Effect of Steel Corrosion on the Strength of Slab-Column Connections

Rahman, A. H.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20374506
Internal Report (National Research Council of Canada. Institute for Research in Construction), 1992-03

National Research Council Canada
Conseil national de recherches Canada

Institute for Research in Construction
Institut de recherche en construction

NRC·CNRC

Effect of Steel Corrosion on the Strength of Slab-Column Connections

by A.H. Rahman

Internal Report No. 626

Date of issue: March 1992

This is an internal report of the Institute for Research in Construction. Although not intended for general distribution, it may be cited as a reference in other publications.

Canada

CONTENTS

EXECUTIVE SUMMARY

Deterioration of reinforced concrete structures due to corrosion of steel reinforcement is an expensive problem in North America and many other parts of the world. Building slabs, particularly parking garage slabs, are among the worst affected structures.

Current knowledge about the effect of corrosion on the strength of slab-column connections is inadequate to make reliable structural evaluations of deteriorated slabs. Evaluations should be reliable enough not only to ensure safety but also to avoid unnecessarily expensive repairs.

This report deals with a preliminary experimental investigation of the effects of simulated steel corrosion on the structural behaviour of slab-column connections in flat plate construction. Both ordinary-reinforced and post-tensioned slabs were investigated. Twelve isolated slab-column specimens were tested to failure under punching load.

The effects of corrosion which were independently studied are loss of ordinary reinforcing steel, loss of tendons, loss of bond between reinforcement and concrete, and concrete delamination. The role of bond between reinforcement and concrete was additionally studied by including epoxy-coating of bars and bar size as test parameters. Boundary forces including membrane force present in real-life slabs were not simulated at the edge of the specimen slabs. However, the effect of a pre-applied membrane force of known magnitude on the punching behaviour was investigated.

The results indicate that significant loss of punching capacity could occur due to loss of reinforcement and tendons. However, to determine the effect of corrosion accurately and to verify if evaluations of the punching capacity using current design code formulae are safe, further tests that include membrane forces are necessary.

1. INTRODUCTION

Many concrete structures in North America are deteriorating badly, mainly from corrosion of reinforcing or prestressing steel. Concrete parking garages are prime examples; the cost of repairing these garages in North America is estimated at billions of dollars. To ensure safety in these deteriorated garages as well as to avoid unnecessary repair expenses, it is important to reliably evaluate the structural effects of deterioration. Current knowledge about the effect of reinforcement corrosion on the strength of slab-column connections is inadequate to make reliable evaluations of deteriorated slabs.

Slab-column connection failure, also commonly known as punching failure, is potentially catastrophic as it can occur without much warning and is progressive. Flat plate slabs found in many parking garages are particularly vulnerable. It is therefore important to determine the effect of reinforcement corrosion on the punching capacity of such slabs.

This report deals with a preliminary investigation of the effect of reinforcement corrosion on the punching capacity of flat plates.

2. PROBLEM DESCRIPTION

In ordinary reinforced concrete slabs, corrosion reduces the effectiveness of reinforcement mainly in two ways. Firstly, corrosion directly reduces the cross-sectional area of bars by converting parts of the bars into rust. Secondly, it reduces the bond between steel and concrete by causing the concrete to crack or delaminate. In prestressed concrete slabs, even the slightest corrosion can precipitate failure of the tendons.

A review of published research on the punching behaviour of slabs shows that the punching capacity depends significantly on the slab's tensile reinforcement ratio. Therefore, corrosion of that reinforcement should affect the punching capacity. But the punching capacity formulae in the Canadian and American design codes do not include reinforcing steel as a parameter. This tends to give the false impression to many practicing engineers that punching capacity remains unaffected by the corrosion of steel. Thus use of these formulae may lead to unsafe evaluation of the punching capacity of deteriorated slabs. Many European design codes, including the CEB-FIP Model Code 1990 [1], include the tensile reinforcement ratio as a parameter of punching capacity.

Review of research on failure behaviour of slabs also reveals that slab failures can be, at worst, in primary shear that occurs suddenly and, at best, in secondary shear after only limited yielding. Thus a slab failure without much warning due to corrosion of its tensile reinforcement is possible. Documented evidence exists of at least one such failure–the collapse of a garage in Minneapolis in 1984 [2]. The effect of corrosion of reinforcement on the punching behaviour of slabs has not been evaluated to date.

3. RESEARCH SIGNIFICANCE

Evaluation of the effect of reinforcement corrosion on the punching behaviour is important to prevent unexpected punching failures in deteriorated slabs. Detailed knowledge of the effect is essential to make rational decisions about the need and urgency of repairs of such slabs.

4. OBJECTIVE AND SCOPE

The principal objective of this study is to experimentally determine the effect of corrosion of ordinary reinforcement and unbonded prestressed tendons on the punching capacity of slabs. The effects of corrosion were simulated in the test specimens. Simulation was preferred to actual corrosion since the desired effects of corrosion could be reproduced more definitively, uniformly and quickly. The effects simulated are loss of area of reinforcing steel and tendons, loss of bond of reinforcing steel, and concrete delamination. Since loss of bond appeared to be a significant effect of corrosion, the role of bond in determining the punching capacity was additionally studied by including epoxy-coating of reinforcing steel and bar size as test parameters. Epoxy-coating of bars is known to reduce their bond with concrete, and using larger size bars while keeping steel ratio the same increases the bond stress.

This preliminary study was limited to flat plate slabs as these slabs are most vulnerable to punching failure. Although punching failure directly under wheel loads is possible in parking garages, punching failure at the columns only was dealt with in this study since it is potentially more catastrophic. Only the case of shear with balanced moments at the column, a condition typical at interior columns, was dealt with.

The specimens tested were isolated slab-column connections. No boundary restraints or forces were applied to simulate membrane forces present in an actual slab. However, the effect of a pre-applied membrane force of known magnitude was investigated.

Thus the test parameters are the following:

- loss of reinforcement and tendons due to (simulated) corrosion
- loss of reinforcement bond due to (simulated) corrosion
- concrete delamination due to (simulated) corrosion
- epoxy-coated bars
- bar size
- membrane force

The objective was to obtain a preliminary estimate of the effects of the test parameters by a comparative evaluation of the results of a limited number of tests.

5. EXPERIMENTAL PROGRAMME

5.1 Specimen Details

Twelve full-scale specimens were constructed of which eight represent ordinary reinforced construction and the remaining four, unbonded post-tensioned construction. An interior panel of each type of slabs was designed assuming 7.5m x 7.5m panels and 300 mm square columns. As shown in Fig. 1, the octagon-shaped specimen represents a part of the slab around a column of the designed slabs. The periphery of the specimen slab is circumscribed by a circle of 1390 mm radius about the centre of the column. This radius was chosen to minimise the error arising from not simulating any bending moment at the specimen periphery during testing. Geometric details of the specimens are shown in Fig. 2.

5.2 Materials

Concrete was delivered to the laboratory by a mixing truck. The specified 28-day compressive strength was 30 MPa and the slump 60 to 75 mm. The specimens were cast in three batches of four per batch. The slump was measured at the beginning of casting each batch and water added as necessary to bring the slump within the specified limits.

Five standard cylinders were cast for each batch, the first one before casting any specimen and the remaining alternately with the specimens. Like the specimens, the cylinders were moist-cured for about 72 hours starting from the day after casting and then air-cured until they were tested for compressive strength. The average cylinder strengths of the three batches are 29.1, 29.4 and 28.8 MPa. The cylinders were tested at an age varying between 110 and 150 days and the specimens between 100 and 160 days. In these ranges of age, the effect of age at testing on the strength of concrete is not significant. An average concrete strength of 29 MPa was considered reasonably representative of all specimens.

Two sizes of bars, #10M and #15M, were used to construct the slabs. Two types of #10M bars were used: uncoated and epoxy-coated. To ensure that the epoxy-coated and uncoated bars have the same yield strength, they were specified to be from the same heat. Tests of three samples from each type indicated average yield strengths of the uncoated and epoxy-coated bars as 494 and 490 MPa, respectively. Only uncoated #15M bars were used with an average yield strength of 445 MPa.

Two sizes of unbonded tendons, 15 and 13 mm, were used for the post-tensioned specimens. The average breaking strengths of these tendons are 1960 and 1925 MPa, respectively.

5.3 Specimen Construction

Wooden forms were constructed to cast the column stub and slab monolithically in one operation. The reinforcement mats were accurately positioned and supported to provide a concrete cover of 20 ± 1 mm. In the post-tensioned specimens, the tendons were placed with a hogging profile to duplicate the profile in actual construction. In addition to the tendons, ordinary steel reinforcement was provided with #10M bars as specified by the design code [3]. Some details of the post-tensioned specimen construction are given in Fig. 3.

5.4 Simulation of the Effects of Corrosion

Corrosion directly reduces the cross-sectional area of bars by converting parts of them into rust. It reduces the bond between the bars and concrete as the intervening layer of rust is weak in transferring the bond stress. Corrosion also causes delamination of concrete at the plane of reinforcement where reinforcing bars are relatively closely spaced such as at columns.

The reduction in area of ordinary reinforcing bars was simulated by providing fewer bars than required by design. In the post-tensioned specimens, broken tendons due to corrosion were simulated by empty sheathes. The loss of bond was simulated by wrapping the bars with a plastic adhesive tape. And the delamination of concrete was simulated by placing a polyethylene sheet between the upper and lower bars of the top reinforcing mesh.

The simulated loss of bond and delamination were limited to an area shown shaded in Fig. 2. To ensure adequate anchorage, the ends of the plastic-wrapped bars were bent downwards at the slab edge. The effects of loss of steel area, loss of bond and delamination were evaluated independently in the ordinary reinforced specimens. The combined effect of loss of bond and broken tendons was evaluated in the post-tensioned specimens.

5.5 Post-Tensioning

The tendons were post-tensioned between 95 tand 100 days from the date of casting the specimens. Two hydraulic jacks were used to apply the post-tensioning in a symmetrical manner with respect to the centre lines of the specimens. To achieve the desirable amount of force, the tendons were overtensioned by an estimated amount to account for the loss due to seating of the anchors. Net force remaining in any tendon was calculated from its net elongation remaining after the anchors were seated. The tendon forces were not adjusted for the loss arising from tensioning of the remaining tendons or from creep of concrete that may have occurred between the times of post-tensioning and testing.

5.6 Specimen Schedule

Table 1 shows the key information for the eight specimens representing ordinary reinforced concrete construction. The membrane forces in Specimen No. 4 were applied at the middle plane of the slab by two post-tensioned tendons in each direction. The key information of the post-tensioned specimens are given in Table 2. In the Specimen No. 12, the ordinary reinforcing top bars were wrapped with plastic tape in addition to simulating a 50% loss of tendons.

All specimens were provided with a bottom reinforcement of #10M @ 600 mm in each principal direction with one bar in each direction passing through the column.

5.7 Instrumentation and Test Set-Up

The upper central bar of the top reinforcing mesh of all specimens was fitted with 5 electrical resistance strain gauges located at 150, 300, 450, 600 and 750 mm away from the centre of the column. A sixth strain gauge was bonded to this bar in each of the specimens no. 5 and 6 at 900 mm from the centre, i.e. just outside the area in which loss of bond and delamination were simulated. Additionally, the lower central bar of the top reinforcing mesh of the specimen nos. 1, 2 and 3 were fitted with 5 strain gauges to monitor reinforcement in the other principal direction.

A cross section of the test set-up is shown in Fig. 4. The specimen is loaded concentrically upward at the column with two 1000 kN hydraulic jacks while downward reactions are applied at its eight corners by a rigid frame anchored to a strong floor. As shown in Fig. 4, the reaction posts have rocker-shaped bottom faces and rest on 20 mm thick steel plates bedded in hydrostone. Deflection measurements were taken by four hybrid track rectilinear potentiometers (HTRP) arranged as shown in the inset of Fig. 4. This facilitated measurements of absolute column displacement as well as relative displacement between the slab and the column after punching has occurred.

Load was calculated from the oil pressure measured in the hydraulic supply line and from known piston area of the jacks. A data acquisition system was used to read the strain gauges, the HTRPs and the pressure transducer every ten seconds during the tests. A remotely controlled camera was mounted above the specimen to take snapshots of the slab at preset intervals of load.

5.8 Test Procedure

Before testing, the top surface of the slab was limewashed to facilitate detection of cracks. After the specimen was concentrically positioned in the frame, the reaction plates were placed on a layer of freshly mixed hydrostone. The specimen was slowly lifted by the loading jacks while the hydrostone was still plastic until it began to be squeezed out from under all the plates. The hydrostone was allowed to set in this position. This procedure ensured an even distribution of reactions to the applied load during testing.

The oil flow to the hydraulic jacks was manually controlled to apply the load at a rate as steady as possible. Plots of load with time showed that the loading rate varied between 25 and 60 kN per minute in the same test and from test to test. This variation is not considered to influence the results significantly.

6. TEST RESULTS AND OBSERVATIONS

6.1 General

A summary of the test results is given in Table 3. Along with the ultimate punching capacities obtained from the tests, the capacities computed by using the design code formulae [3] are given. Note that while the capacities given by the code are one and the same for the ordinary-reinforced slabs, they are different for the post-tensioned slabs. This is because the code formula for the ordinary-reinforced slabs is independent of the test variables but that for the post-tensioned slabs depends on the amount of prestress. It can be seen that except for the cases where there is a 50% reinforcement loss or a 100% tendon loss, the capacities given by the code are quite conservative.

All specimens failed in punching mode indicated by an abrupt drop in the load as the ultimate load was reached. The column deflection at failure and slab-column separation after failure are good indicators of the failure mode. In general, a higher column deflection at failure indicates a more ductile failure, and a higher slab-column separation after failure indicates a more pronounced punching.

The effects of the parameters of study on the punching capacity, column deflection at failure and slab-column separation after failure are summarised in Table 4. Observations about the effects of each individual parameter are given below.

6.2 Loss of Reinforcement

It can be seen from Table 4 that for a 50% loss of reinforcement, the punching capacity decreased by 34% for the slabs reinforced with uncoated bars. A similar reduction of 35% is observed for the slabs reinforced with epoxy-coated bars. Most test results available in the literature are for slabs with tensile reinforcement ratio, ρ, greater than .01, which indicate a smaller influence of reinforcment on the punching capcity [4]. A research carried out by Kuang and Morley [5] has just been published. The ρ values of their slabs are closer to those of the present tests although slab thickness and restraint conditions are different. For a 70% reduction in the reinforcement area of slabs with edge beams, they observed a decrease in the punching capacity by about 34% for a 40 mm thick slab and 40%for a 60 mm slab.

Table 4 also shows that column deflections increased and slab-column separation after failure decreased by large proportions due to the loss of reinforcement. This means that a 50% loss of reinforcement significantly reduces the brittleness of punching failure. In other words, a slab losing reinforcement due to corrosion is likely to show significant increases in deflection before eventually failing by punching. The load-deflection diagrams of Fig. 5 illustrate this observation graphically.

6.3 Loss of Tendons

The reference specimen for this parameter was the first to be tested for this investigation. It was unloaded after reaching about 500 kN of applied load because a problem in the load measurement system was suspected. After verifying the measurements, the specimen was reloaded to failure. But failure occurred prematurely by crushing of concrete at the tendon anchorage. This was not expected as the computed maximum compressive stress in concrete at the anchorage due to the combined forces applied by the tendons was about 17 MPa, well below the concrete compressive strength of 29 MPa.

While the load to cause a punching failure of the reference specimen would be certainly higher, it is difficult to estimate that load. Therefore, comparison was based on the capacity of the reference specimen as obtained from the test. As shown in Table 4, the decreases in punching capacity thus calculated are 26% and 55% for losses of tendons equal to 50% and 100%, respectively. It should also be noted that the 50% loss of tendons is nominal only; based on tendon force, the loss is about 45% in one direction and 34% in the other (see Table 2).

The load-deflection behaviours of the specimens with 50% and 100% lost tendons are compared with those of the reference specimen in Fig. 6. Both the first and final loading curves of the reference specimen are shown. As expected, the slabs failed in an increasingly ductile manner with the loss of tendons. However, Table 4 shows that the reduction in post-punching slab-column separation due to loss of tendons is not as high as that for loss of reinforcement. In other words, post-tensioned specimens with lost tendons still fail pronouncedly by punching.

6.4 Loss of Reinforcement Bond

The loss of bond was simulated by wrapping the reinforcing bars with adhesive plastic tape. Table 4 shows that for both ordinary-reinforced and post-tensioned slabs, there is a 9%

increase in the punching capacity and a 32 to 34 percent increase in column deflection due to loss of bond of the reinforcement. The load-deflection behaviours are compared in Fig. 7.

The increase in column deflection was expected because unbonded bars undergo higher elongation under the same load than well-bonded bars. Fig. 7 shows that specimens with taped reinforcement start to deflect more at an early stage of loading. But since loss of bond also increases cracking and crack depth, a decrease in punching capacity was expected.

Table 4 also shows that the slab-column separation after failure increased by 48% in reinforced specimens but decreased by 92% in post-tensioned specimens. Further tests are required to verify and explain this apparently anomalous behaviour.

6.5 Concrete Delamination

Delamination of concrete in the plane of the corroding reinforcing mesh was simulated by placing a polyethylene sheet between the upper and lower layers of the top reinforcing mesh. Table 4 shows that while the column deflection increased by about 14%, the punching capacity remained unchanged. Again, a decrease in punching capacity was expected as delamination of concrete reduces reinforcement bond. Fig. 7 shows that the specimen with delamination started to deflect more at an early stage of loading. Also, the slab-column separation increased by a mere 8%.

6.6 Epoxy Coating

Epoxy-coated bars are known to have a weaker bond to concrete and thus it was expected to decrease punching capacity and increase column deflection at ultimate load. But Table 4 shows that the punching capacity remained essentially unaffected and the column deflection increased only slightly when epoxy-coated bars were used. Also, it is seen from Fig. 5 that the load-deflection behaviours of specimens with uncoated and epoxy-coated bars are almost identical.

6.7 Bar Size

Table 4 shows that due to using #15M size bars instead of #10M but keeping steel ratio the same, punching capacity decreased by 6%. However, apart from increasing bond stress, the larger size bars decreases the average effective depth by about 3% since the same amount of concrete cover of 20 mm was maintained. Also, the #15M bars have a low yield strength of 445 MPa compared to 490 MPa of the #10M bars. These two factors together are perhaps sufficient to cause the observed decrease in punching capacity. Thus the effect of increased bond stress on the punching capacity is at best insignificant.

As seen from Fig. 8, the specimen with #15M bars behaves in a more ductile manner than that with #10M bars. This is at least partially explained by the lower yield strength of the #15M bars. However, as shown in Table 4, the larger size bars increase the post-punching slab-column separation by 74% indicating that the punching is still pronounced.

6.8 Membrane Force

A membrane force of about 290 kN in each direction was applied to the slab, which amounts to an average compressive stress of about 0.6 MPa at the column face. Table 4 shows that this membrane force increased the punching capacity by 16%. The 13% decrease in column deflection and 21% increase in slab-column separation indicate that punching failure is more brittle and pronounced due to the membrane force. The effect of membrane force on the load-deflection behaviour is shown in Fig. 8.

7. DISCUSSION

In the case of ordinary-reinforced slabs, it was observed that the loss of punching capacity due to loss of reinforcing steel area is significant. The loss of punching capcity is large enough to make the usually conservative code estimate unsafe for a slab that has lost 50% of its steel. But the failure was observed to be more ductile and the punching less pronounced. Together, these observations indicate that while a slab with corroded steel will fail by punching at a lower load than its original capacity, it will also perhaps show warning signs such as higher deflection and increased cracking before failing.

However, the tests did not include membrane forces that develop in an actual slab. Other investigators [4,5] have found that membrane forces such as from lateral restraint can significantly increase punching capacity. This investigation confirms that finding; but additionally, it indicates that membrane force increases the brittleness of punching failure. Membrane forces are present in the original as well as the deteriorated slab and are likely to enhance the punching capacity of both by the same magnitude. Thus, because of the loss of steel area, a deteriorated real-life slab is likely to fail at a load lower than its original capacity, but not necessarily lower than the code capacity, and in a more brittle manner than indicated by the present tests.

In the case of post-tensioned slabs, the loss of punching capcity due to loss of tendons was observed to be even more significant than in the case of ordinary-reinforced slabs. However, the code estimate of the punching capacity is still conservative when 50% tendons are broken. When all the tendons are broken, the code estimate becomes unsafe. But if membrane forces are considered, the code estimate may not necessarily be unsafe for the slab with all tendons broken.

Therefore, to determine the actual effect of the loss of reinforcement and tendons on the punching capacity and mode of failure, either load tests on actual slabs in the field should be carried out or the boundary forces should be simulated in testing isolated slab-column specimens.

In this investigation, it has been consistently observed from several tests that punching capacity does not decrease, rather increases slightly, due to loss of bond between reinforcement and concrete. This is somewhat puzzling since, as noted before, loss of bond should increase the width and depth of cracks and thus decrease the area of concrete resisting shear. It has to be noted however that the loss of bond was simulated only in the immediate vicinity of the column, within a boundary only 750 mm from the column face, and adequate anchorage of the bars was provided beyond that boundary. In reality, corrosion can occur further along the bars from the column. Further study is required to explain the observed behaviour. The strain gauge data acquired from the tests should be analysed in search of an explanation.

8. CONCLUDING REMARKS

To determine the effect of corrosion on the strength of slab-column connections, a limited number of tests were carried out in this investigation on isolated slab-column specimens in which the boundary forces were not simulated. The following are the most significant findings:

1. Loss of reinforcement and tendons significantly reduces the punching capacity of flat plates.
2. Significant enhancement of punching capacity can occur due to membrane forces in the slab. These forces must be included to realistically determine the effect of reinforcement corrosion on the punching capacity and thus to verify if code provided formulae can assure safe evaluation of the punching capcity of deteriorated slabs.
3. Loss of reinforcement bond with concrete does not appear to affect the punching capacity of flat plates.

Further research is required to reliably evaluate punching capacities of deteriorated slabs. Future tests should be carried out on either actual slabs in the field or on isolated slab-column specimens in which boundary forces are simulated. Also, actual corrosion under controlled conditions should be induced in the slabs of such tests for more realistic results.

9. ACKNOWLEDGMENT

Partial funding for this investigation was received from Public Works Canada which is gratefully acknowledged. The laboratory tests were carried out and the results analysed with the indispensable help of P. Daly (retired), D. Guenter, C. Kingsley, A. Laberge, and R. Pilon.

10. REFERENCES

[1] **Comité Euro-International du Béton,** *CEB-FIP Model Code 1990,* CEB Bulletin D'Information No. 195 and 196, March 1990.

[2] **Engineering News Record,** *Salt flattens old garage*, McGraw-Hill Inc., June 14, 1984.

[3] **Canadian Standards Association,** *Design of Concrete Structures for Buildings, A national Standard of Canada,* CAN3-A23.3-M84, 1984.

[4] **Regan, P.E. and Braestrup, M.W.,** *Punching Shear in Reinforced Concrete–A State-of-the Art Report,* CEB Bulletin D'Information No. 168, June 1985.

[5] **Kuang, J.S. and Morley, C.T.,** *Punching Shear Behaviour of Restrained Reinforced Concrete Slabs,* ACI Structural Journal, Vol. 89, No. 1, pp13-19, January-February, 1992.

List of symbols

h	=	Thickness of slab, mm
P_{test}	=	Ultimate punching load from test, kN
P_{code}	=	Punching capacity given by code, kN
s	=	Spacing of reinforcing bars, mm
Δ	=	Absolute deflection of column, mm
δ	=	Slab-column separation after punching, mm
ρ	=	Reinforcement ratio

Table 1 Schedule of reinforced specimens

Spec. No.	Top reinforcement					h, mm	Parameter
	Type	Size	s, mm	ρ	Condition		
1	Uncoated	#10M	100	.006	Intact	200	Reference
2	Uncoated	#15M	200	.006	Intact	200	Bar size
3	Uncoated	#10M	200	.003	Intact	200	Loss of steel – uncoated
4[1]	Uncoated	#10M	100	.006	Intact	200	Membrane force
5	Uncoated	#10M	100	.006	Tape-wrapped[2]	200	Loss of bond
6	Uncoated	#10M	100	.006	Poly. sheet[3]	200	Concrete delamination
7	Epoxy	#10M	100	.006	Intact	200	Epoxy coating – reference
8	Epoxy	#10M	200	.003	Intact	200	loss of steel – coated

[1]This specimen was subjected to membrane forces of 292 kN in one direction and 291 kN in the other by two post-tensioned tendons of straight profile in each direction.

[2]All top bars were wrapped with a plastic adhesive tape.

[3]A polyethylene sheet was placed between the upper and lower bars of the top reinforcing mesh.

Table 2 Schedule of post-tensioned specimens

Spec No.	No. and size of tendons	Tendon force, kN	h, mm	Parameter
9	NS 8-15 mm EW 3-13 mm	NS 1155 EW 311	165	Reference
10	NS 6-13 mm and 2 empty sheaths EW 2-13 mm and 1 empty sheath	NS 639 EW 205	165	50% loss of tendons
11	NS 8 empty sheaths EW 3 empty sheaths	NS 0 EW 0	165	100% loss of tendons
12	NS 4-15 mm and 4 empty sheaths EW 2-13 mm and 1 empty sheath	NS 600 EW 213	165	50% loss of tendons plus loss of bond in renf.

Table 3 Test Results

Specimen No.	P_{test}, kN	P_{code}, kN	Δ, mm	δ, mm	Parameter
			Reinforced specimens		
1	547	403	19.0	15.9	Reference for specimens 2 thru' 7
2	514	403	25.9	27.7	Bar size
3	361	403	43.0	2.9	50% reinf. loss – uncoated
4	634	403	16.55	19.25	Membrane force
5	596	403	25.00	23.5	Loss of bond
6	549	403	21.70	17.25	Delamination
7	556	403	19.95	18.65	Epoxy coating (also ref. for 8)
8	359	403	50.00	1.25	50% reinf. loss – coated
			Post-tensioned specimens		
9	564[1]	458	18.75	17.85	Reference for specimens 10 and 11
10	416	397	22.70	10.05	50% tendon loss (also ref. for 12)
11	255	295	30.25	12.95	100% tendon loss
12	453	394	30.45	0.91	50% tendon loss plus loss of bond in non-tensioned reinf.

[1]Failure occurred prematurely by crushing of concrete at the tendon anchorages.

Table 4 Effect of various parameters on punching behaviour

Parameter		Percent change[1] in		
		Punching capacity	Column deflection	Slab-column separation
50% loss of reinforcement	uncoated	-34	+126	-82
	coated	-35	+151	-93
Loss of tendons[2]	50%	-26	+21	-44
	100%	-55	+61	-28
Loss of reinforcement bond	reinforced	+9	+32	+48
	post-tensioned	+9	+34	-91
Concrete delamination		0	+14	+8
Epoxy coating	100% steel	+2	+5	+17
	50% steel	0	+8	-53
Bar size		-6	+36	+74
Membrane force		+16	-13	+21

[1]A +ve sign indicates increase and a -ve sign decrease. Values of the punching capacity, column deflection and slab-column separation, including the reference values, for calculating the percentages are given in Table 3.

[2]The reference specimen failed prematurely at tendon anchorage.

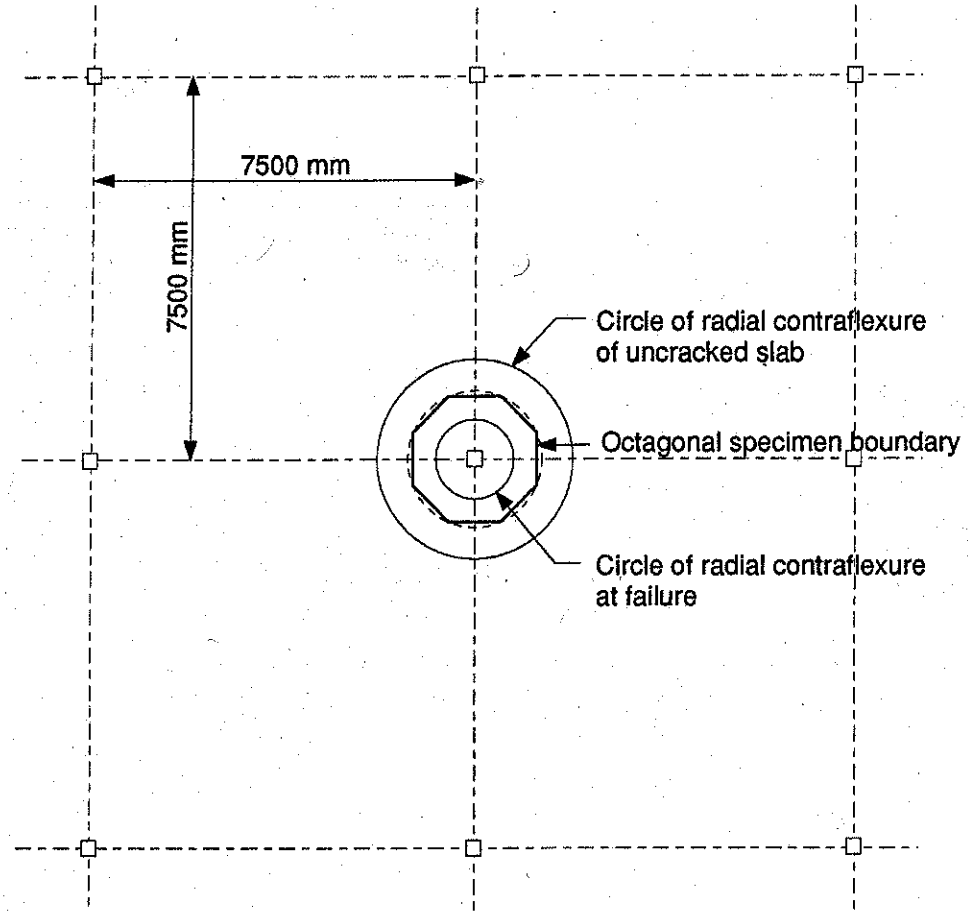
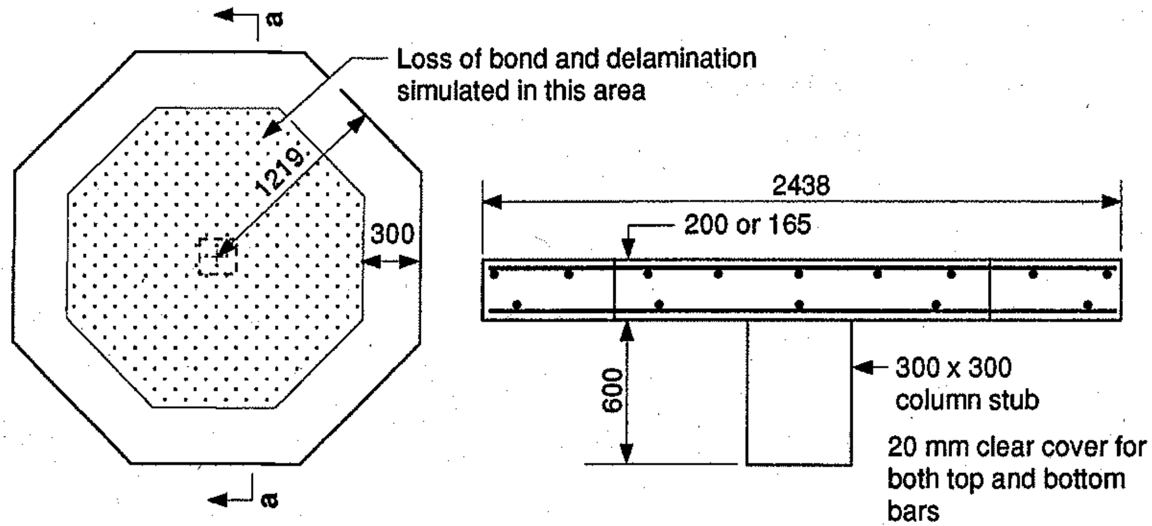


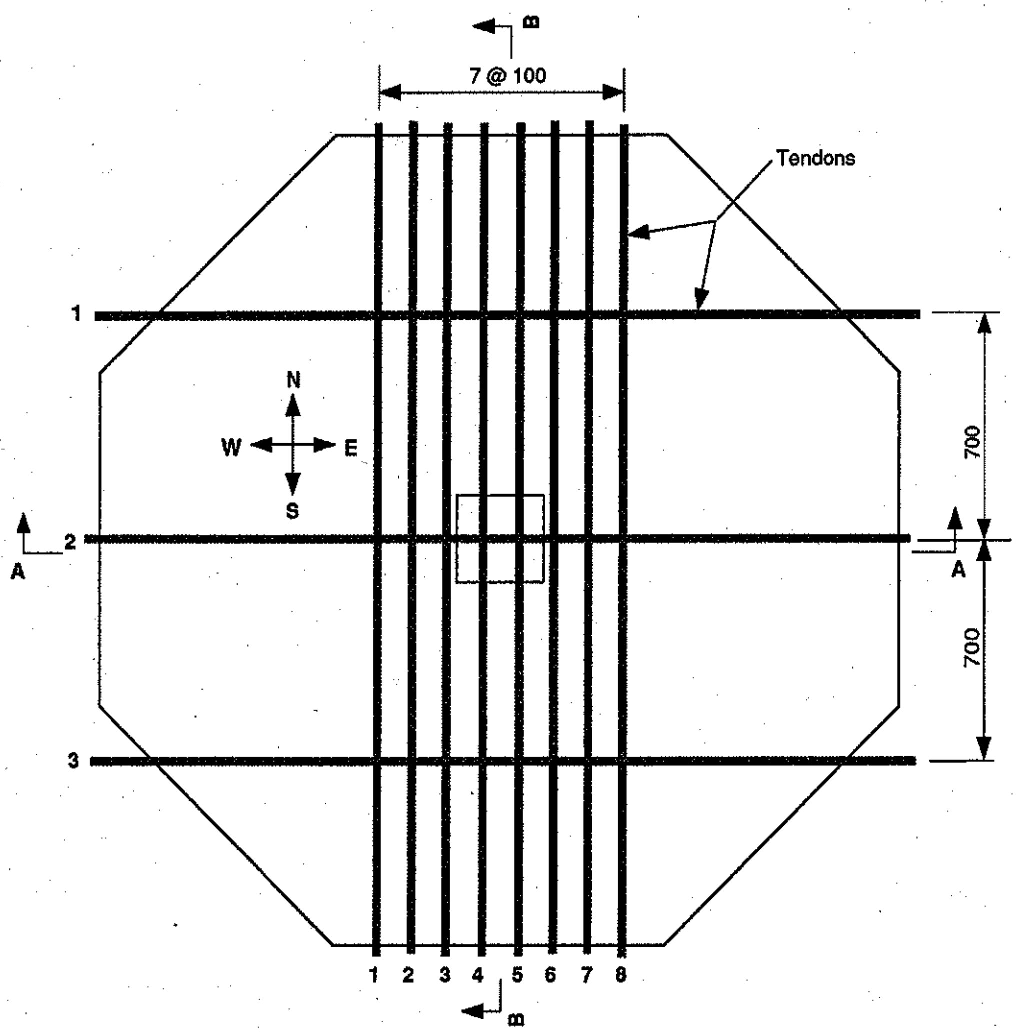
Fig. 1 Part plan of slab showing specimen location



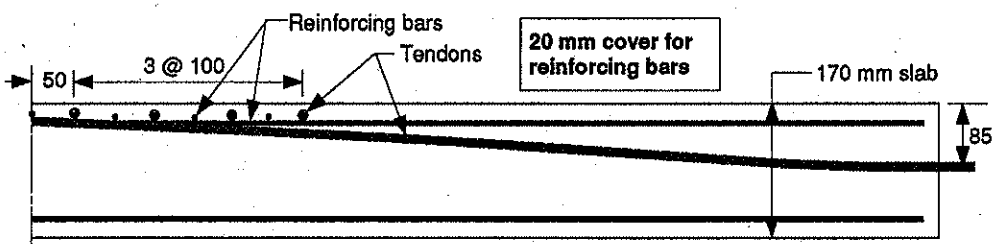
(a) Plan

(b) Section on a-a

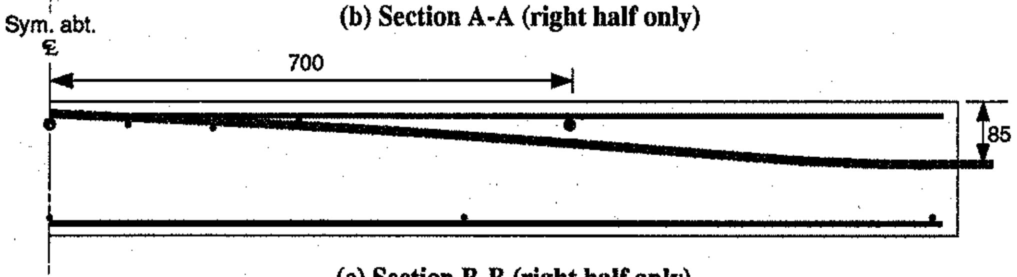
Fig. 2 Construction details of specimen



(a) Plan of slab showing prestressing scheme



(b) Section A-A (right half only)



(c) Section B-B (right half only)

Fig. 3 Construction details of post-tensioned specimens

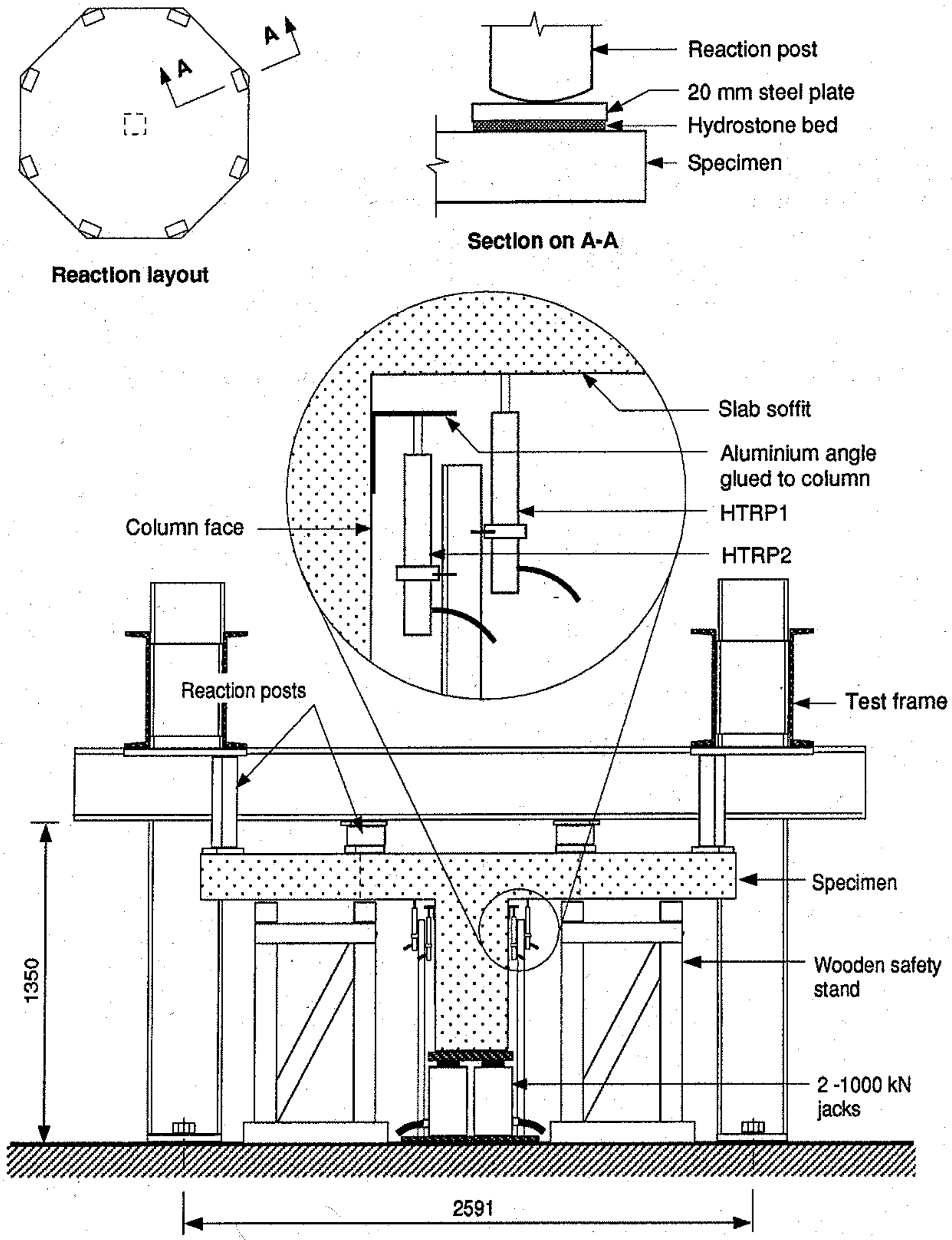


Fig. 4 Details of test set-up

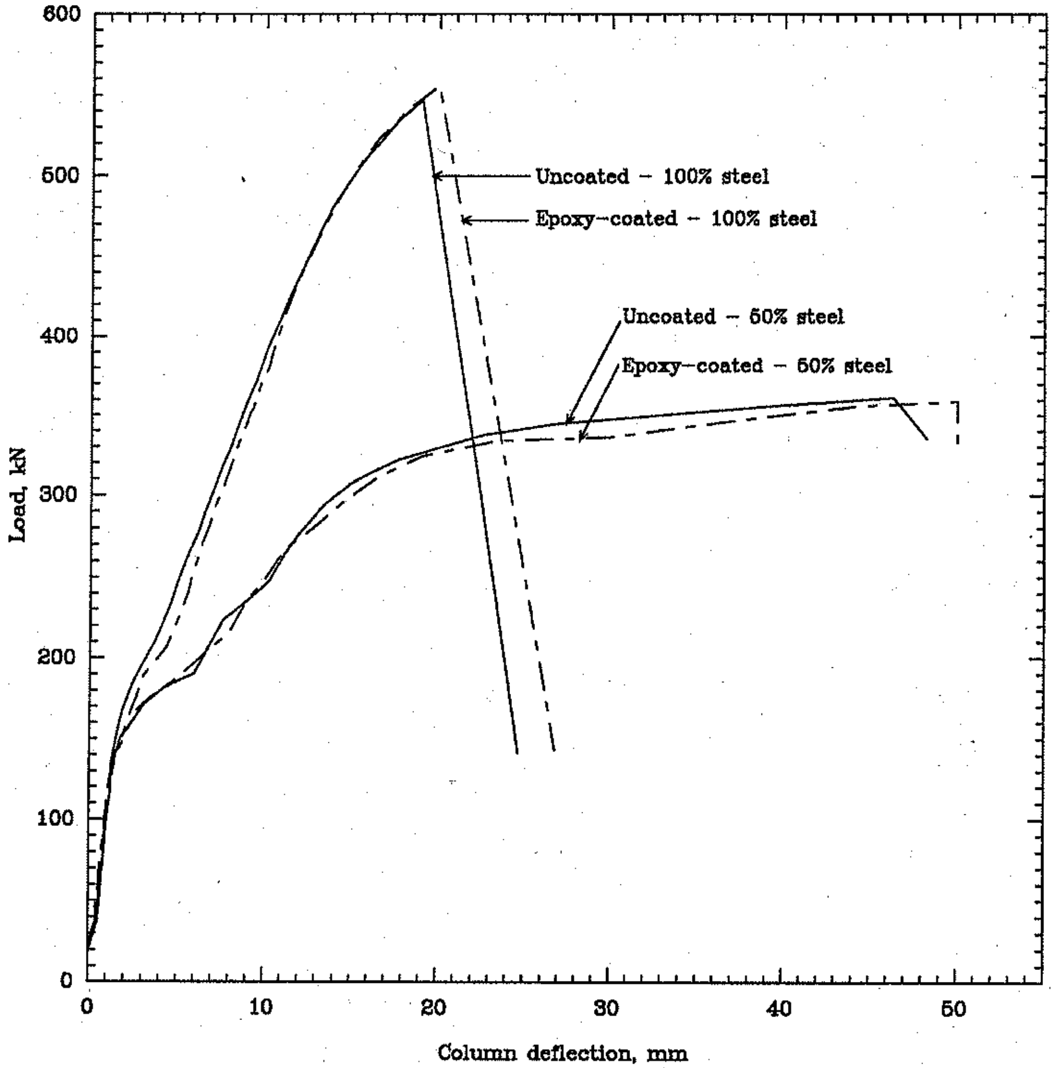


Fig. 5 Effect of 50% loss of reinforcement on load–deflection behaviour

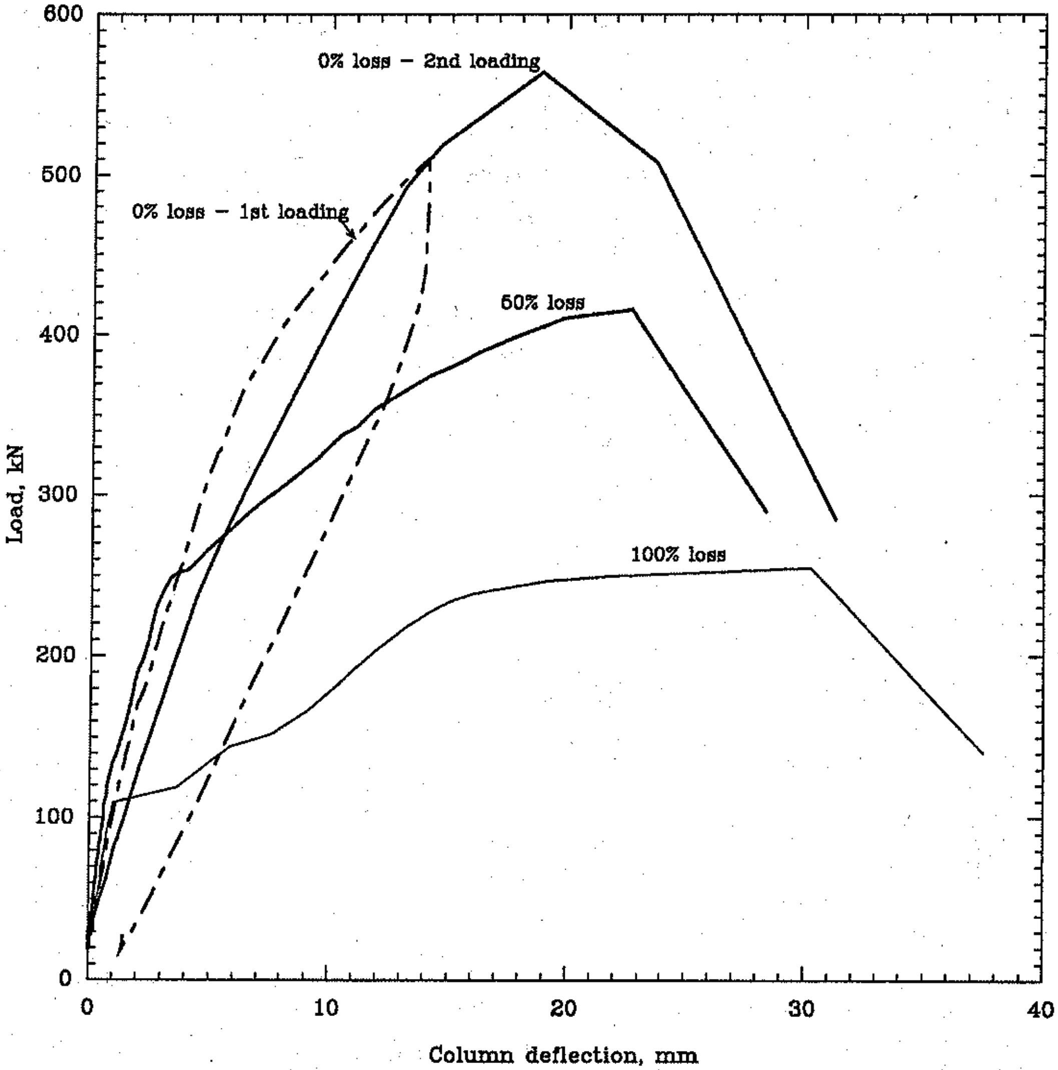


Fig. 6 Effect of loss of tendons on load–deflection behaviour

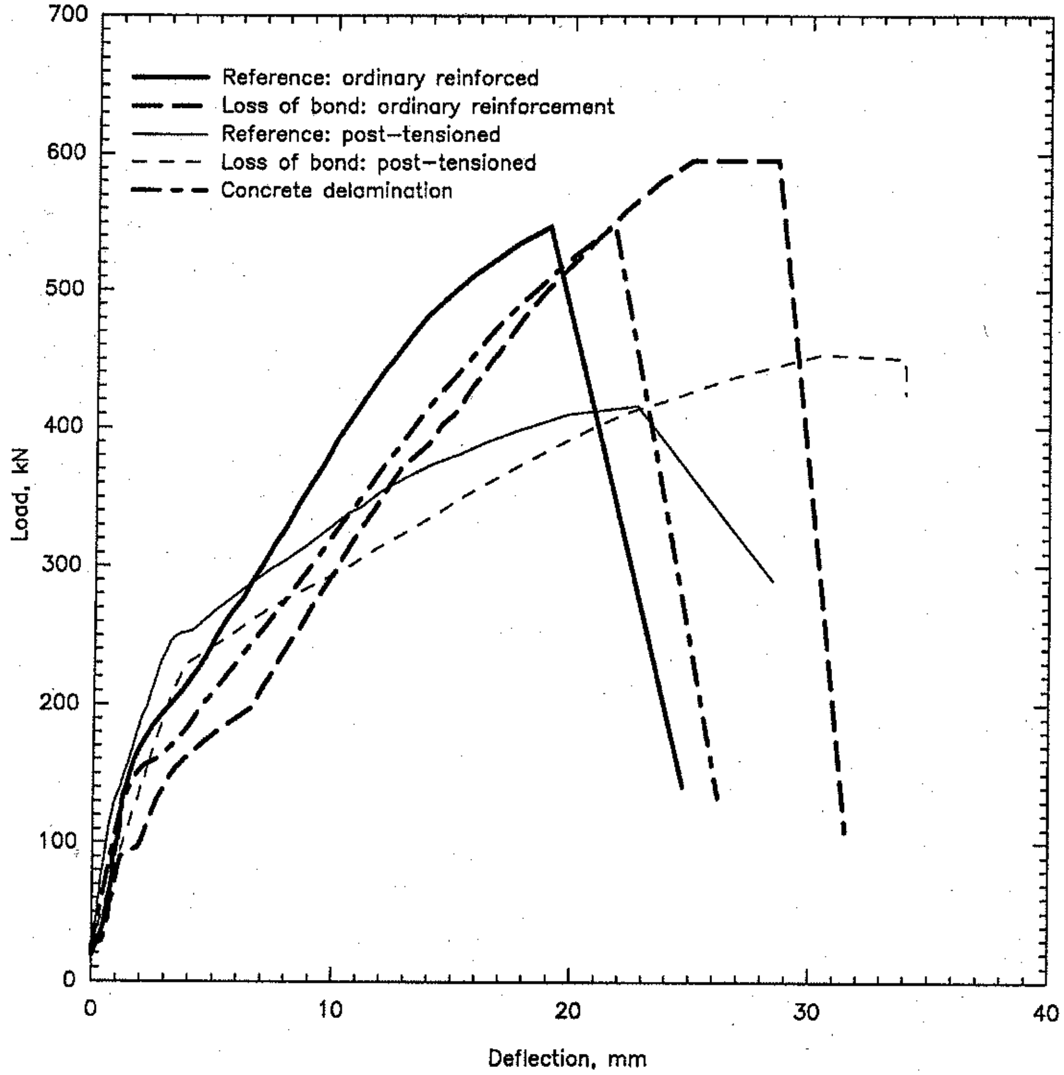


Fig. 7 Effect of reinforcement bond loss and concrete delamination on load–deflection behaviour

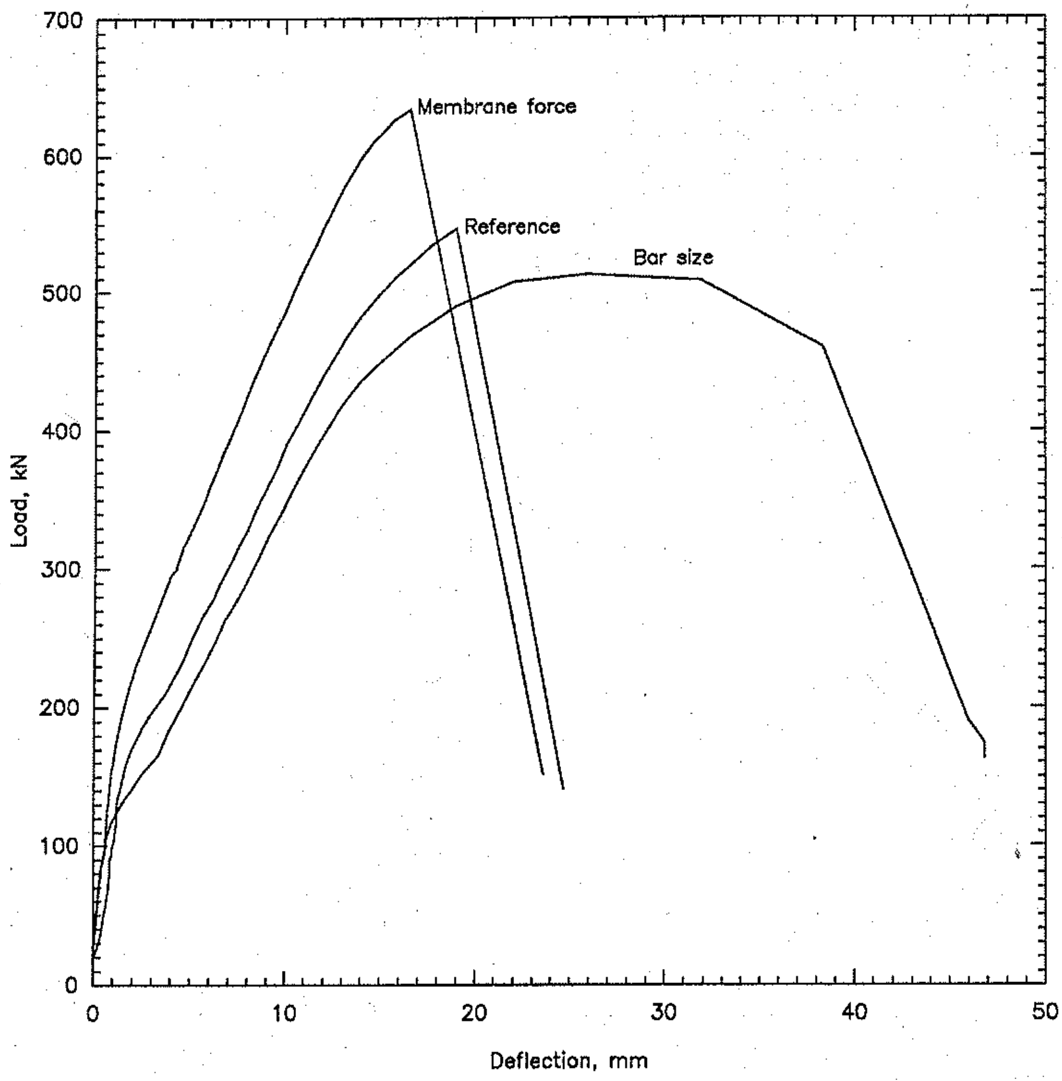


Fig. 8 Effect of bar size and membrane force on load–deflection behaviour