PUNCHING SHEAR STRENGTH OF TRANSVERSELY PRESTRESSED CONCRETE DECKS

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ABSTRACT

In the Netherlands, there is a need to determine the capacity of bridge decks as a large number of them were built back in the 60's and 70's. Since then, not only a lot of additional safety requirements have been incorporated into the modern codes but the traffic flow has also increased drastically. The current research deals with this question by taking into account arching action or compressive membrane action (CMA) in transversely prestressed decks on concrete girders. CMA is a phenomenon that occurs in deck slabs with edges restrained against lateral movement by stiff boundary elements. This restraint induces in-plane forces in the slab affecting both the flexural and the punching shear capacities. Existing methods were modified and a MATLAB program was developed to include the effect of CMA and the transverse prestressing to calculate the punching shear capacity of bridge decks. It was concluded that transverse prestressing enhances the CMA and improves the structural behaviour. However, detailed experiments are being carried out to further investigate the effect of different parameters, like geometry of the deck and the Transverse Prestress Level on the punching shear strength.

INTRODUCTION

One of the biggest challenges that structural engineers are facing today is to investigate if the old structures, especially bridges are still safe. It has been discovered that traditional methods of bridge design based on flexural failure theories are very conservative as under concentrated wheel loads, the deck slabs mostly fail in punching shear mode rather than flexural mode. Such behavior is attributed to the development of membrane forces in the deck slab. Compressive Membrane Action (CMA) or arching action occurs in laterally restrained slabs and provides enhanced strength in both flexure and punching shear. It is also logical that transverse prestressing of deck slabs can further enhance the capacity hence thinner deck slabs are possible with no problems of serviceability. This is of high importance because in The Netherlands many bridges have to be investigated, with very thin transversely prestressed decks cast in-situ between the flanges of precast girders. Using the actual design codes for the verification of the bearing capacity leads to values showing that the safety standards are not met. However, theoretical analyses show that nevertheless sufficient residual capacity might be available.

PAST RESEARCH ON COMPRESSIVE MEMBRANE ACTION

A lot of research has been done in past on the flexural and punching strengths considering compressive membrane action focusing on reinforced concrete bridge deck slabs. CMA was first reported by Ockleston (1955) during tests on a 3-storey building in South Africa. Subsequent research in the bending strength area was done by Wood (1961) and Park and Gamble (1980). Research conducted at Queen's University, Canada in the late 1960's has led to compressive membrane action been incorporated in the current Ontario Highway Bridge design Code (OHBDC, 1979) and the New Zealand Code (2003).

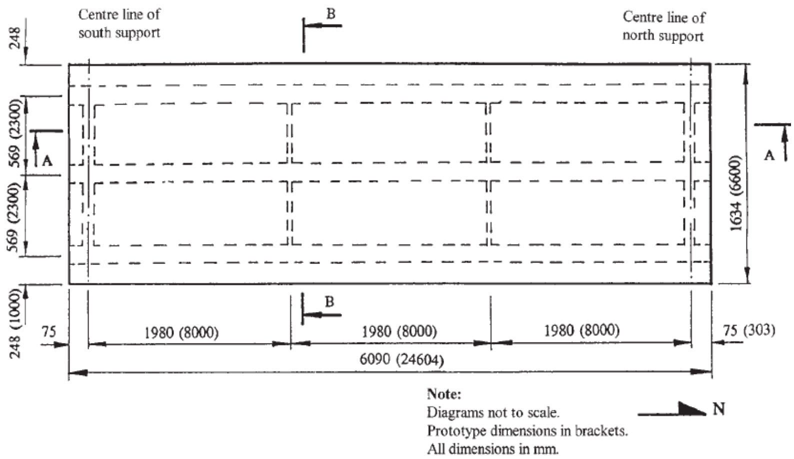
Another rational treatment of the compressive membrane action has been done in the UK Highway Agency Standard BD81/02 which resulted from the research done at Queen's University Belfast (Taylor et al, 2002; Rankin & Long, 1997; Kirkpatrick et al, 1984).

The most significant contribution in punching shear considering CMA was made by Hewitt and Batchelor (1975) who modified the Kinnunen and Nylander (1960) punching shear model (K&N model) by including an empirical restraint factor to show the impact of boundary restraint (H&B model). It was recommended that the boundary restraint should vary between 0.0 for no restraint to 1.0 indicating perfect restraint (Hewit & Batchelor, 1975).

PUNCHIING SHEAR FAILURE IN TRANSVERSELY PRESTRESSED DECKS

Punching is a common mode of failure for slabs directly supported by columns and for bridge decks having concentrated loads. Typically in a slab subjected to a concentrated load in the middle, a conical plug of concrete pushes out of the slab directly under the load. Freyssinet (1945) tested a prestressed concrete runway at Orly Airport and obtained 5 to 10 times higher strength as expected. Rankin in his PhD thesis (1978) stated that the punching strength of a prestressed slab is enhanced by both the prestress and the compressive membrane forces.

Some tests were done in Queen's university, Kingston Canada (Savides, 1989; He, 1992) on a model bridge of approximately ¼ scale having transversely prestressed concrete deck with steel girders. Savides used a constant transverse prestress level of 4.37 MPa throughout the deck slab and He varied the TPL. Both were able to effectively show that prestressing postponed the commencement of lateral movements and delayed cracking of panels. He also showed that the TPL varied linearly with the failure loads. It was concluded that the punching strength of deck panels depended on the CMA reflected from lateral movements. Lesser the lateral movement possible, higher was the level of CMA.



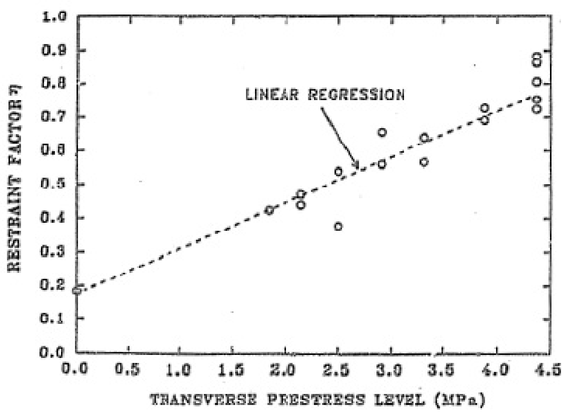


Fig. 1 Model bridge deck plan (Savides, 1989). Fig. 2 TPL-Restraint factor relationship (He, 1992).

However, the tests were done on small scale models and till today there has been insufficient research done to include CMA in current codes for prestressed decks with precast concrete girders. Therefore, this research aims to investigate transversely prestressed concrete decks by doing experiments on 1:2 scale model van brienenoord bridge near Rotterdam. Apart from experiments, some theoretical approaches have also been explored to study this behaviour.

(1) Modified Hallgren Model

In 1996, Mikael Hallgren proposed a mechanical model of punching based on the model by Kinnunen and Nylander (1960). The ultimate tangential concrete strain was the failure criterion in the K&N model and was based on a set of semi-empirical expressions developed from the strains measured in punching shear tests and no size effect was considered. In the Hallgren model, the main modification was the ultimate tangential concrete strain derived from a simple fracture mechanics model reflecting both the size effect as well as the brittleness of the concrete (Hallgren, 2007). The model did not take into consideration the lateral restraint. However, it was open for further development by introducing forces from the boundary restraint and prestressing.

Therefore, a modified form of the Hallgren model has been proposed in this paper and applied to relevant set of experimental data. In Fig. 3, boundary forces, F_b and M_b, have been introduced into the Hallgren model of a slab with diameter or equivalent diameter, C and depth, h. F_b(max) and M_b(max) are developed for rigid boundary conditions and are calculated using idealized slab displacements (Brotchie & Holley, 1971). An empirical restraint factor η, proposed by Hewitt and Batchelor (1975) is used in the Hallgren model to estimate the boundary forces.

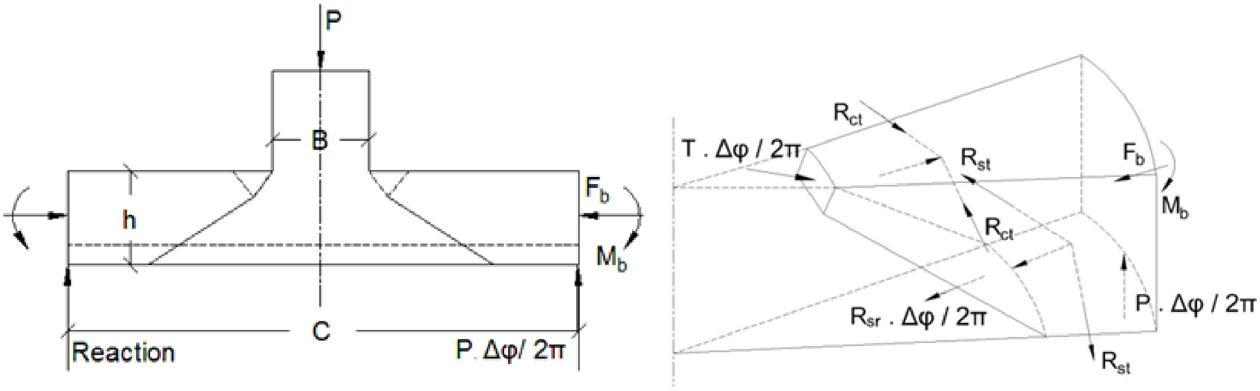


Fig. 3 Modified Hallgren Model for CMA, where $F_b = \eta F_{b(max)}$ and $M_b = \eta M_{b(max)}$.

This modified model can be used for both reinforced and transversely prestressed decks with compressive membrane action.

Fig. 4 shows capacity predictions for reinforced concrete decks by UK Highway BD81/02, Rankin and Long method and modified Hallgren model.

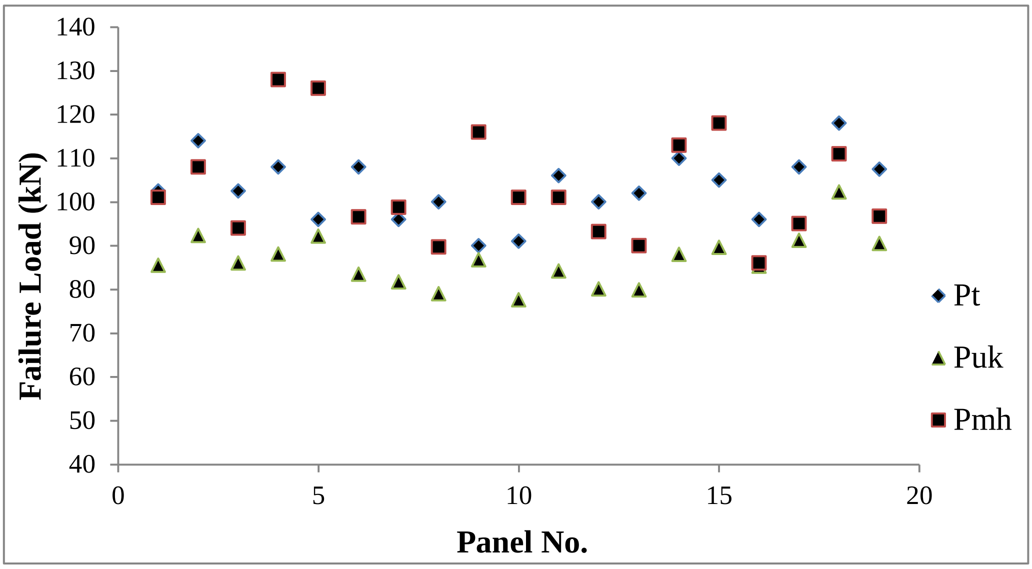


Fig. 4 Tests by Kirkpatrick et al (1984) evaluated by various methods.

Dowel action is ignored in the modified method for simplicity and a MATLAB program has been developed since it is an iterative procedure.

(2) Alternate Approach

The prestressing reinforcement can be converted into an equivalent reinforcement ratio (Rankin, 1978) and charts from NZ code may be used to estimate the ultimate capacity.

$$\rho_e = \rho_s + \frac{\rho_{ps} f_{pe}}{f_y} \qquad (1)$$

APPLICATION TO EXPERIMENTAL DATA

Various approaches have been tried to incorporate the effect of prestressing and compressive membrane action into the MATLAB script. Following two techniques are deemed to be the best methods of using the program: (1) Variable restraint factor and (2) Method of superposition.

(1) Variable Restraint Factor

In this method, the restraint factor is varied to estimate the test load observed during experiments. This approach can be used to estimate the level of restraint developed during a test. Table 1 shows the results for the tests done by Savides (1989) and He (1992). A maximum restraint factor of 0.72 was developed during the tests. For traditional composite systems with concrete deck and concrete girders, the restraint factor is expected to be even higher.

Table 1 Variable Restraint Factor (Tests in Queen's University, Kingston, Canada)

Test Panel	A_p (mm^2)	TPL (MPa)	P_t (kN)	η
SW-1A	0.0869	1.84	53.1	0.4
SE-1B	0.0869	1.84	53.04	0.4
CW-2B	0.105	2.15	54.82	0.41
CE-2B	0.105	2.15	57.26	0.42
NW-2A	0.1198	2.5	63.85	0.45
NW-2B	0.1198	2.5	48.7	0.32
CE-1B	0.14	2.91	74.43	0.55
CW-1A	0.14	2.91	65.82	0.47
SE-2B	0.1549	3.32	66.31	0.475
SW-2A	0.1549	3.32	72.97	0.522
NE-1B	0.176	3.88	80.54	0.58
NW-1A	0.176	3.88	77.52	0.56
CE-1A	0.19	4.37	94.12	0.72
NE-2A	0.19	4.37	92.28	0.69
NW-3B	0.19	4.37	80.11	0.58
CW-4B	0.19	4.37	82.66	0.605
SE-5B	0.19	4.37	87.3	0.67
SW-6A	0.19	4.37	92.23	0.69

A relationship between the restraint factor and transverse prestress level is also developed and is shown in Fig. 5. The graph can be used to estimate the restraint factor for various TPLs. For no prestressing present, the restraint factor can be taken equal to 1.5 – 0.2 when all other conditions of adequate restraint are satisfied.

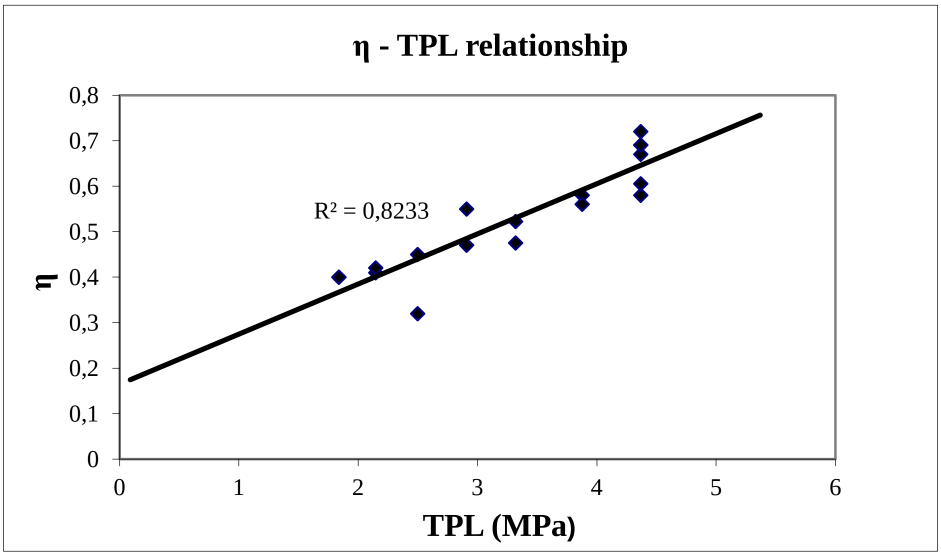


Fig. 5 Restraint Factor (η) - TPL relationship.

(2) Method of Superposition

The second approach uses the method of superposition. In this method, the prestressing effect is separated from the restraint effect by non-prestressed slabs. First the prestressing is ignored and a restraint factor of 0.2 is assumed (suitable value for non-prestressed slabs). Then the slab is assumed to be restrained only by the transverse prestressing force. The results of the two calculations are then added together to obtain the total punching failure load, P_{mh}. In Table 2 and fig. 6, H&B model is also used to calculate the capacity of tests done by Savides (1984) and He (1992). Clearly the modified Hallgren model is an improvement over H&B model. Also, equivalent reinforcement ratio method is used to calculate the punching capacity by the New Zealand code as well.

Table 2 Method of Superposition

Test Panel	A_p [mm^2]	TPL [MPa]	P_t [kN]	$P_{h\&b}$ [kN]	P_{mh} [kN]	P_{NZ} [kN]	P_t/P_{mh}	P_t/P_{NZ}
SW-1A	0.0869	1.84	53.1	55.96	59.77	67.39	0.89	0.79
SE-1B	0.0869	1.84	53.04	55.96	59.77	67.39	0.89	0.79
CW-2B	0.105	2.15	54.82	60.18	64.16	70.45	0.85	0.78
CE-2B	0.105	2.15	57.26	60.18	64.16	70.45	0.89	0.81
NW-2A	0.1198	2.5	63.85	64.17	67.57	71.68	0.94	0.89
NW-2B	0.1198	2.5	48.7	64.17	67.57	71.68	0.72	0.68
CE-1B	0.14	2.91	74.43	67.65	72.08	74.74	1.03	1.00
CW-1A	0.14	2.91	65.82	67.65	72.08	74.74	0.91	0.88
SE-2B	0.1549	3.32	66.31	62.71	75.42	76.58	0.88	0.87
SW-2A	0.1549	3.32	72.97	62.71	75.42	76.58	0.97	0.95
NE-1B	0.176	3.88	80.54	68.18	80.15	79.65	1.00	1.01
NW-1A	0.176	3.88	77.52	68.18	80.15	79.65	0.97	0.97
CE-1A	0.19	4.37	94.12	63.68	83.42	80.87	1.13	1.16
NE-2A	0.19	4.37	92.28	63.68	83.42	80.87	1.11	1.14
NW-3B	0.19	4.37	80.11	63.68	83.42	80.87	0.96	0.99
CW-4B	0.19	4.37	82.66	63.68	83.42	80.87	0.99	1.02
SE-5B	0.19	4.37	87.3	63.68	83,42	80.87	1.05	1.08
SW-6A	0.19	4.37	92.23	63.68	83.42	80.87	1.11	1.14
						Average	0.96	0.94
						St. deviation	0.10	0.14

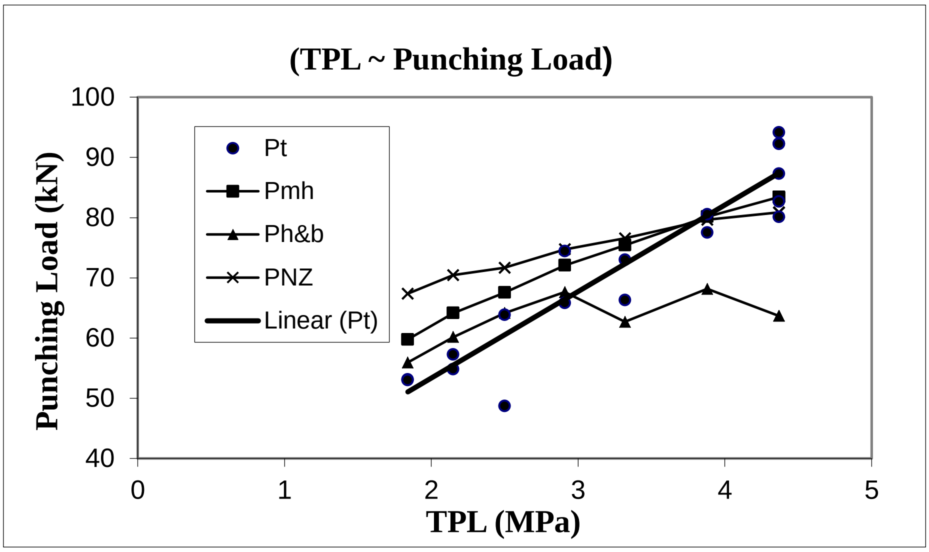


Fig. 6 Comparison of test results with various methods.

FUTURE TESTS

In the Netherlands, about 70 bridges have to be investigated and using the actual design codes leads to values showing that the safety standards are not met. However, theoretical analyses show that nevertheless sufficient residual capacity might be available. In order to confirm the validity of the calculations large scale laboratory tests are carried out.

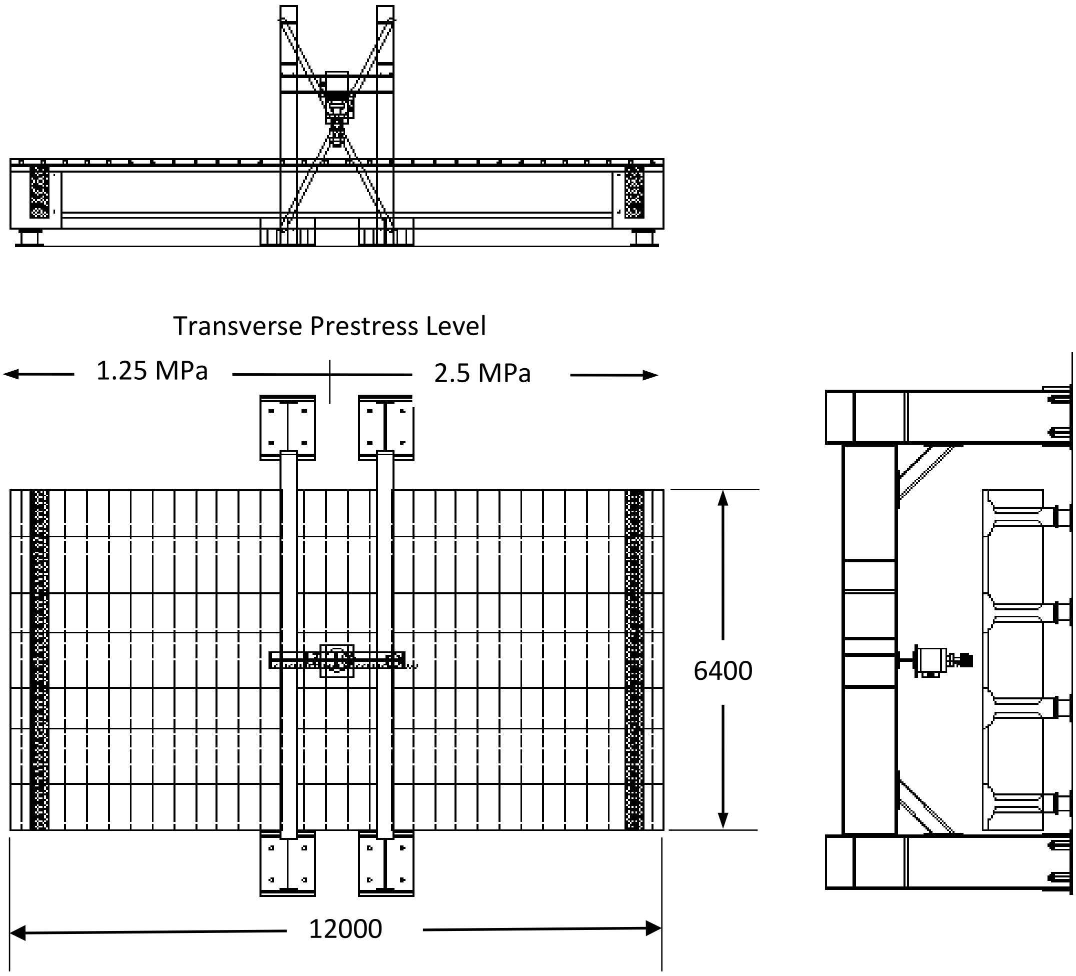


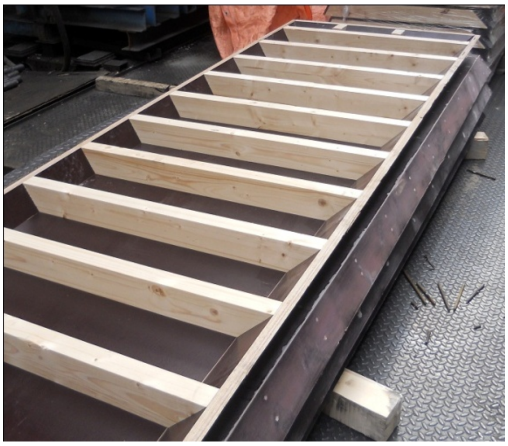
Fig. 7 The scale model test set-up (All dimensions are in mm).

Fig. 7 shows the test setup of the 1:2 scale model of the van brienenoord bridge near Rotterdam. A transversely prestressed concrete deck will be cast in-situ between precast concrete girders. The main parameters to be explored are the effect of transverse prestressing, development of compressive membrane action and the skewness of the joint between the girders and the slab. Crossbeams are provided at the edges to make sure the system behaves as one unit. However, the scale model is still in the design stage and many variables are yet to be determined. To ensure adequate confining effect and the failure within the slab portion, girders have been over designed and a suitable overhang is provided to the external girders for the development of compressive membrane forces. It is expected that a restraint factor, η, of atleast 0.5 will be observed during the tests. Fig. 8 shows preparations being done for the experiments.

(a) Reinforcement for the girders

(b) Mould for the girders

(c) Skewed and rough interface of girder flange



(d) Wooden mould for the girders

Fig. 8 Preparations for the experiments.

CONCLUSIONS

It is clear from the research done for transverse prestressed concrete decks that the modified Hallgren model gives good predictions for the failure loads. The MATLAB program is easy to use and facilitates in the calculation work. Currently, a nonlinear finite element model is also being developed for the scale model to get predictions for the tests. However, the actual experiments need to be done to show the positive effect of compressive membrane action and transverse prestressing in concrete decks.

NOTATIONS

Φ Angle of sector element of slab
ρ_e Equivalent reinforcement ratio
ρ_{ps} Prestressing steel reinforcement ratio
ρ_s Steel reinforcement ratio
f_{pe} Effective prestress in unbounded tendon
f_y Yield stress of steel reinfrocement
B Width of loaded area
F_b Boundary restraining force
F_p Prestressing force
M_b Boundary restraining moment
P, P_t Failure load in tests or applied test load
$P_{h\&b}$ Predicted ultimate capacity from Hewitt & Batchelor Model
P_{mh} Predicted ultimate capacity from Modified Hallgren Model
P_{NZ} Predicted ultimate capacity from the New Zealand code
R_{ct} Horizontal force in concrete crossing the shear crack
R_{sr} Horizontal force in reinforcement at right angles to the radial cracks
R_{st} Horizontal force in reinforcement crossing the shear crack
TPL Transverse Prestress Level

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