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NUMERICAL INVESTIGATION OF THE BEARING CAPACITY OF TRANSVERSELY PRESTRESSED CONCRETE DECK SLABS

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The paper investigates the effect of various geometrical and material parameters on the bearing (punching shear) capacity of transversely prestressed concrete deck slabs by numerical methods. Experiments on a 1:2 scale model of such a bridge were carried out in the laboratory and a 3D nonlinear finite element (FE) model was developed in the finite element analysis software package TNO DIANA (2012) to study the structural behavior in punching shear. A comparison of the experimental and numerical ultimate loads show that the non-linear FE models can predict the load carrying capacity quite accurately with a standard deviation of 0.1 and the coefficient of variation of only 10%. The effect of varying the transverse prestressing level, the presence and size of the ducts, size of the loading plate and the concrete class is also described as part of the parametric study. It was observed that sufficient saving in cost could be made if calibrated numerical models are employed to investigate existing structures rather than doing expensive experimental studies.

Keywords: Bridge, Finite element analysis, Nonlinear, Numerical modeling, Punching shear, Parametric study.

1 INTRODUCTION

In the Netherlands, there are a large number of transversely prestressed bridge decks that were built in the 50s and the 60s and need to be investigated for their remaining lifetime capacity against the modern traffic loads. The shear capacity as prescribed by the codes is more conservative in the recently implemented EN 1992-1-1:2005 (CEN 2005) than the formerly used Dutch NEN 6720:1995 (1995). As a result, many existing bridges are found to be critical in shear when assessed using the Eurocode. This paper describes the numerical research carried out to investigate the capacity of a 1:2 scaled model of a bridge with a thin transversely prestressed concrete deck slab, cast between precast concrete girders subjected to concentrated loads. Experiments were also performed in the Stevin II laboratory, Faculty of Civil Engineering and Geosciences, Delft University of Technology on the scaled model of such a bridge. A comparison of the nonlinear finite element analysis and the experimental analysis is presented in detail in Amir (2014). In this paper, the ultimate loads found from the numerical and experimental analyses are presented and compared. Furthermore, the effect of some selected parameters like the transverse prestressing level, number of loads, the presence and size of the ducts, size of the loading plate and the concrete class on the punching shear capacity is discussed.

2 EXPERIMENTAL PROGRAM

The details of the real bridge can be found in Amir (2014). In order to simulate an actual bridge as closely as possible, a 1:2 scale was used to design the prototype. Figure 1 shows the prototype in the laboratory.

Figure 1. Prototype in the laboratory.

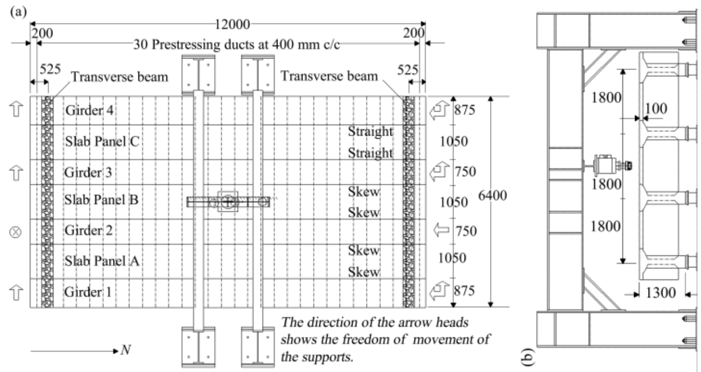

Figure 2. Test setup: a) plan view b) side view.

The deck prototype was 12 m long and 6.4 m wide consisting of four precast concrete girders placed at 1800 mm c/c distance (Figure 2a and b). The exterior girders had an extended width of 125 mm at the exterior flanges to make sure that the prestressing and the confining effect was introduced adequately. The cross section of the girders is as shown in Figure 3. Some of the interfaces between the deck slab panel and the girder flange were skew (1:20) and their location in plan is shown in Figure 2a. The deck slab was cast in-situ and post-tensioned in the transverse direction with a clear span of 1,050 mm and had a thickness of 100 mm. The transverse prestressing steel consisted of Φ15 mm unbonded bars post-tensioned to the desired level. The interface between the slab and the girder was indented and had an inclination of 1:20. The two transverse beams, 810 x 350 mm, were cast at 525 mm from each end of the bridge deck (Figure 2a). The prestressing consisted of Φ15 mm bars in the transverse direction stressed to the same level as the deck slab. Reference is made to Amir (2014) for more details of the test setup.

2.1 Material Properties

For the deck slab and the transverse beams, the concrete compressive cylinder strength was 65 MPa, the tensile strength was 5.41 MPa and the modulus of elasticity, E_c was calculated as 39 GPa (Eurocode 2). For the girders, the concrete compressive cylinder strength was 75 MPa, the tensile strength was 6.30 MPa and E_c was 41 GPa. The steel reinforcement had yield strength of 525 MPa and the prestressing steel had a characteristic tensile strength of 1,100 MPa.

2.2 Load Assembly and Testing Program

Figure 4 shows the test loading positions in the plan view of the deck slab. In all the tests, a concentrated load (wheel print load) was applied through a 200 × 200 mm, 8 mm thick rubber bonded to two 200 × 200 × 20 mm steel plates. The concentrated load was according to Eurocode 1 Load model 1, NEN-EN 1991-2:2003 (CEN 2003) scaled down according to 1:2.

Four types of tests were performed: a) Single point load acting at mid span of deck slab panel (P1M); b) Single point load acting close to the girder flange-deck slab interface/joint (P1J); c) Double point loads at 600 mm c/c acting at mid span of deck slab panel (P2M); d) Double point loads at 600 mm c/c acting close to the girder flange-deck slab interface/joint (P2J).

In the tests performed close to the girder flange-deck slab interface, load was placed at 200 mm c/c from the joint except in two tests, BB3 and BB4 (Table 3) where it was placed at 110 mm c/c. In test BB9, the size of the loading plate was 115 × 150 mm.

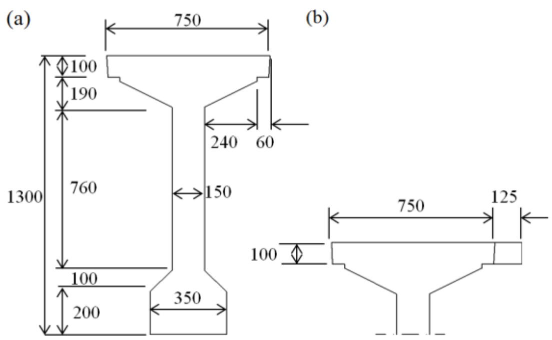

Figure 3. Cross section of prototype girder: a) Typical interior girder; b) Extended width of 125 mm at the exterior flange of the exterior girder. All dimensions are in mm.

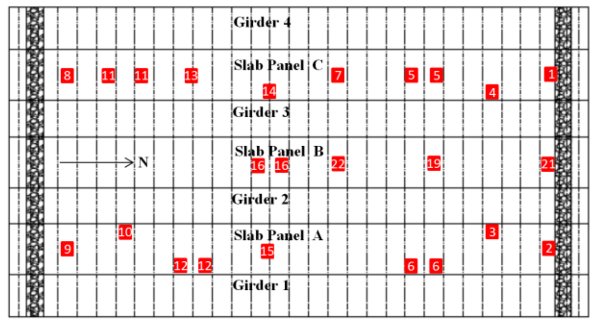

Figure 4. Deck slab test positions (BB1-BB22). Duct positions are also labeled.

3 3D FINITE ELEMENT MODEL

For the numerical analysis, a 3D solid finite element model of the prototype bridge deck (Figure 5) was made in the FEA software package DIANA (FX+ 9.4.4). The model consisted of 3D solid elements (CHX60 and CTP45) with a fine mesh around the loading area and a course mesh away from the loading to reduce the time for computation. Ducts at 400 mm c/c were provided only in the fine mesh area around the loading. Prestressing pressure was applied according to the required level of transverse prestressing in the deck slab and the transverse beams.

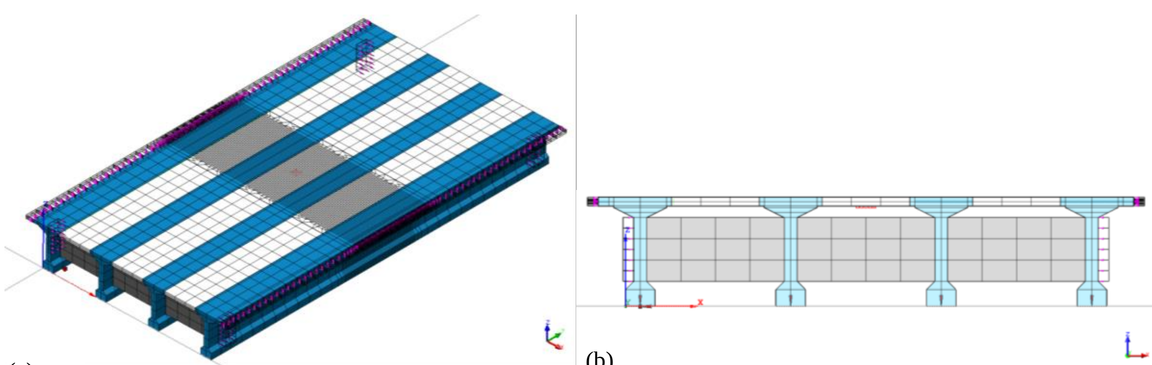

Figure 5. The 3D solid finite element model developed in DIANA: a) 3D model; b) Cross-section.

For most cases the deck slab was analyzed non-linearly while the girders and the transverse beams remained in the linear range. The only exceptions to this were the tests BB3 & 4. The flange of the adjoining girder was analyzed as nonlinear since the load was too close to the interface (110 mm c/c) and linearity of the flange would have induced a much higher capacity than in reality. An embedded reinforcement grid based was provided in the deck slab panels at the top and bottom in the horizontal as well as the vertical direction.

3.1 Material Models and Additional Nonlinear Material Properties

For the material properties of the girders and transverse beams that were analyzed as linear, reference is made to section 2.2.1. For the nonlinear analysis of the deck slab, a smeared cracking "Total strain crack rotating model" was selected. An elastic-perfectly plastic model, CONSTA, was used for the concrete behavior in compression, whereas, an exponential softening curve, HORDIJK, (Hordijk 1990) was used for the concrete behavior in tension. A fracture energy (G_f) of 0.15 N/mm was assumed for the deck slab concrete. The Poisson ratio, ν, for all the concrete components, was taken as 0.2. For the embedded grid reinforcement, the von Mises plasticity criterion was used with a Poisson ratio of 0.3.

3.2 Iteration Method and Convergence Criteria

Both physical and geometrical nonlinearities were applied to the system. An incremental-iterative procedure was used for the nonlinear analysis and modified Newton Raphson method was used for the solution. The prestressing load was applied to the bridge deck in a single step. After that a displacement-controlled load was applied with a step size of 0.1 mm unless the solution diverged, in which case the displacement increment was reduced to 0.05 mm. Since the applied load was displacement-controlled, the default force and energy based convergence criterion was employed.

4 DISCUSSION OF RESULTS

The ultimate loads observed in the experimental and numerical analyses are summarized in the Table 1. Generally, for single load tests, the finite element approach gives conservative results, while for double loads, the bearing capacities are overestimated but within reasonable limits as compared to the experimental results. The only exception to this is of test BB12 FE simulation which gave an error of 21% as compared to the experimental result but this test had failed at an unexpectedly lower load. The results of the parametric study are presented below.

4.1 Transverse Prestressing Level

The transverse prestressing level (TPL) was varied from 0.5 to 4.5 MPa for single loads and from 0.5 to 2.5 MPa for double loads to study its effect on the punching shear capacity (Figure 6). It was observed that increasing the TPL increases the punching shear capacity of the deck slab and the relationship is almost linear. It can also be observed that for both midspan and interface load cases, double loads show a higher bearing capacity as compared to single loads.

4.2 Presence of Ducts and Size of the Ducts

The influence of the presence and the size of the ducts have been investigated by making 3D bridge finite element models with no ducts, 25 mm Φ ducts and 45 mm Φ ducts. Figure 7 shows that the ultimate bearing capacity increases linearly for a decreasing duct size, the highest being for no ducts in the decks as a larger volume of concrete is available for carrying the load.

Table 1. Summary of test results.

Test	Slab panel– Load type & position- Interface	TPL (MPa)	P_T (kN)	P_{FEA} (kN)	P_T/P_{FEA}
BB1	C-P1M-ST	2.5	348.7	302.3	1.15
BB2	A-P1M-SK	2.5	321.4	302.3	1.06
BB7	C-P1M-ST	2.5	345.9	302.3	1.14
BB19	B-P1M-SK (SLP)	2.5	317.8	306.0	1.04
BB8	C-P1M-ST	1.25	284.5	271.4	1.05
BB9	A-P1M-SK	1.25	258.2	271.4	0.95
BB13	C-P1M-ST (AD)	1.25	322.9	363.1	0.89
BB15	A-P1M-SK (AD)	1.25	359.7	363.1	0.99
BB21	B-P1M-SK	0.5	243.8	274.6	0.89
BB22	B-P1M-SK	0.5	257.5	274.6	0.94
BB3	A-P1J-SK	2.5	441.6	429.9	1.03
BB4	C-P1J-ST	2.5	472.3	429.9	1.10
BB10	A-P1J-SK	1.25	340.3	300.7	1.13
BB14	A-P1J-ST (AD)	1.25	295.9	294.0	1.01
BB5	C-P2M-ST	2.5	490.4	529.9	0.93
BB16	B-P2M-SK	2.5	553.4	592.7	0.93
BB11	C-P2M-ST	1.25	377.9	453.4	0.83
BB6	A-P2J-SK	2.5	576.8	537.0	1.07
BB12	A-P2J-SK	1.25	373.7	454.9	0.82
		Mean			1
		Standard deviation			0.1
		Coefficient of variation (COV)			0.1

Note: TPL = Transverse Prestressing Level; P_T = Test ultimate load and P_{FEA} = Finite element analysis (FEA) ultimate load; ST = Straight joint; SK= Skewed joint; SLP = Small loading plate (115×150mm); AD = Test done above a prestressing duct.

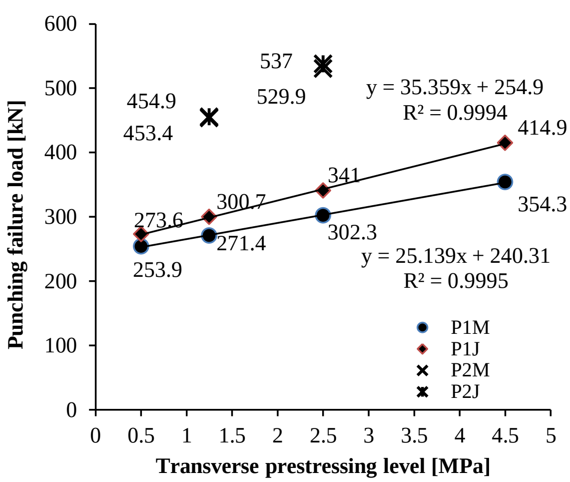

Figure 6. Influence of the TPL and the number of loads (single or double) on the punching shear capacity.

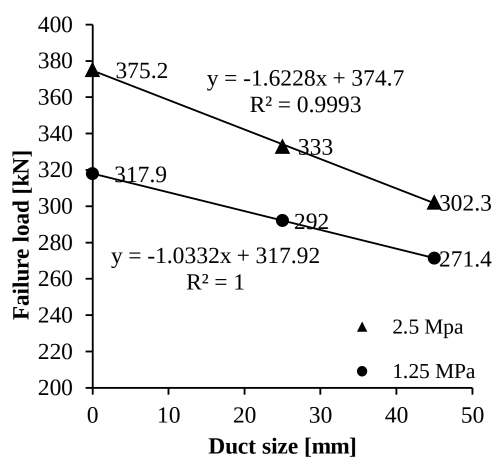

Figure 7. Influence of the size of the ducts on the failure loads. TPL = 1.25 and 2.5 MPa.

4.3 Size of the Loading Area (Wheel Print/Loading Plate)

Figure 8 shows the load-deflection behavior of the deck slab when the load is applied on a 125×150 mm loading area. Comparison is made with BB19, which had a loading plate of size 115×150 mm. It can be observed that the load-deflection behavior of the FEA model is stiffer as compared to test BB19; however, the ultimate loads show excellent agreement.

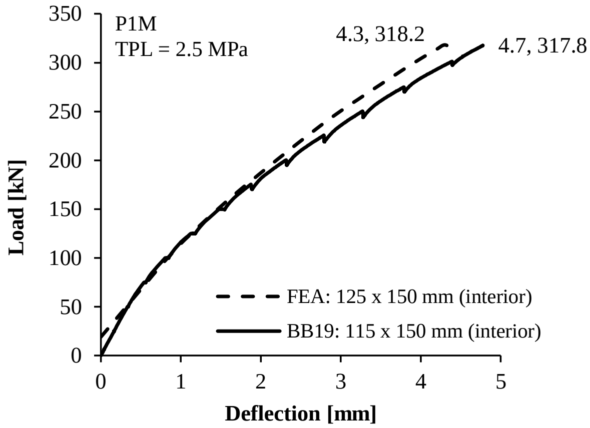

Figure 8. Influence of the loading area.

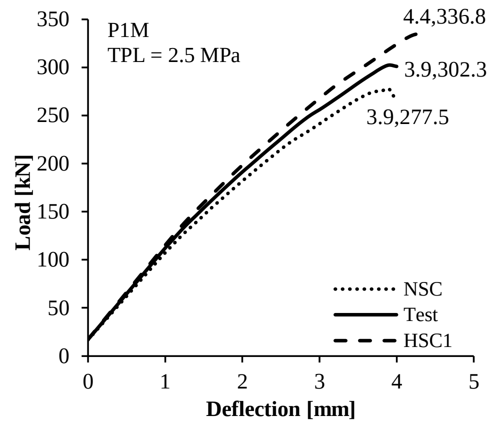

Figure 9. Influence of the concrete strength.

4.4 Concrete Class

The influence of the concrete strength was studied by varying the important material properties of the concrete. A normal strength concrete (NSC) with a mean compressive cylinder strength of 50 MPa, mean tensile strength of 4.5 MPa and a fracture energy of 0.13 N/mm and a high strength concrete, HSC1 with a mean compressive cylinder strength of 91.3 MPa, mean tensile strength of 6.21 MPa and a fracture energy of 0.179 N/mm was used. Figure 9 shows that using a higher concrete class improves the capacity but the response is stiffer with more brittle behavior.

5 CONCLUSIONS

The research shows that the bearing (punching shear) capacity of a bridge deck can be improved if the deck slab is prestressed in the transverse direction and that the punching shear failures can be reasonably modeled with non-linear finite element analysis of 3D solid models.

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