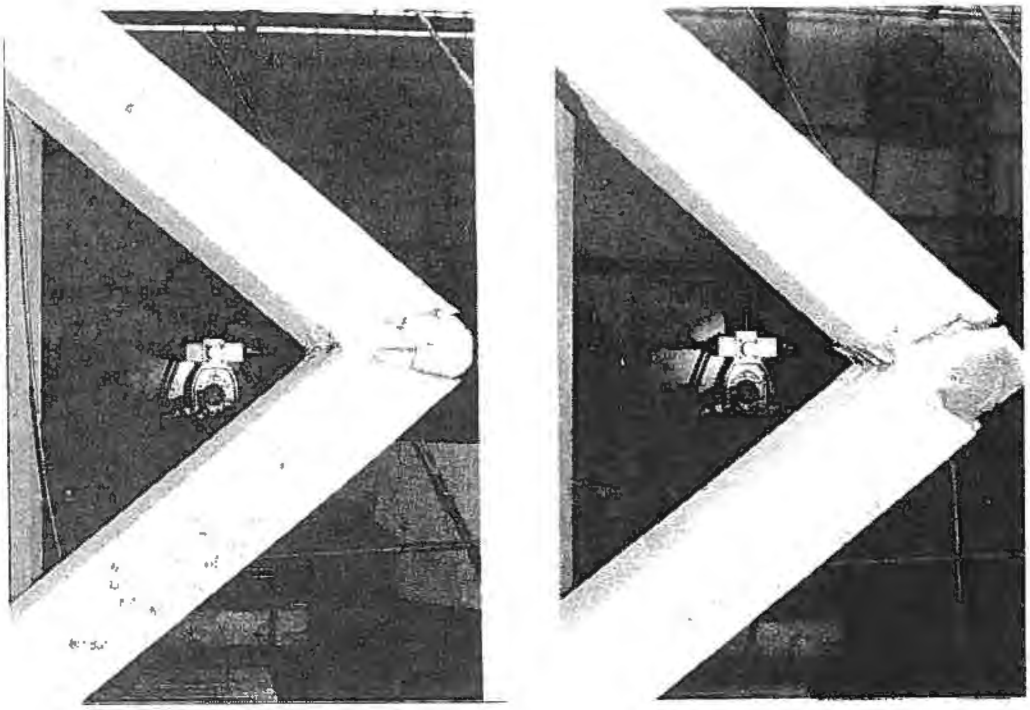

Fig. 12. Specimens with high reinforcement ratio at maximum deformation. The specimen to the left has conventional reinforcement and the specimen to the right has the new detailing.

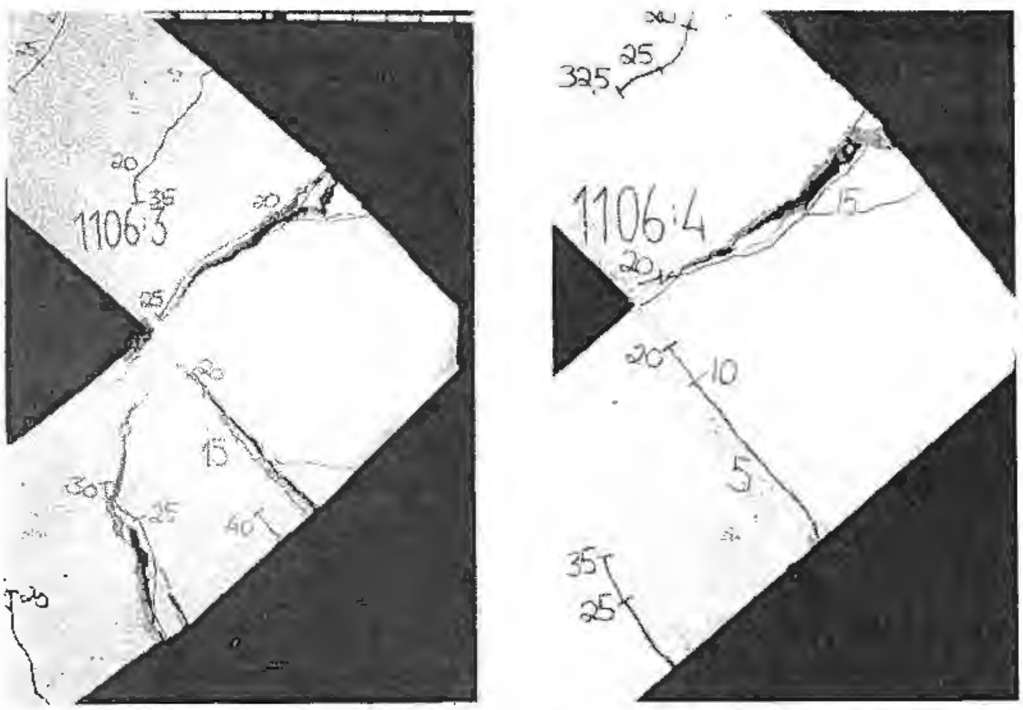

Fig. 13. Specimens with low reinforcement ratio at maximum deformations. The specimen to the left has conventional reinforcement and the specimen to the right has the new detailing.

detailing. A plastic hinge forms in the weakest section, and the yield hardening does not lead to a sufficient increase in the load to cause yielding in the section with the higher capacity.

As a consequence of the uneven strength in the sections adjacent to the corner, the specimens with conventional reinforcement detailing obtained a higher maximum load than the specimens with the new detailing, see Table 3. The load-displacement relationships are shown in Figure 14. Apart from the fourth specimen, the maximum displacements were governed by limitations in the geometry of the test rig. For specimen number RV 4, the final failure was reached when the reinforcement was torn off. The other tests were not performed to final collapse of the specimens. However, all of the specimens obtained considerable plastic rotation, and the loads decreased to a value notably less than that of the maximum load.

Table 3: Test results with reinforcement detailing for civil defence shelters.

Test specimen	Reinf. ratio $[10^{-3}]$	Reinf. detailing	Max. load [kN]	Deform. at max. load [mm]	Max. deform. [mm]	Rot. hinge	Rotational capacities (at % of max. load)		
							95 % [rad]	90 % [rad]	85 % [rad]
RV 1	7,5	conv.	175	61	165	double	0.057	0.066	0.079
RV 2	-"-	new	134	98	165	single	0.075	0.088	0.100
RV 3	1,9	conv.	44	45	239	double	0.029	0.080	0.163
RV 4	-"-	new	37	93	144	single	0.086	0.093	0.096

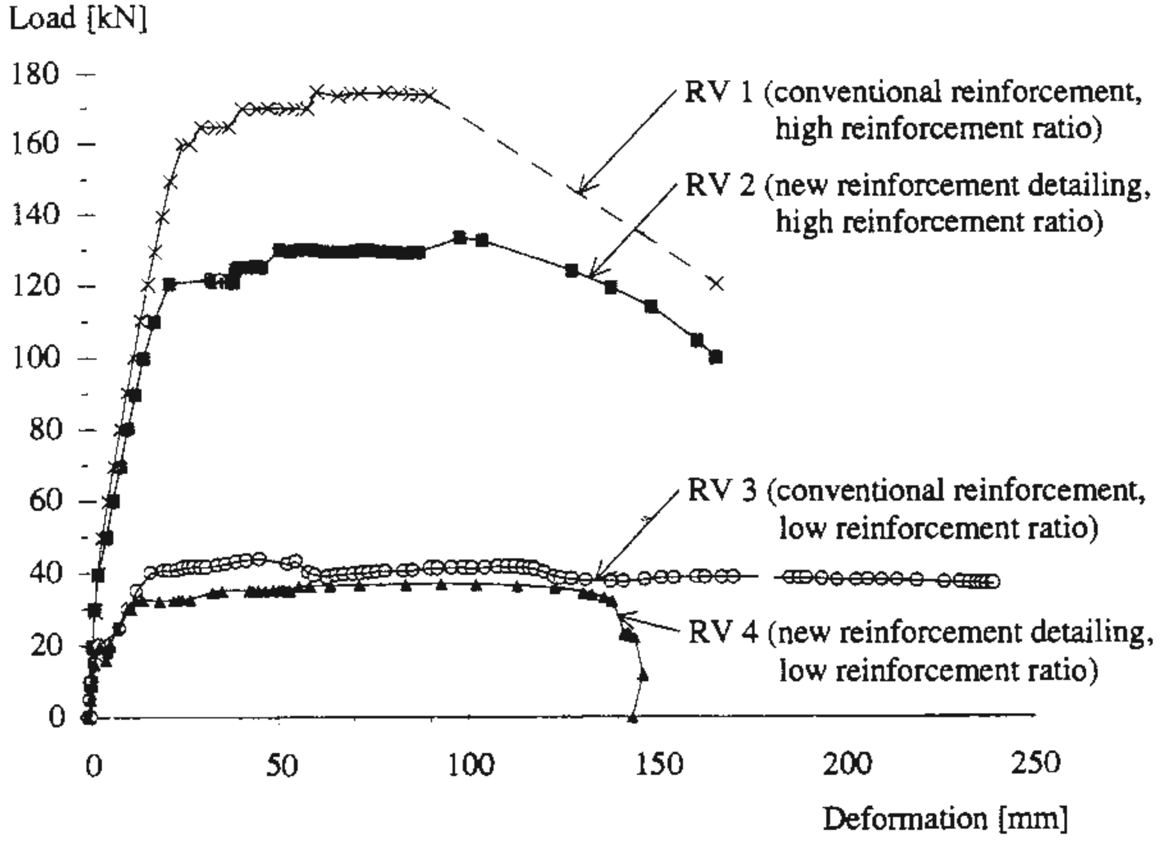

Fig. 14. Load-deformation curves from the tests with reinforcement detailing for shelters. The maximum deformation was determined by the geometry of the test set-up for all specimens except for RV 4.

4.5 Concluding Remarks

The test specimens with conventional reinforcement were found to have a somewhat higher capacity due to the increased amount of reinforcement required across construction joints, according to the Shelter Regulations. Since all reinforcement was spliced within the frame corner in the specimens with the new reinforcement detailing, the increase in the amount of reinforcement produced a higher capacity in only one of the cross sections adjoining the corner. The uneven strength of the adjoining sections also meant, for the new detailing, that a plastic hinge developed at only one side of the corner, which lead to a lower rotational capacity for the new reinforcement detailing that had low reinforcement ratio.

As a modification of the new reinforcement detailing it is therefore proposed that the adjoining cross sections is given the same capacity, so as to allow both sections to develop plastic hinges. The test results indicated that the new reinforcement detailing, after this modification, should perform as well as the conventional detailing, for the type of loading that was used in the test series.

5 CONCLUSIONS

5.1 General

The tests performed have not shown any essential difference so far between frame corners with unspliced reinforcement and those with all reinforcement spliced within the corner area. The capacities of the test specimens were determined, in all cases, by the capacity in one of the cross sections adjoining the frame corner. Anchorage failure along the lap lengths was not indicated in any case. The construction joints had no negative influence on the behaviour of the test specimens.

In the case of reinforcement detailing for slab frame bridges, the splicing consisted of an ordinary overlapping reinforcement splice with the lap length according to the concrete codes. The test results showed that the reinforcement stresses in the mid-section of the corner were considerably smaller than in the cross sections adjoining the frame corner, which indicates that the reinforcement was not spliced in the most strained section.

The influence of the bending radius on the fatigue strength of the reinforcement was obvious in the test results. The fatigue tests also showed shortcomings in the regulations in the Swedish concrete codes, concerning spalling of the side cover, in cases where two parallel reinforcement layers were bent with the same radius in a frame corner.

In the new reinforcement detailing for civil defence shelter design, the reinforcement forces were transmitted by loops which were placed next to each other for a very short length. Here, the forces were presumably transmitted by compression in the concrete core which was enclosed by the reinforcement loops. In the tests conducted here, the behaviour of the new reinforcement detailing was not quite as good as that of the conventional reinforcement detailing. However, this shortcomming will probably be eliminated by a modification of the new detailing which provides both cross sections adjacent to the frame corner with the same capacity.

Altogether, the test results support the idea of splicing the reinforcement within the corner area and serve well as a basis for further research, that aims to establish the behaviour of spliced frame corners.

4.2 Future Research

To facilitate the use of reinforcement splices within frame corners, it is essential to obtain a clear understanding of the mechanical behaviour in the corner region, as it pertains to different kinds of reinforcement detailing. Non-linear fracture mechanics and numerical modelling with the finite element model are believed to be most powerful tools for this purpose.

At present, frame corners with reinforcement detailing for slab frame bridges are being analysed within the project Fracture Mechanics for Concrete Bridges. In this project, the frame corner region is analysed with the non-linear finite element method to obtain a better understanding of the failure process.

The new reinforcement detailing proposed for civil defence shelters has to be modified, to give both cross sections, adjoining the frame corner, the same capacity. Non-linear fracture mechanics together with finite element analysis are also needed here, together with more tests, to gain a better understanding of the mechanism for frame corners with the modified new reinforcement detailing. The influence of shock wave loading also has to be examined to insure the performance of the frame corners in case of shelters.

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