論文 Cracking and Ultimate Strength of Externally Prestressed Steel-free Concrete Deck Slabs

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ABSTRACT: Punching tests on six full scale steel-free slabs transversely prestressed with unbonded external bars are reported in this paper. The slabs were completely devoid of internal steel in order to avoid the corrosion of internal reinforcement and therefore the early deterioration of the concrete. The influence of the prestressing level and the concrete compressive strength on the structural behavior, punching shear capacity and occurrence of cracks in the slabs was investigated. The results observed show that unbonded prestressing and concrete strength increase the ultimate punching load to some extent but have no considerable effect on increasing the crack occurrence load. Prestressing, however, proved efficiency in controlling cracks development, which means a great improvement on the serviceability of the slab. A review of the steel-free deck slab concept and background is given along with the experimental results.

KEYWORDS: steel-free slab, unbonded prestressing, high-strength concrete, punching shear, cracking

1. INTRODUCTION

Corrosion of the steel reinforcement bars, and therefore the early deterioration of concrete deck slabs is a major problem in concrete slab-on-girder bridges. In order to avoid this problem, a new system, called steel-free deck slab system, has been developed and experimented in Canada during the past ten years[1)].

The concrete slabs of girder bridges (deck slabs) are conventionally considered in pure bending. Research confirmed that deck slabs, have a high ultimate resistance and are much stronger than slabs in pure bending because of an internal compressive membrane action (arch action) caused by the restraining action in the lateral direction as shown in Fig. 1. Those slabs failed in a punching shear mode at a much higher load than that predicted by bending type of analysis.

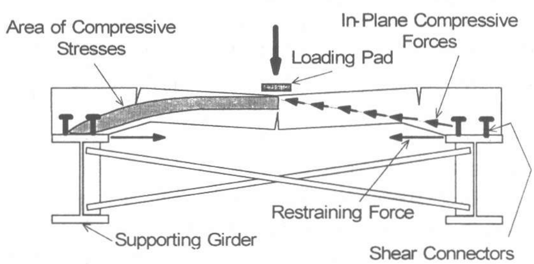

Fig.1 Compressive membrane action in deck slabs

This research also confirmed that the amount of steel reinforcement in deck slabs can be reduced considerably by taking into account the internal arching action. In addition, it has been shown that the internal arching action of the deck slabs of girder bridges can be harnessed by connecting the slab to the girders using shear connectors and by transverse confinement provided using external bars or straps[2)]. More than five bridges have been built in different Canadian provinces using this system[3)].

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The deck slabs that were tested and constructed in Canada were totally devoid of all internal steel reinforcement and restrained by external steel straps. The removal of steel from the concrete deck eliminates the cancerous problem of rapid bridge deck deterioration and subsequent repair due to corrosion of the steel reinforcement. Thus, the steel-free deck slab is both economical and highly durable. It has been shown that it is feasible to use other transverse confinement systems besides straps, particularly non-prestressed steel bars[4].

The major deficiency in steel-free deck slabs is a longitudinal crack that develops along the full length of the underside of the deck at mid span between adjacent girders. In order to overcome this problem, prestressing has to be considered. Researchers at Queen's University in Canada tested small-scale steel-free slabs transversely prestressed using bonded steel and FRP bars[5][6] placed at mid depth of the slabs. These tests showed that the ultimate punching shear strength of the deck slabs varied linearly with the transverse prestress level, but did not report the effect of prestressing on the development of the cracks.

A new approach for the steel-free deck slab has been tested in the following experiment. A concrete deck slab was cast without any internal reinforcement and was confined using steel bars that pass, unbonded, through sheaths left in the concrete. Two new parameters, which their effects on the steel-free slabs haven't been tested before, are investigated: The bars were prestressed to different levels of prestressing force for each different slab in order to study the effect of prestressing stresses. In addition, one set of the slabs was cast using normal concrete and the other set using high strength concrete in order to study the effect of concrete strength.

2. EXPERIMENTAL PROGRAM

The experimental program for the investigation of the effect of prestressing and concrete strength on steel free slabs comprised testing of six full scale concrete deck slabs. The test parameters included prestressing stress and compressive strength of the concrete.

2.1 SPECIMEN DETAILS

A total of 6 one-way rectangular concrete slab-on-girder specimens were cast and tested. The specimens were made composite with the girders using shear studs. As for the free ends, the slabs were left without any edge stiffening in order to simulate the behavior of a one-way slab as it is in the field slabs.

The dimensions of the slabs and the distribution of steel bars are shown in Fig. 2. The slabs were designed with haunches over the girders in order to maintain the ability to inspect steel corrosion and the ability of early detection of any deficiency in the prestressing system. The steel bars pass through sheaths left into the concrete of the haunches as can be seen in the cross section in Fig. 3.

Three specimens were made with normal strength concrete with different prestressing levels, the other three specimens were made with high strength concrete also with different prestressing levels. Details of the concrete strength and prestressing stresses in each specimen are given in Table 1.

Table 1 Specimens specification

Slab name	Prestressing stress in each bar N/mm^2	Tensile stress at upper fiber N/mm^2	Compressive stress at lower fiber N/mm^2	Concrete strength* N/mm^2
DS1	0	0	0	37.8
DS2	130	0.84	1.60	37.4
DS3	200	1.43	2.41	38.4
DS4	0	0	0	90.7
DS5	200	1.53	2.72	94.0
DS6	400	3.00	4.70	88.4

*Strength at 8days (Age of testing)

2.2 MATERIALS

In all the Canadian experiments, the fiber reinforced concrete is recommended for using in steel-free slabs in order to control the shrinkage cracking. The added fibers usually do not contribute to the strength of concrete nor it is believed to change cracking behavior under loading[2].

Since shrinkage cracking is out of the scope of this experiment and only the effect on initial cracking was of primary concern, fiber was not added to the concrete of the slabs.

All specimens were air-cured for seven days and tested in the afternoon of the eighth day.

The concrete used for the first set of specimens (DS1, 2 and 3) has a strength at the time of testing that varied between 37 to 38 N/mm^2 as shown in Table 1. For the second set of specimens (DS4, 5 and 6) the strength ranged between 88 to 94 N/mm^2 at testing day.

For comparison reason, in this study concrete strength of DS1, DS2 and DS3 was considered equal to the average of their strengths, that is, 38 N/mm^2. The same applies for DS4, DS5 and DS6 where average concrete strength was 91 N/mm^2

The prestressing bars were 17 mm diameter round bars with an average yield strength of 958 N/mm^2.

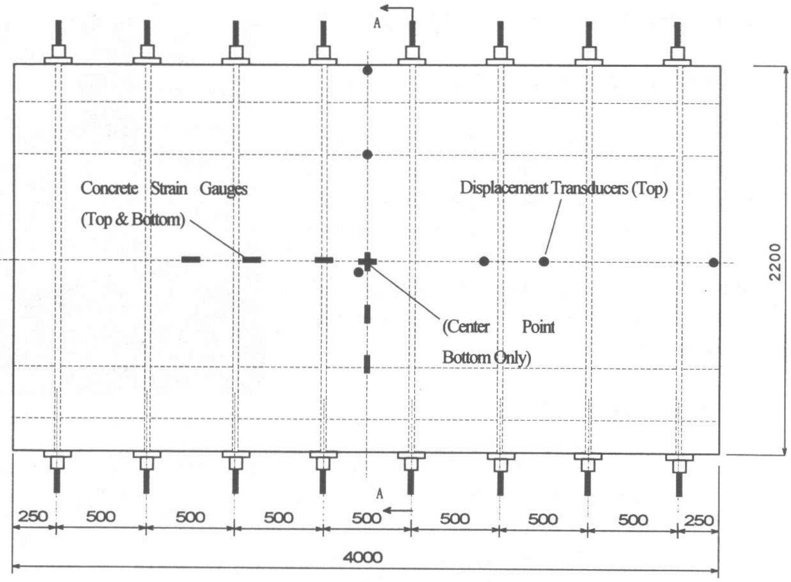

Fig.2 Plan view of a tested specimen

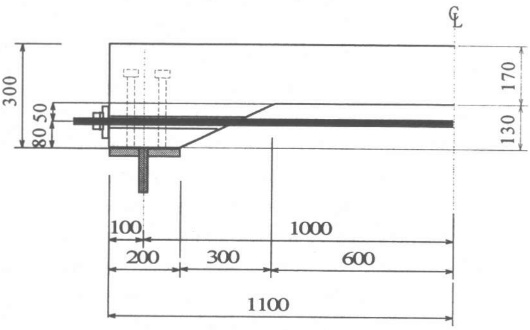

Fig.3 Transverse cross section A-A

2.3 TEST ARRANGEMENTS AND TESTING

Figure 4 shows the test arrangement for the slabs. It should be noted that the slabs weren't connected directly to a conventional I-beam girder as in the case of a real structure, instead, the specimens were cast to a plate that have welded shear studs on one side and imbedded and welded threaded bolts on the other side. Those bolts were used to fix the plate to a girder that has holes in its upper flange using nuts and washers. In other words, the specimen has the upper flange of the girder only, as an integrated part at time of casting as shown in Fig. 3.

Displacement transducers were used to record the slab deflections along the two central lines and strain gauges were pasted on the top and bottom surfaces of the slabs as illustrated in Fig 2.

The specimens were loaded at their geometric center by a hydraulic jack with a capacity of 1000 kN through a 400x200 mm and 40 mm thick steel loading plate, simulating a concentrated load. An overall view of a specimen in position ready for testing is shown in Fig. 5.

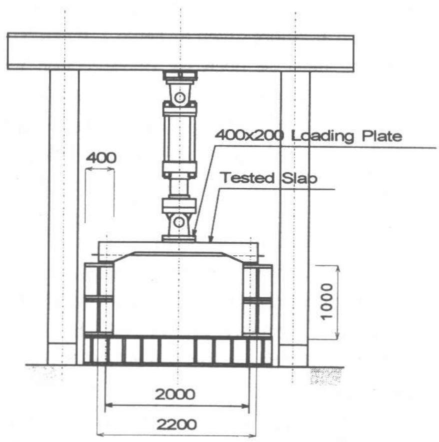

Fig.4 Loading setup

3. TEST RESULTS AND DISCUSSION

3.1 ULTIMATE LOAD CAPACITY

All the slabs failed in punching shear mode in which the punched-out cone had an area at the top equal to the size of the loading pad. The damage at the lower surface of the slabs was roughly circular in plan and was limited between the lines of the haunches. A summary of the test results is presented in Table 2, where cracking loads of each specimen are also given.

(1) Effect of prestressing

The relationship between ultimate punching load and prestressing stress is plotted in Fig. 6. It can be seen that in some cases increasing the prestressing stress didn't change the ultimate load, (Comparing DS2 with DS3, or DS4 with DS5). In other cases the prestressing increased the ultimate strength by 34 % (Comparing DS1 with DS2) and by 13 % (Comparing DS5 with DS6). As can be noticed from Fig. 6, a slightly lower value for DS2 and slightly higher value for DS5 would have given an almost linearly proportional relationship between prestressing and ultimate punching load. Thus, considering the previously mentioned tests at Queen's University[5)6)], and taking into account the limited number of tested specimens in this experiment, it can be concluded that there was a increase in ultimate punching load of the slabs as the prestressing stresses increased.

This result can be better proved by looking to the effect of prestressing stress on the ultimate deflection at failure given in Table 2. It can be seen from the ratio of decrease of deflection to the increase of prestressing stress that a linear inversely proportional relationship exists between the prestressing stress and the ultimate deflection at failure, which reinforce the above conclusion.

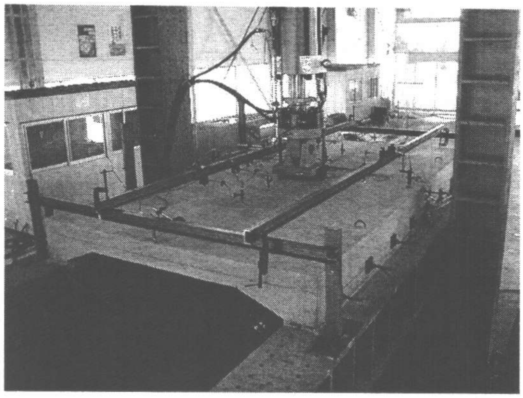

Fig.5 An overall view of a specimen ready for testing

Table 2 Summary of test results

Slab name	Ultimate Punching Load kN	Maximum Deflection at Ultimate mm	First Cracking Load kN	Longitudinal Cracking Load kN
DS1	554.6	8.28	99	255
DS2	746.2	7.78	124	441
DS3	730.9	7.44	147	510
DS4	862.9	13.45	157	319
DS5	853.2	10.25	225	539
DS6	980.5	8.77	231	784

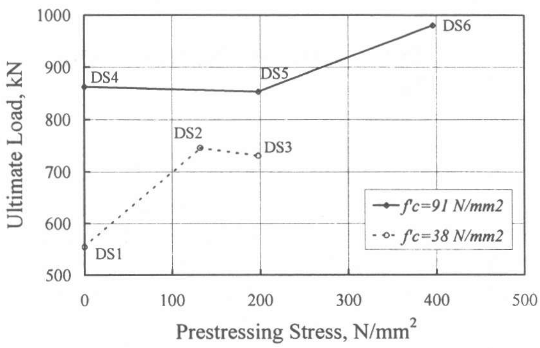

Fig. 6 Influence of prestressing stress on ultimate punching capacity

(2) Effect of concrete strength

Figure 7 shows the influence of concrete compressive strength on ultimate punching capacity. Comparing the non-prestressed specimens DS1 and DS4 (the lower inclined line in Fig. 7) shows that increasing the concrete strength by 2.5 times (from 38 to 91) has increased the ultimate load by 55%. This rate is approximately equal to the rate of increasing the square root of the compressive strength, a term that usually appears in most shear equations.

Comparing another two similar slabs with prestressing, DS3 with DS5, shows that in this case the increase in ultimate load was by 17%. It can be concluded that concrete strength has a definite effect on ultimate punching load of the steel-free slabs, but the rate of that effect differs according to the prestressing level.

3.2 DEFLECTIONS AND CRACKING LOADS

Load deflection curves are given in Fig. 8 for all the slabs. As the applied load increased an initial small crack appeared near the center of the bottom surface of the slab. This crack, that was undetectable by eye observation, caused a change in the concrete strain measured by the gauges pasted in that area. The development of the cracks was different between the prestressed specimens and the non-prestressed ones. In the non-prestressed specimens, a longitudinal crack developed along a limited length at the middle of the bottom surface. This length kept increasing with other radial cracks developing until it reaches the free edges (marked points in Fig.8).

In the prestressed specimens, the first crack to appear was a transverse one. This crack increased in length with other radial cracks developing. Those cracks took a more defined radial shape than the ones in the non-prestressed specimens. One of the radial cracks from each side increased in length until it reached the free edge (marked points in Fig.8). Figure 9 shows a typical crack patterns on the underside of a failed prestressed specimen.

Prestressing, as can be seen from Fig. 8, resulted in a smoother load deflection curves and in a less brittle change of the deflection at the load when the longitudinal crack reached the free edge.

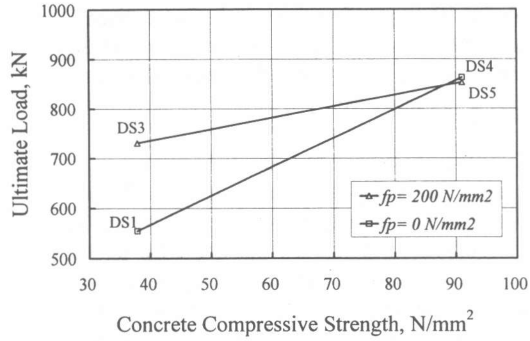

Fig. 7 Influence of concrete strength on ultimate punching capacity

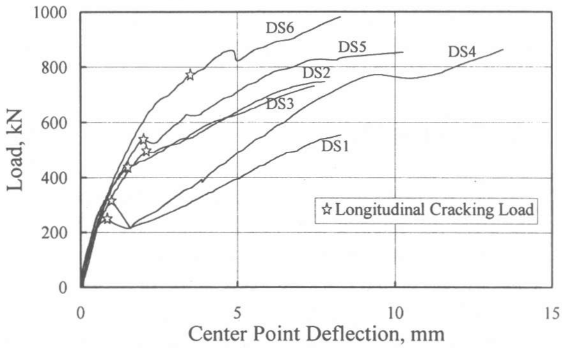

Fig. 8 Load deflection curves for the tested slabs

Two criteria were established to judge cracking strength of the tested slabs in this experiment; the first is the cracking load obtained from the first change in the concrete strain measured by the gauges located at the center of the bottom surface of the slabs. The second criterion is the load where a longitudinal crack reaches the free edge of the slab. The reasons behind considering this criterion is the fact that the longitudinal crack is the major problem in the steel-free slabs, and the slab would be considered out of serviceability limit after the occurrence of this crack.

(1) Effect of prestressing

Figure 10 shows the change in the load where the first crack appeared and the load where the longitudinal crack reached the free edge for the different prestressing stresses. It can be seen that prestressing didn't have a noticeable effect on the first cracking load. On the other hand, prestressing increased the load where the longitudinal crack reached the free edge initiating the beginning of the critical stage for the slab (the state after which the slab is considered out of its serviceability limit). Test data showed that prestressing had increased the load where this longitudinal crack first appeared as well.

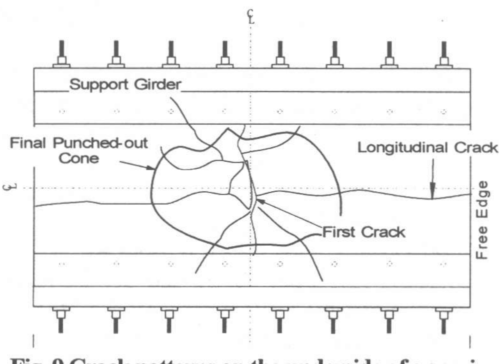

Fig. 9 Crack patterns on the underside of a specimen

Figure 10 shows that there is in fact a linearly proportional relationship between prestressing stress and the load where the longitudinal crack reaches the free edge.

(2) Effect of concrete strength

Fig. 11 shows the change in the load where the first crack appeared and the load where the longitudinal crack reached the free edge for the different concrete strengths. Comparing the inclined lines in Fig. 11 (DS1 with DS4 and DS3 with DS5) for both first crack and longitudinal crack shows that increasing concrete strength had increased the cracking loads by 20 to 50%. Thus the effect of concrete strength is clearly established, although the increase in cracking loads is not proportional to the increase in concrete strength (250%), nor to its square root (55%).

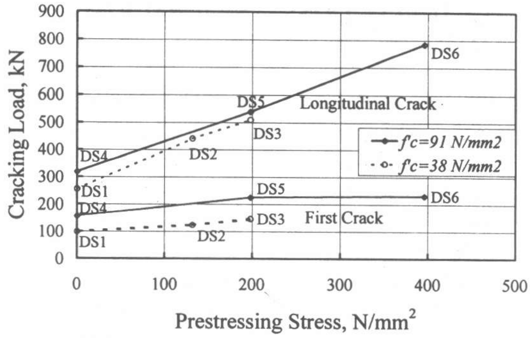

Fig. 10 Influence of prestressing stress on cracking loads

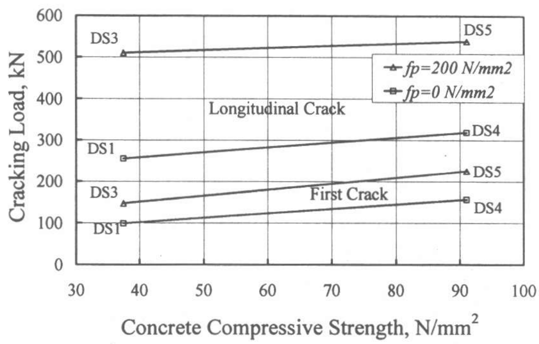

Fig. 11 Influence of concrete strength on cracking loads

4. CONCLUSIONS

The paper presented an experimental study on the effect of external unbonded prestressing and concrete strength on the ultimate punching shear capacity and on the cracking loads of the steel-free deck slabs. The study concluded the followings:

1. Both prestressing and concrete strength have an effect on increasing the ultimate punching load.
2. Prestressing didn't influence the appearance of the first crack in the slabs, while concrete strength had a small effect on delaying the occurrence of the first crack.
3. Prestressing had an obvious effect on delaying the occurrence of the longitudinal crack which is considered a major problem in the steel-free slabs. The load where this crack reaches the free edge increased linearly with prestressing resulting in increasing the limit serviceability load of the slab. Concrete strength had a less considerable effect on this longitudinal crack.

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