Behavior of Skew Reinforced and Prestressed Concrete Composite Decks

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Abstract: Over the past fifty years, many countries have recognized benefits of using composite concrete slabs in building construction and highway bridges. In this paper, experimental study was carried out to study the effect of skew angle, percent of concrete shear keys and prestressing on behavior of skew composite decks with reinforced or prestressed concrete precast corrugated panels under cyclic loading. A skew folded corrugated panel was proposed and prestressed to allow its use as integral part of bridge composite deck. The proposed precast panels are of high strength concrete with small thickness while, the cast in situ top slab is of normal concrete strength. The experimental program consists of six specimens of 3100 mm long (3 with traditional reinforcement and 3 with post-tensioned reinforcement) with overall height of 250 mm. The precast panel is of thickness 50 mm for both inclined and top parts of specimens, and thickness of 50 mm for the top layer. The corrugation angle of the web and skew angle of the longitudinal direction are 60° and 20° respectively. The post-tensioned panels are prestressed by two 15.24 mm diameter strands. From experimental results, it was observed that no visible rotational effect occurred throw the test for angles less or equal to 20°. No longitudinal cracks appeared in all tested specimens and no failure occurs at the bearing area of the specimen, the failure mode was flexure mode. The use of concrete shear keys as a shear connector affects its behavior (concrete and steel strains, deflection, and failure load).

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1. Introduction

The composite concrete-concrete deck slab is that type of structural system which consists of a precast panel of either reinforced or prestressed concrete with a cast in-situ layer. The composite deck slab has been widely used in buildings and bridge constructions since the last fifty years. The advantages of using composite slab were saving in cost and construction time.

Flat precast prestressed panel is the convention type of panels currently used in bridge deck construction due to its easy production sequence. The use of composite deck with reinforced concrete corrugated precast panel has been proposed in 1995 [1], and the dynamic behavior of prestressed composite girder bridges strengthened with external tendons were investigated in 2000 [2], but the use of composite deck with prestressed concrete corrugated precast panel has been proposed in 2002 [3]. The researchers approved the actual pronouncement of using concrete in corrugated shape rather than to be used in flat shape but they ignored the effect of skew.

The effect of torsion on externally prestressed segmental concrete bridge with shear key were studied experimentally in 2009 [4]. The effect of skew angle on determination the need for continuity diaphragms in skewed precast prestressed concrete girder bridges was investigated in 2007 [5] and its effect on live load reactions at piers of continuous prestressed concrete bridges was studied in 2007 [6].

In this paper, the last studied corrugated panel was modified, prestressed and made with a skew angle of 20° as a simulation of construction requirements. Figures 1, 2 and 3 show the dimensions and reinforcement for all the test specimens.

Experimental investigation was carried out on skew composite deck with precast prestressed folded corrugated panel to examine its behavior under cyclic loading using different percentage of shear keys relative to the contact surface as shown in figure 2. The experimental results were compared to similar deck but with reinforced concrete precast panel.

2. Experimental Work

To study the behavior of skew composite deck with reinforced and prestressed corrugated precast panels with different interface conditions (0, 20 and 40 % as shear area) under cyclic loading, six numbers of 3100 mm long specimens, (3 with traditional reinforcement and 3 with post-tensioned reinforcement) with dimensions shown in figure 1. The post-tensioned specimens were prestressed by two 15.24 mm diameter strands were prepared and tested. The precast panels were covered by a light weight reinforced concrete toping layer with thickness of 50 mm and reinforced with minimum reinforcement as shown in figure 1.

The reinforcement mesh for all precast panels were of 11 bar with 6 mm in diameter in the longitudinal direction supported on transverse bars of 6 mm in diameter spaced at 15 cm along the panel length. The reinforcement mesh for all cast in-situ layer were of 7 bar with 6 mm in diameter in the longitudinal direction supported on transverse bars of 15 bars with 6 mm in diameter along the panel length. The labels of the specimens with reinforced concrete precast panels were (OR00, OR20 and OR40) and (PR00, PR20 and PR40) for specimens with prestressed concrete precast panels. The numbers (0, 20 and 40) refer to the percentages of the concrete shear keys relative to the contact surface area between the two layers.

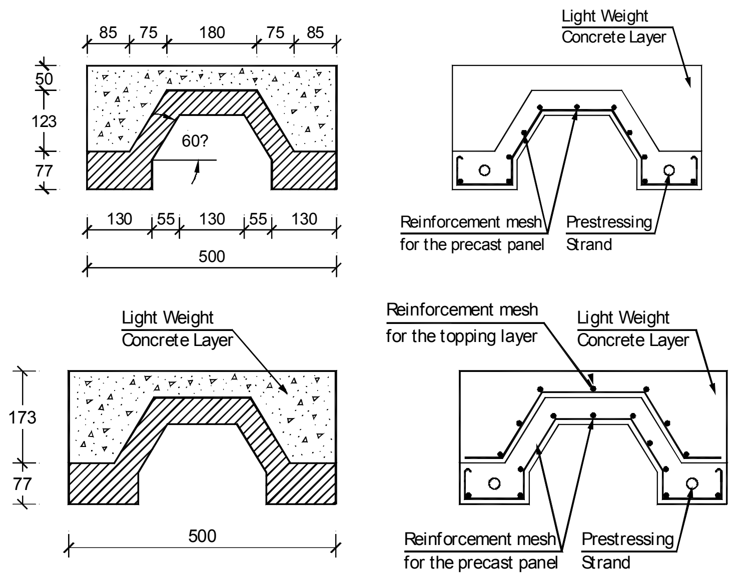

Fig. 1: Dimensions and reinforcement for all slabs (all dimensions are in mm)

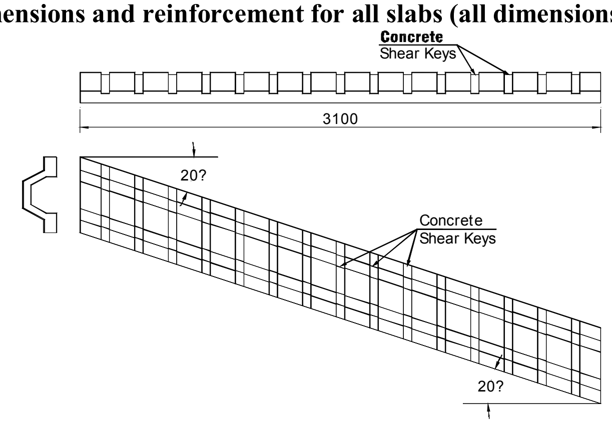

Fig. 2: The skew angle of the tested slabs and the shear keys (all dimensions are in mm)

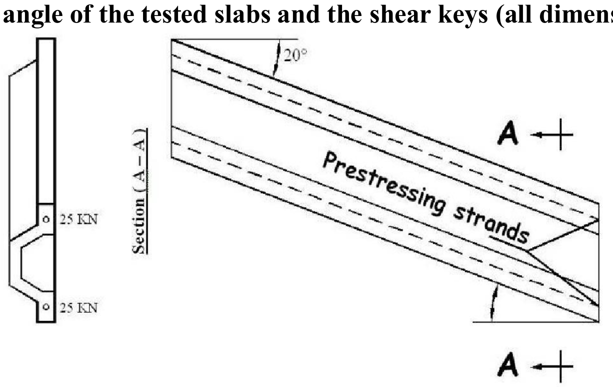

Fig. 3: Prestressing forces for all specimens

Materials

The materials used in the preparation of the tested specimens were locally produced. Tests were carried out to determine the mechanical properties of the materials according to the Egyptian Standard Specifications. The used fine aggregate was sand and coarse aggregate was crushed stone with percentages of 34 % and 66 % respectively. The cement used of type “Egyptian Ordinary Portland Cement”. The amount of cement used for concrete mixes were 500 kg/m^3 and 350 kg/m^3 for the precast and cast in-situ concrete layers respectively while, the water cement ratios (w/c) were 0.38 and 0.55 by weight of cement respectively.

Steel Reinforcement

The used steel reinforcements for both precast and cast in-situ layers are mild steel bars of 6 mm in diameter in the longitudinal and transverse directions with yield strength of 355 Mpa and ultimate strength of 495 MPa.

Prestressing steel

The three panels were prestressed by two 15.24 mm diameter 7-wire strands with tensile strength of 1860 MPa.

Prestressing technique

The prestressing system consists of a hollow core single acting piston of 200 KN in capacity as shown in figure 4, a hand pump of 400 KN maximum in capacity and a pressure sensor attached at the pressure line connected to a digital indicator which shows the pressure value in form of force value. The steel strands were prestressed to reach 25 KN for each one. The strands were over-tensioned by about 10 % of the required prestressing force for about 4 minutes and then relaxed to the original value to avoid any losses due to relaxation.

Fig. 4: Prestressing Process

Construction of specimens

For the cast in-situ layer, the precast slab was prepared by removing any loose particles from its top surface using steel brush. The precast slab was simply supported on its shorter sides on very rigid steel beams to simulate the actual site behavior of such type of slabs as shown in figure 5.

Fig. 5: Preparation and curing of composite decks

Preparation and testing of control specimen

Quality control during the mix of the concrete for the slab layers was made by the determination of the mechanical properties of the concrete by testing cubes with dimensions 15 x 15 x 15 cm and standard cylinders of 15 cm in height and height of 30 cm. A plain concrete beam with dimensions equal to 10 x 10 x 70 cm was prepared. The control specimens were cast at the same time of casting each layer of the composite deck. Tables 3 summarize the mechanical properties of hardened concrete for both precast and cast in-situ layers.

Six cubes have been prepared with each of the composite slab component. Three cylinders of 15 cm in diameter and 30 cm in height were casted with each layer of the composite deck and cured in its condition. The cylinders were tested according to the standard specifications for determining the concrete tensile strength as shown in figure 6.

Table 3: Properties of materials for both precast panels and topping layer

Group	% Top Surface	28-day compressive strength MPa	Flexural Strength MPa	Splitting Tensile Strength MPa	Young's modulus MPa
Prestressed Panels	00	37.6	8.8	3.3	36700
	20	34.1	7.6	3.0	35100
	40	36.4	7.9	3.2	36300
R.C. Panels	00	37.8	8.3	3.3	36900
	20	36.0	7.9	3.2	36200
	40	35.2	8.4	3.1	35700
Topping Layer Over Prestressed Panels	00	22.9	6.8	2.6	28700
	20	21.8	6.6	2.5	28100
	40	21.0	6.5	2.4	27600
Topping Layer Over R.C. Panels	00	21.2	6.5	2.4	27700
	20	20.8	5.9	2.3	27400
	40	22.1	6.8	2.5	28200

Fig. 6: Plain Concrete Beam and Concrete Cylinders under Test

Testing equipment and loading arrangement

Hydraulic jack with a maximum capacity of 300 KN was used for applying concentrated load to the loading arrangement. Figure 7 shows the used loading system set up to perform uniformly distributed load. All the six specimens were supported along their short sides on very rigid steel beams while the long sides of the composite deck specimen were left free.

The tests were conducted in two stages, in the first stage; a slab was loaded with small load increments. The small loading increments were chosen to provide a good record of the slab behavior before and after cracking and to determine the first crack's load. The load was removed and the slab was loaded and unloaded for three times to study the behavior of these slabs under cyclic loading. In the second stage, the load increments were based on deflection measurement rather than load. The loading was gradually increased until the slabs failed completely.

Instrumentation

Three electrical strain gauges of 10 mm length and average resistance 120.2±0.2 ohms, were installed to measure the strains of the reinforcement mesh of the precast and cast in-situ layers.

The strain gauges were continuously attached to the data acquisition system while testing and checked by voltmeter before attaching. Mechanical dial gauges with a sensitivity of 0.01 mm were used in measuring the vertical displacements. Concrete compressive and tensile strains were measured using demec-point station by using a dial gauge with 0.8 x 10^{-5} mm/mm accuracy to measure the deformation along a 200 mm gauge length.

(LVDT) of accuracy 0.001 mm were placed at two locations at distance of 150 mm from the support line.

Fig. 7: Test setup before loading

3. Results and Discussion

Table 4 summarizes the results of testing of six specimens of composite decks with reinforced or prestressed concrete precast panels. The comparison between results were made by means of cracking load, failure load, maximum deflection, steel tensile strain and end-slip at the end of the specimens between the two layers of concrete by using two (LVDT) of accuracy 0.001 mm.

Deformation characteristics

Figure 8 shows the load vertical movements due to prestressing effect at mid span of each precast unit by using dial gauges with a sensitivity of 0.01 mm at the bottom surface of different precast unit surface shape. The shape of the top surface of the precast unit affects the estimated camber due to prestressing process.

Crack pattern and mode of failure

The first crack was observed at mid-span section at loads equal to (14.3, 15.0, 16.0, 18.0, 20.6 and 21.8 KN) for (OR00, OR20, OR40, PR00, PR20 and PR40), respectively which approved that the presence of shear keys as well as its percentage and the presence of the prestressing force increased the first crack's load. The cracks were extended vertically through the precast layer only. The load was increased until the failure occurs to the specimen. No bearing failure occurs at the bearing area of all specimens.

The mode of failure for all specimens was flexural behavior as shown in figure 9. The cracks pattern at the bottom surface of the specimens extended with skew equal to the skew angle of the specimens as shown in figure 10.

Load deflection relationship

Figures 11 and 12 show the load mid-span deflection relationship for all slabs and it was observed that the presence of shear key affects the slope of the load deflection curve which means that the stiffness is increased with the increase of the shear keys. It was observed that the stiffness of the member was decreased due to the effect of cyclic loading on specimens.

From the results of measured deflection at mid span of the composite slabs with prestressed concrete precast units it can be observed that, the shear key percentage affects the maximum deflection of the specimens by (29.86 % and 43.89 %) for (20 % and 40 %) percentage of shear keys from surface area.

Table 4: Test Results at Final Loading

Type of Composite Slab	Specimen	% Shear Keys	Cracking Load (KN)	Failure Load (KN)	Maximum Deflection (MM)	Tensile Steel Strain at Maximum Load	End Slip (MM)
e with Reinforced Precast	OR00	00	14.30	51.94	10.260	0.0021	0.0131
	OR20	20	15.00	53.18	16.125	0.0021	0.0040
	OR40	40	16.00	55.22	19.85	0.0058	0.0029
e with Prestressed Precast	PR00	00	18.00	82.00	44.288	0.0145	0.0170
	PR20	20	20.60	85.74	31.063	0.0130	0.0089
	PR40	40	21.80	88.67	24.850	0.0125	0.0057

Load steel tensile strains relationship

Figures 13 and 14 show the load longitudinal steel tensile strain relationship for all slabs and it can be seen that the stiffness of the slab decrease due to cyclic loading and the presence of shear key affects the tensile strains of the longitudinal reinforcement.

Load concrete compressive strains relationship

Figures 15 and 16 show the load concrete compressive strain relationship for all slabs and it was observed that increase in shear keys decreased the concrete compressive strains at the same load.

Load end-slip relationship

Figures 17 and 18 show the load end slip relationship for all slabs. The presence of prestressing affects the value of end slip on specimens and the increase in shear keys decreased the measured end-slip between the two layers at the same load

Maximum load

The capacity of the slab increases with the increase of shear key area. The presence of 20 % shear key increase the capacity of the slab with 2.4 % and with 4.6 % for composite slabs with reinforced and prestressed concrete precast panels respectively. The presence of 40 % shear key increase the capacity of the slab with 6.3 % and with 8.1 % for composite slabs with reinforced and prestressed concrete precast panels respectively.

The prestressing force affects the capacity of the specimens by 57.9 %, 61.2 % and 60.6 % for specimens with 0 %, 20 % and 40 % shear keys respectively.

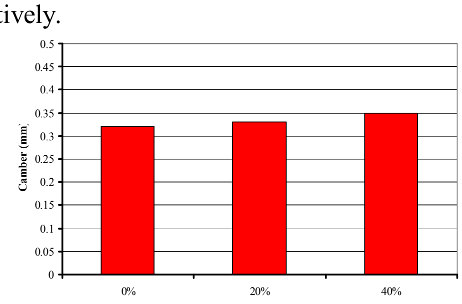

Fig. 8: Measured Camber Experimentally

Fig.9: Flexural Behavior of Specimen

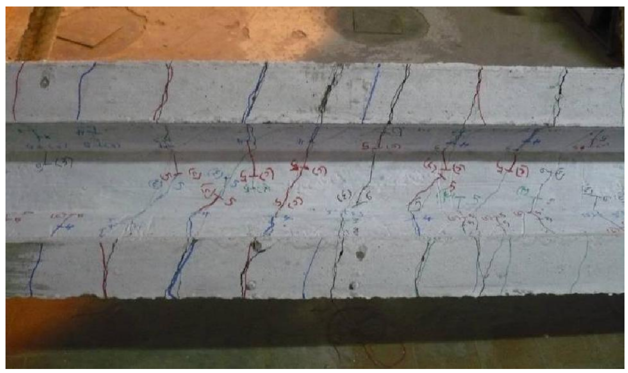

Fig.10: Crack Distributions at the Bottom Surface

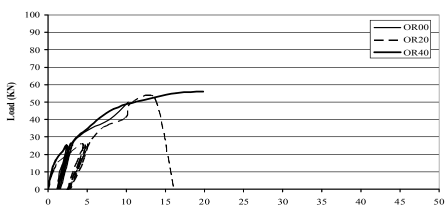

Fig.11: Load Mid-span Deflection Relationship for Slabs with R.C. Precast Panels

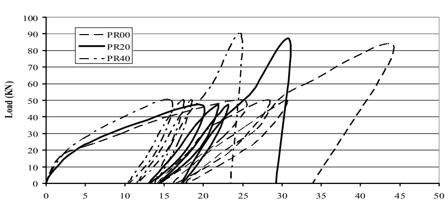

Fig.12: Load Mid-span Deflection Relationship for Slabs with Prestressed Concrete Precast Panels

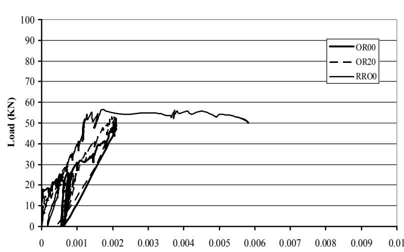

Fig.13: Load Steel Tensile Strain Relationship for Slabs with R.C. Precast Panels

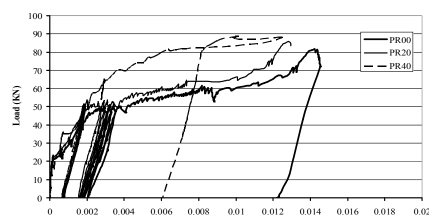

Fig.14: Load Steel Tensile Strain Relationship for Slabs with Prestressed Concrete Precast Pane

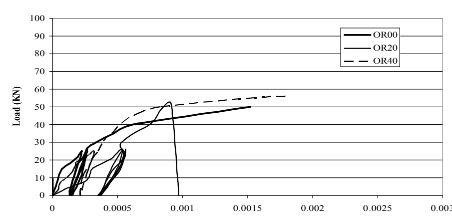

Fig.15: Load Concrete Compressive Strain Relationship for Slabs with R.C. Precast Panels

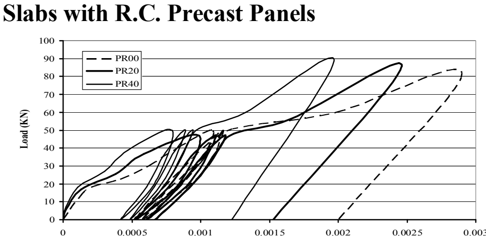

Fig.16: Load Concrete Compressive Strain Relationship for Slabs with Prestressed Concrete Precast Panels

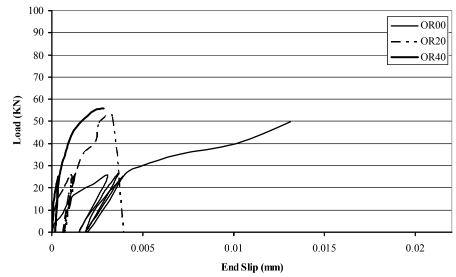

Fig.17: Load End-Slip Relationship for Slabs with R.C. Precast Panels

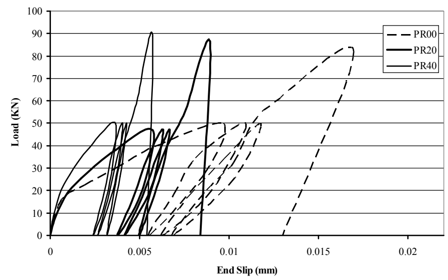

Fig.18: Load End-Slip Relationship for Slabs with Prestressed Concrete Precast Panels

Conclusions

In the limitation of this study, experimental investigation has been carried out to study the behavior of composite slab with reinforced and prestressed concrete precast skew panels.

A number of tests were conducted to study the behavior of all specimens due to the effect of skew angle, shear keys and prestressing under cyclic loading. The following conclusions were obtained:

1. The mode of failure for all specimens was flexure.
2. The increase in percentage of shear keys increases capacity of specimens and decreases tensile and compressive strains.
3. The cyclic loading decreases stiffness of specimen with increase of number of cycles at the same load.
4. The skew and geometry of the composite deck affects crack pattern on the bottom surface of specimens.
5. The presence of prestressing affects the behavior of specimens that it increases capacity of composite slab, and decreases end slip between the two surfaces of concrete.
6. No bearing failure occurred at supports due to loading or due to cyclic loading effect.

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