STRENGTHENING OF BRIDGE SLABS ON COLUMNS

Ghassem Hassanzadeh, Ph.D. student
Royal Institute of Technology, KTH
Department of Structural Engineering
SE-100 44 Stockholm - Sweden
E-mail: ghahas@struct.kth.se

Håkan Sundqvist, Prof. Structural Design and Bridges
Royal Institute of Technology, KTH
Department of Structural Engineering
SE-100 44 Stockholm – Sweden
E-mail: hsund@struct.kth.se

Abstract

This paper presents the result of 3 different strengthening methods for slabs without ordinary shear reinforcement on columns. The methods aimed at increasing the load carrying capacity against punching loads. Testing was done on 5 circular slabs, which had almost the same concrete strength, size and flexural reinforcement as slabs tested previously. The punching tests have been carried out on circular specimens, which were supported on the periphery and were loaded by a hydraulic jack, placed beneath the circular column. Some flexural reinforcement bars were instrumented by electrical resistance strain gauges glued to the opposite sides of each bar to measure the strain in the tangential direction at different distances from the column. Concrete strains were measured on the bottom side of each slab, in radial and tangential direction, with electrical resistance strain gauges glued to the concrete surface at a distance of 6 mm from the column. Observed punching failure loads have been compared with the load capacity of one non-strengthened test slab, with results from earlier tests on identical slabs with and without reinforcement and with corresponding punching load calculated according to the Swedish Handbook for Concrete Structures BHB, /1/. The tests were successful and the methods tested proved to satisfy the need for improving the strength that were set up before the tests.

Key words: *slabs, punching, strengthening.*

1 Introduction

There are many bridges in Sweden, more than one thousand, which are constructed as slab bridges, see **Figure 1**. They are mostly used as highway over-passes. Nowadays this kind of bridges is less used because the columns are considered as a risk for the traffic underneath.

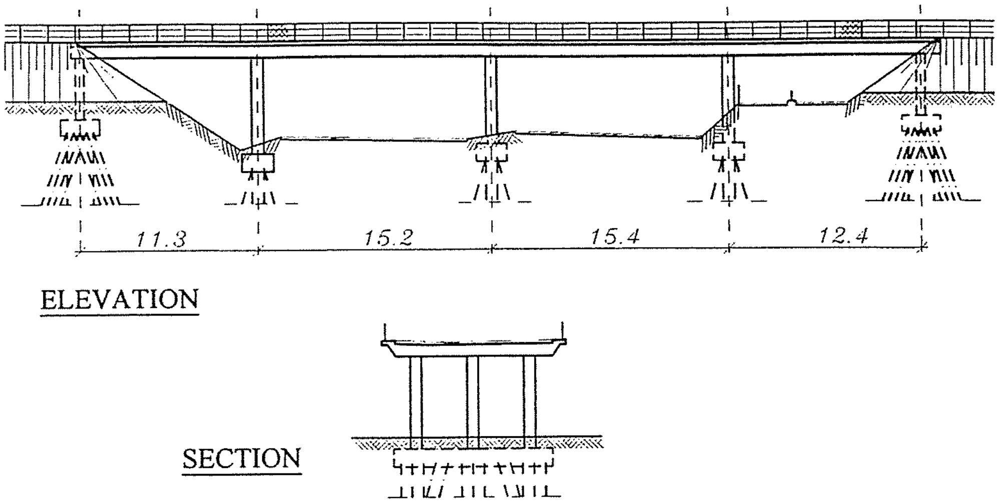

Figure 1 *A typical Swedish slab bridge.*

Since there are so many bridges of this type, the preserving and upgrading of these bridges are very important. Many of these bridges need to be strengthened and the Dept. of Structural Design at KTH has been commissioned by the Swedish National Road Administration to perform both tests and theoretical calculations in a strengthening program for this type of bridges.

2 Reasons for Strengthening

The transfer of vertical loads and moments between the slab and column in flat-plate structures causes high stresses at and near the column faces. These stresses could lead to cracking and punching failure. This type of failure is a result of the combined effect of normal and shear stresses. The main reasons for strengthening the bridges are:

- New loads in codes. New Swedish codes allow 24 m long 60 ton trucks on most main roads. This load level is higher than in most other countries and is mainly due to the needs for transportation of timber.
- Eurocodes will in the future allow still higher axle loads than axle loads defined in the Swedish code.
- Degradation of concrete in many older bridges gives a sufficient occasion to make an overall upgrading of the structure including some strengthening.
- New calculation methods which in some cases are more conservative than the ones used when the bridge originally was designed.

3 Aims and Problems

In principle there are three different methods to increase the load capacity of a bridge against punching load:

- Developing new and more effective design and calculation methods.

- Designing repair methods that can be performed when the bridge is closed for traffic.
- Developing repair methods that can be performed while the bridges are used and while full traffic loads are allowed.

The aim of this test series was to develop strengthening and repair methods which

- allow repair during traffic,
- are aesthetically acceptable,
- are cost effective,
- are durable
- have high fatigue strength.

Figure 2 shows some examples of strengthening methods performed from the upper side of bridge slab.

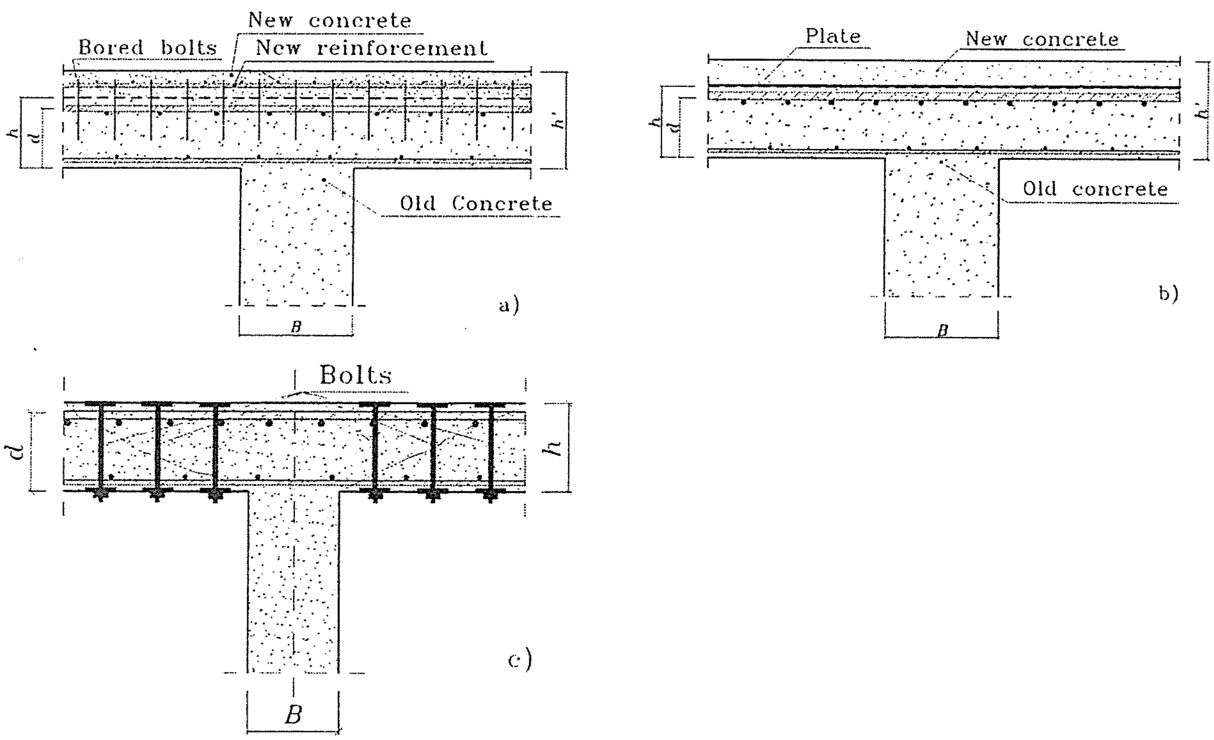

Figure 2 *Examples of strengthening methods from the upper side of the bridge slab.*

These kinds of strengthening could only be applied while the bridge, at least partly, is closed for traffic. Methods a) and b), see **figure 2,** use added flexural reinforcement either ordinary reinforcement or bonded steel plates. Inserting new vertical bolts as new shear reinforcement, tensioned or untensioned, as indicated in figure c) is a simple and effective method.

Figure 3 shows some examples of strengthening methods carried out from the bottom side of the bridge slab, enabling repair under traffic.

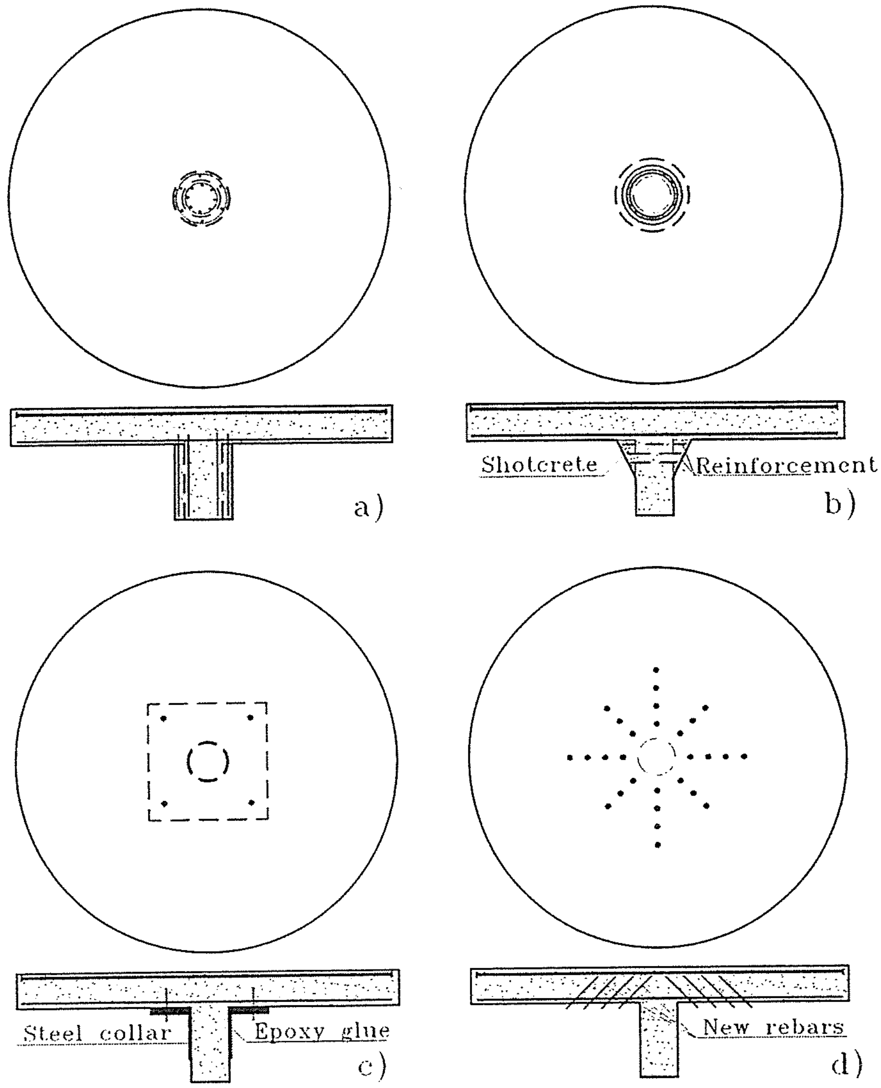

Figure 3 *Examples of strengthening methods from the bottom side of the bridge slab. These kinds of strengthening could be applied while the bridges are open for traffic.*

The four shown methods can be described as follows:

a) Widening of the column using shotcrete or ordinary concrete. This method might be useful if also the columns have to be strengthened.

b) Constructing a new column head using shotcrete or some injection method.

c) Adding some sort of steel structure around the column.

d) Adding new shear reinforcement.

4 Tests

4.1 General

The performed test series had two main purposes:

- to study how easy and cost effective the different methods are

- to investigate how structurally effective the different methods are.

In order to compare the effectiveness of the different methods, some non-strengthened slabs are needed as reference slabs. Two series of tests were used for this purpose. The specimens in the first series, which were presented in /3/ are named NS1, NS2, NS1.s and NS2.s. The slabs NS1.s and NS2.s had shear reinforcement in the form of bent down flexural reinforcement and the slabs NS1 and NS2 were without shear reinforcement. To complete this series of tests, one more "zero"-test was included in the present investigation. This latter slab is denoted NS and is shown in **Figure 4**. The main difference between the slabs in /3/ and the slab NS is the presence of bottom reinforcement in the slab NS. All slabs were cast using the type of concrete usually used in the period when most of these bridges originally were constructed. They were allowed to cure for at least 28 days before the different strengthening methods were applied.

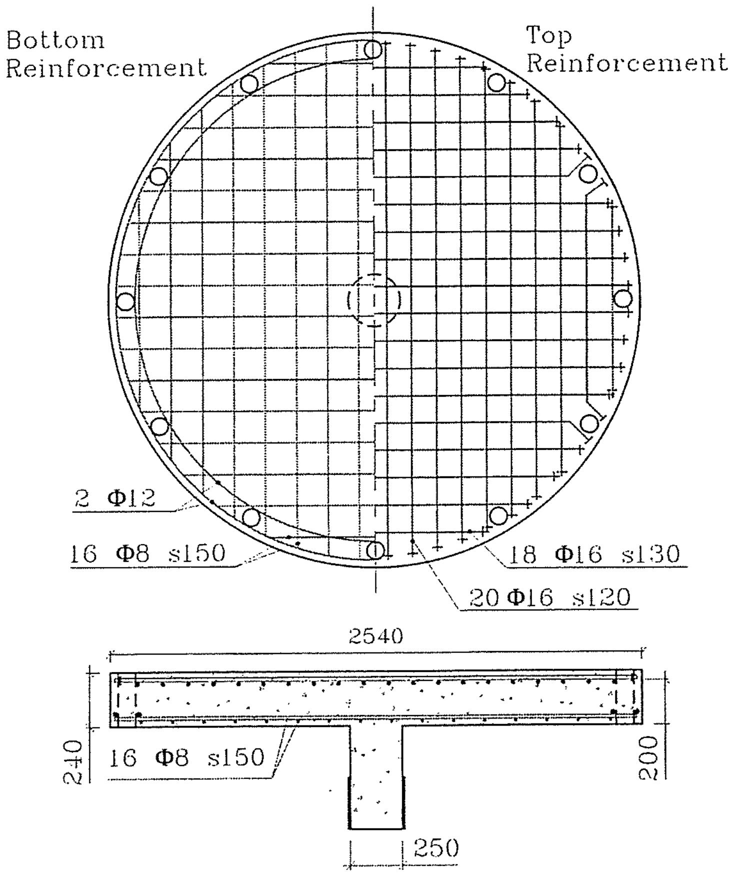

Figure 4 *Non-strengthened "zero"-slab named NS without shear reinforcement used to compare the effectiveness of the different strengthening methods tested.*

In addition to the "zero" tests the following slabs were tested in the present test series:

- Two slabs with new shear rebars inserted in bored holes and bonded to the concrete, denoted SS1.s and SS3.s, see **Figure 3** d).
- Two slabs with shotcreted column heads, denoted SS2.k and SS4.k, see **Figure 3** b).

- One slab with steel column head epoxy bonded to the bottom side of the slab, denoted SS5.p, see **Figure 3** c).

4.2 New shear reinforcement

The first method for strengthening of slabs against punching failure was provided by the insertion of shear reinforcement steel bars into drilled holes around the column-slab connection. The two slabs with added shear reinforcement SS1.s and SS3.s were almost identical, but the amount of added reinforcement was 20 ϕ 16 in slab SS1.s and 28 ϕ 16 in slab SS3.s. One of these two slabs, SS3.s, strengthened with added shear reinforcement is shown in **Figure 5**. The method used was to drill holes with an inclination of 45° from the underside of the slab up to the level of the bending reinforcement. The anchorage between concrete and shear reinforcing steel bars was provided by a special grout, developed by Hilti (Inc.). Immediately after injection of the hole with grout the reinforcement bar was inserted into the hole. The results of these tests indicate that inserted shear reinforcing steel bars provide a substantial increase in both strength and ductility, if these bars are sufficiently bonded to concrete. The anchorage between the shear bars and concrete was tested with a separate pull-out experiment. The result of this test showed that the anchorage strength between the shear bar and concrete was larger than the tensile strength of the shear bar.

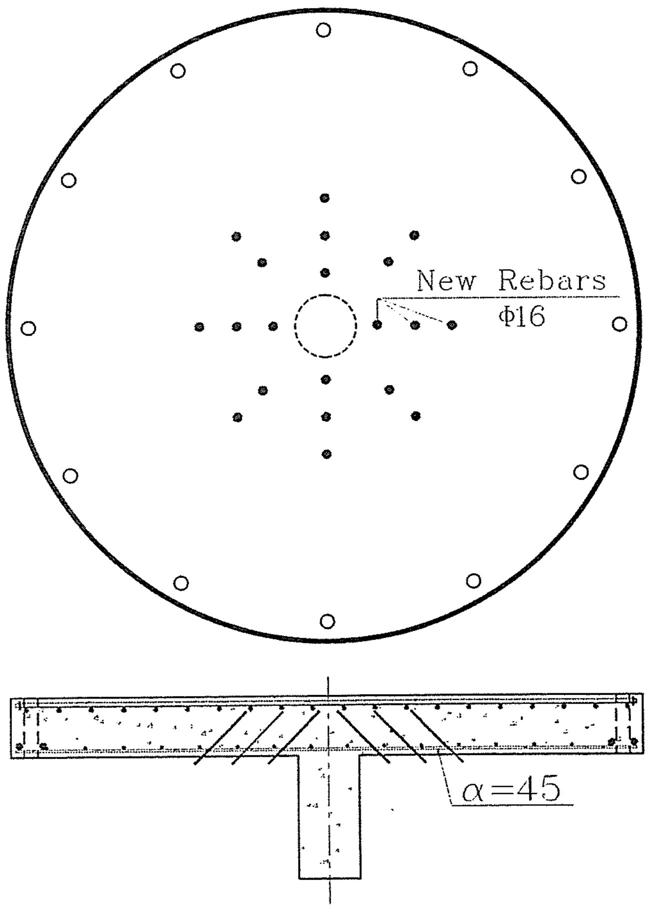

Figure 5 *Test slab SS3.s with added shear reinforcement.*

This strengthening method was very simple to apply and fast to execute. The punching failure load, as can be seen in **Table 1** increased with about 55 % in comparison with a non-strengthened slab. This value is somewhat higher than the punching load capacity of a slab with initial shear reinforcement. It shows that the new added shear reinforcement configurations were at least as effective as ordinary shear reinforcement.

The result of this method can be summarised as follows:

Advantages

- Effective
- Fast
- Non-expensive

Disadvantages

- Durability questionable (ought to be investigated)
- Fatigue strength questionable (ought to be investigated).

4.3 New shotcreted column heads

The second method of strengthening against punching failure was widening of the column with help of a column head, which increased the critical shear perimeter. The column head was constructed by reinforced shotcrete, that was less complicated to carry out than cast in place concrete in formwork. The concrete cover of the top of the column and a part of the bottom of the slab was carefully removed with a jackhammer. These surfaces were sandblasted in order to increase the roughness of the surface, remove microcracking, if any, caused by the jackhammer, and achieve better cohesion between old concrete and shotcrete. Dry shotcrete was used in several thin layers of 20-30 mm to form the column head. Each layer was allowed to cure for a while. Three reinforcement rings according to **Figure 6** were placed in the upper part of the column head. They should at first keep the shotcrete in place during the formation of the column head and secondly take tensile stresses inside the column head if this type of stress would arise inside the rings under loading. These three rings were provided with strain gauges to measure the strain at the column head. After application of the final shotcrete layers, the reinforcement had been covered with the prescribed concrete cover. The column heads were cured for about 28 days before testing.

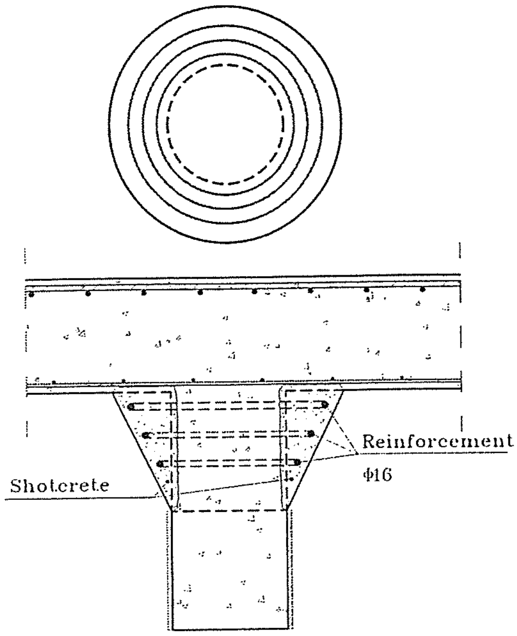

Figure 6 *Test slab SSK4.k with a new shotcreted column head.*

The results of these tests showed that the punching load capacity increased about 60 % with a doubling of column width, slab SS4.k, and about 100 % with a trebling of column width, slab SS2.k, in comparison with a similar non-strengthened slab NS. The new column head worked as a column constructed with a column head from the beginning.

This method of construction was straightforward and simple, but took rather long time to execute. The new column heads (steel or shotcrete) worked as if the columns had the equivalent diameter of the top of the new column heads according to the Swedish Handbook for Concrete Structures BHB, /1/.

The result of this method can be summarised as follows:

Advantages

- Effective
- Reliable
- Durable
- Fatigue safe

Disadvantages

- Time consuming to execute
- Expensive.

4.4 Steel column head ("steel collar")

The third method for strengthening of slabs was a steel collar bonded to the slab and to the column as shown in **Figure 7**. The way of constructing this solution was as follows. The concrete of the top of the column and a part of the bottom side of the slab was carefully sandblasted to take away loose particles, oil and other material that could reduce the bond between steel and concrete. Epoxy resin was applied to the surfaces of the slab and the upper part of the column. The steel collar was placed and pressed to the slab using expander bolts. The steel collar itself was provided with screws that allowed the collar to be pressed to the surface of the column. The test of this slab was done about one week after the strengthening.

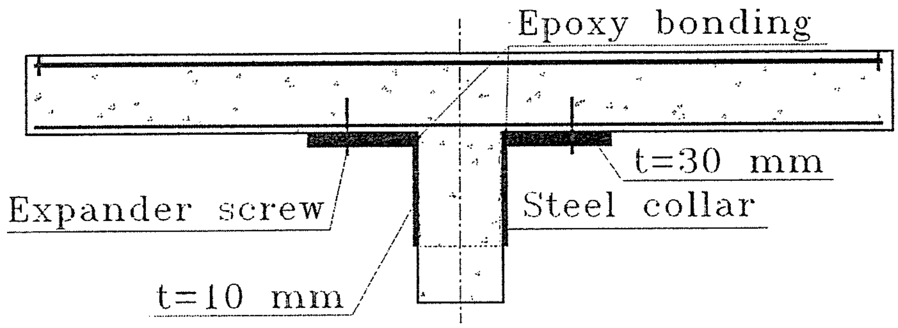

Figure 7 *Test slab SS5.p with a new steel column head.*
This "steel collar" is made in two halves, which are screwed together and epoxy-bonded to the bottom side of the slab and to the column stub.

The punching load capacity increased about 70 % by this strengthening method. It was not so simple and it took a long time to adjust the steel collar. The result of this method can be summarised as follows:

Advantages

- Effective
- Fast

Disadvantages

- Complicated to fix the steel collar before gluing
- Problems with tolerances
- Fatigue strength questionable (ought to be investigated)
- The durability might be good but there are questions regarding the durability of the epoxy joint (ought to be investigated).

5 Test Results

The main test results are presented in **Table 1**.

Table 1 *Comparison of test slabs and main test results.*

Slab	Effective depth	Cube strength	Flexural reinforcement			Shear reinforcement		Ultimate load
			Bar diam.	percentage	yield strength	No.		
No.	d	$f_{c,cube}$	ϕ	$\rho \cdot 10^2$	f_{sy}	of bars	ϕ	P_u
	[mm]	[MPa]	[mm]		[MPa]		[mm]	[kN]
NS1	200	30,3	16	0,80	657	-	-	603
NS2	199	28,6	16	0,80	670	-	-	600
NS1.s	195	31,1	16	0,82	669	32	10	894
NS2.s	195	29,5	16	0,82	673	32	10	851
NS	199	36,9	16	0,80	493	-	-	590
SS1.s	200	39,5	16	0,80	493	20	16	915
SS2.k	200	39,4	16	0,80	493	-	-	1190
SS3.s	199	39,6	16	0,80	493	28	16	935
SS4.k	199	44,9	16	0,80	493	-	-	950
SS5.p	197	32,9	16	0,80	493	-	-	1008

NS1, NS2, NS1.s and NS2.s are slabs presented in Tolf /3/. The two latter slabs are slabs with shear reinforcement. Slab NS is a new "zero"-slab used to compare the effectiveness of the strengthened slabs SS1.s, SS3.s with new shear reinforcement, SS2.k, SS4.k with new shotcreted column heads and SS5.p with a new steel column head.

6 "Basic" Punching Research

There is a lack of knowledge concerning the basic behaviour of slabs on columns. At Department of Structural Engineering, KTH, different models for this behaviour have been developed starting with the model presented by *Nylander* and *Kinnunen* in 1960 */2/.* The work for improving this model is still continuing. Therefor, the "zero"-slab NS was also used to make some basic punching research. Special concrete strain measurement devices were cast into the slab close to the column according to **Figure 8**. Special attention was also paid to measuring the strains in the reinforcement in different directions and at different distances from the column.

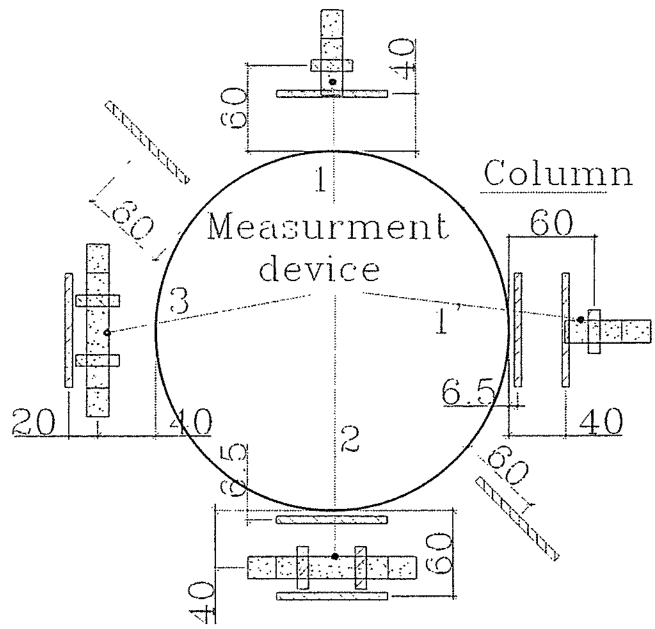

Figure 8 *The "zero"-slab NS was also used to perform some basic punching research. Special concrete strain measurement devices were cast into the slab close to the column according to the figure.*

The results of these measurements have been presented in reports /4/ and /5/.

The NS slab was also used to test the effectiveness of reinforcement on the bottom side of the slabs over the columns. **Table 1** shows that the bottom reinforcement did not contribute to the maximum loading capacity of the slab. This type of reinforcement could, however, contribute to the safety and the remaining strength after failure.

7 Conclusions and Need for Further Research

The results of the tests were all successful and they showed that these different strengthening methods worked better than what could have been expected. The first strengthening method, adding new shear reinforcement was the easiest method to apply. If there is a need to increase the punching load capacity by more than about 55 %, the second strengthening method, new shotcrete column head, is more effective and also easy to execute. For practical strengthening of bridges, there are still questions regarding durability and fatigue strength to be evaluated and tested.

8 Acknowledgements

The strengthening methods have been developed in collaboration with some Swedish companies. These companies have also partly performed the strengthening work at our laboratory and paid for some work and material. These companies are Stabilator (Inc.), performing shotcreting, Hilti (Inc.), performing drilling and gluing of shear reinforcement bars and Betongindustri (Inc.), delivery of concrete.

9 Literature

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