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Comparative study of prestressed steel – concrete composite bridge of different span length and girder spacing

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ABSTRACT : *Prestressed Concrete and Steel Concrete Composite (SCC) are commonly used for constructing bridges. Construction of prestressed concrete is time taking and lower reliable. SCC bridges have problem of excessive deflection under dead and live load, and deflection due to shrinkage and creep of deck slab concrete.*

External post-tensioning for strengthening of existing bridges has been used in many countries and has been found to provide an efficient and economic solution for a wide range of bridge types and conditions. External prestressing is now being used for construction of new bridges also.

This paper introduces a new concept of Prestressed Steel-Concrete Composite (PSCC) bridge, in which external post-tensioning is used in the SCC bridge. In the PSCC bridge, high tensile wires are tensioned by means of jacks bearing on the end block of the concrete deck slab and anchored. As a result, longitudinal stress level of the concrete deck slab is raised, which not only eliminates shrinkage and creep strains but also improves its fatigue performance.

In the present study effects of the total area of steel girder, prestressing force required in the cables, and stress in the deck slab are presented for various span lengths and girder spacings. The total steel girder area required in 4-girder system is nearly 20% lower than that of 5-girder system. Stresses in the deck slab due to prestressing were raised between 2 N/mm^2 to 10 N/mm^2 for 4-girder system. In the 50% of live load hogging deck case, the range of stresses in deck slab is lower than that of the no hogging case. Maximum stress in the deck slab for 4-girder system with the 50% of live load hogging case is also reduces to 9.96 N/mm^2 from 12.27 N/mm^2 in comparison to the no hogging case. It is concluded that prestressing raises stress level of the deck slab concrete resulting in its better fatigue performance, and also improves strength and stiffness of the bridge considerably.

Keywords: *Prestress, Composite, Bridge, Shrinkage, Post-tension*

I. INTRODUCTION

For highway bridges, composite bridge deck using a reinforced concrete slab over two or more steel girders is more popular than steel bridge and concrete bridge. The composite bridge also reduces noise and vibration levels in comparison to steel bridge, and is, therefore, environmentally friendly. Composite bridges are lighter, guarantee better quality and have easier and faster erection than concrete bridges [7, 13].

In recent trend pre-stressed concrete bridges [4, 14] have been expanding the applicable span length and are becoming a hard competitor against steel bridges and concrete bridges. Steel bridges, therefore, need new ideas to regain competitiveness. Steel plates have high tensile strength but are relatively vulnerable to buckling caused by compressive forces and need to be stiffened and strengthened. Resistance against buckling of the composite structure increases when steel girders are combined with reinforced concrete deck slab.

The use of external post-tensioning for the strengthening of existing bridges has been reported [1, 5] to provide an efficient and economic solution for a wide range of bridges. The technique is growing in popularity because of the speed of construction and hence external post-tensioning for prestressed concrete bridges is used in many countries in the construction of new bridges [15]. While new bridges are constructed using external post-tensioning, over the last two decades external post-tensioning has also been considered as one of the most powerful techniques for structural strengthening and rehabilitation.

The presence of early age transverse cracking in concrete bridge decks is often what leads to the eventual structural deficiency of bridges in the long run [2, 17], because these cracks permit the ingress of harmful substances into concrete bridge decks. With the presence of cracks in concrete bridge decks, water, sulfates, chlorides, and other potentially corrosive agents able to permeate to the interior of the bridge deck and cause further deterioration in the form of even larger cracks, spalling, potholes and eventually a loss of cross section of the bridge deck or reinforcing steel, which ultimately leads to an unsafe bridge. The repair of concrete bridge decks is often difficult and expensive because alternate routes are sometimes difficult or impossible to come by. To prevent deterioration from starting in the first place, concrete must not be allowed to crack, especially at an early age. For a concrete structure, to be serviceable, cracking must be controlled and deflections must not be excessive. It must also not vibrate excessively. Concrete shrinkage plays a major role in each of these aspects of the service load behaviour of concrete structures [16, 19].

Serviceability failures of concrete structures involving excessive cracking and/or excessive deflection are relatively common. Numerous cases have been reported, in Australia, Europe and elsewhere [6, 7], of structures that complied with code requirements but still deflected or cracked excessively. In a large majority of these failures, shrinkage of concrete is primarily responsible. Clearly, the serviceability provisions embodied in different codes [8, 9] do not adequately model the in-service behaviour of structures and, in particular, fail to account adequately for shrinkage.

Cracking can significantly reduce the service life of concrete bridge decks, pavements and other concrete structures. If cracking due to concrete shrinkage could be eliminated, a bridge's service life could be two to three times longer, and costly repairs could be avoided [3, 18].

In the prestressing technique [10], the prestressing tendons are placed outside the concrete section and the prestressing force is transferred to the concrete by means of end anchorages, deviators and saddles.

In the PSCC bridge, the external tendons may be used for prestressing of the composite reinforced concrete deck slab with steel plate girder for long span bridges. The reinforced concrete deck slab is first cast over the plate girder incorporating end anchorages and ducts to house the tendons. When concrete attains sufficient strength, the high tensile wires are tensioned by means of jacks bearing on the end block of the deck slab and anchored. Singh [20] explained that the prestressing force is transmitted to the deck slab concrete which will raise the stress level of the concrete deck slab and improve its behaviour under fatigue loading significantly, and eliminate the deck slab concrete shrinkage. Additional undesirable compression due to anchoring of tendons in the plate girder is also avoided by anchoring the tendons in the end block of the deck slab concrete.

The primary objective of this paper is to compare the total area of steel girder and prestressing force required in the cables, and stresses in the deck slab using various span lengths and girder spacing.

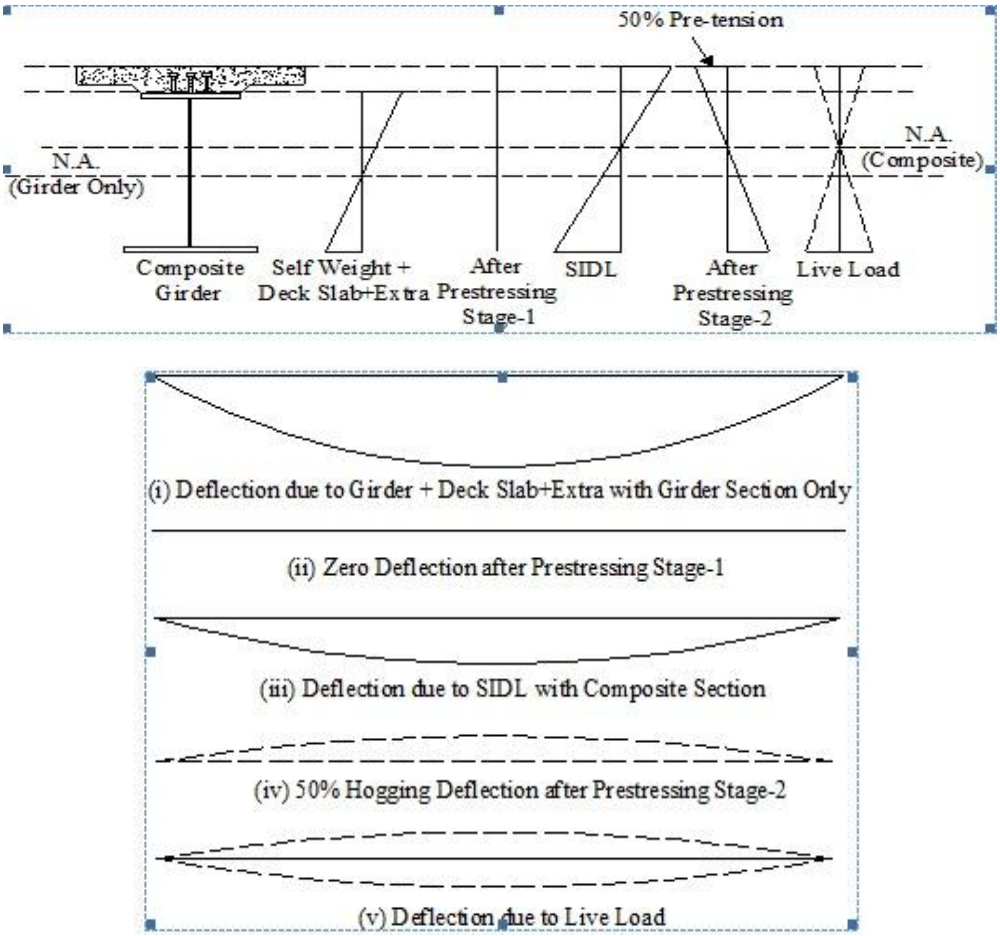

Fig. 1. Variation of flexural stress and deflection for 50% of LL hogging case

Parameters which are common for all the span bridges are:

Grade of concrete	=	M40
Width of deck	=	12 m
Thickness of deck	=	200 mm
Number of cross beams	=	7
Number of cables	=	14

Position of cables = Anchored at the bottom end of cross beams

The following variable parameters were considered in this study:

- Span lengths: 20 m, 40 m, 60 m, 80 m and 100 m
- Girder spacing: 4 girders at 3.0 m and 5 girders at 2.5 m
- Hogging case: 50% of live load deflection

In the hogging case (Fig. 1), in PSCC bridges prestressing is done intentionally to develop upward deflection (hogging) so that bridge curvature under live load is reduces to half. Prestressing is done to provide initial hogging deflection of the 50% of full LL. In service condition the deflection and flexural stresses from the horizontal references are only the 50% of full LL deflection and flexural stresses of the bridge.

II. ANALYSIS OF BRIDGES

PSCC Bridges are designed as per Indian Standards [11, 12] for comparison. Figure. 2 show the typical design of 40.0 m span bridge with 5-girder system.

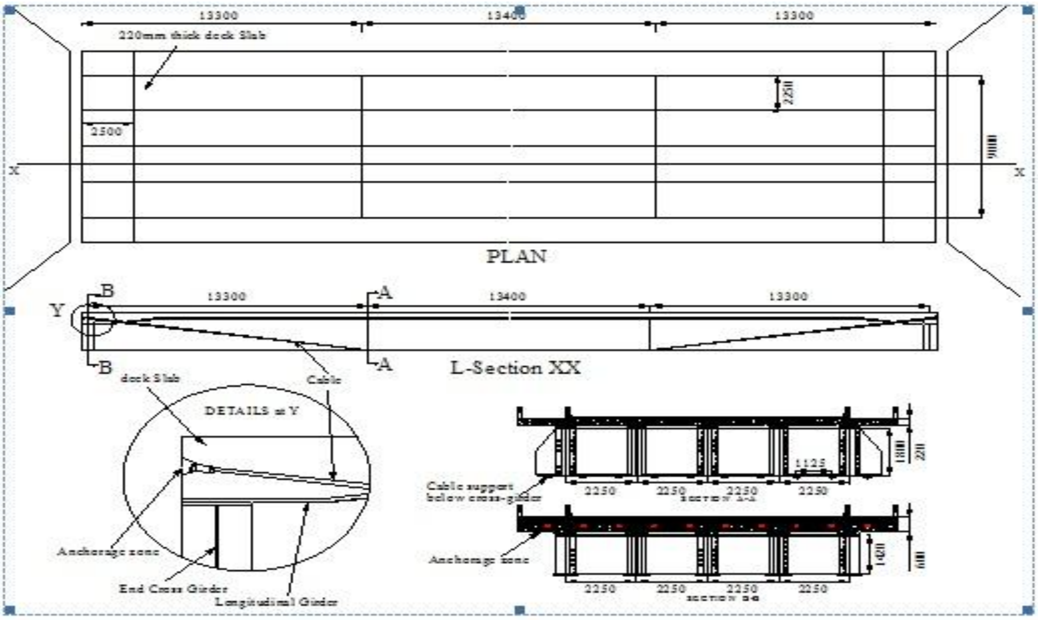

Fig.2. Typical design of 40.0 m span PSCC Bridge with 5-girder system

Figures 3-a and 3-b shows the cross section of 5-girders and 4-girders system, respectively.

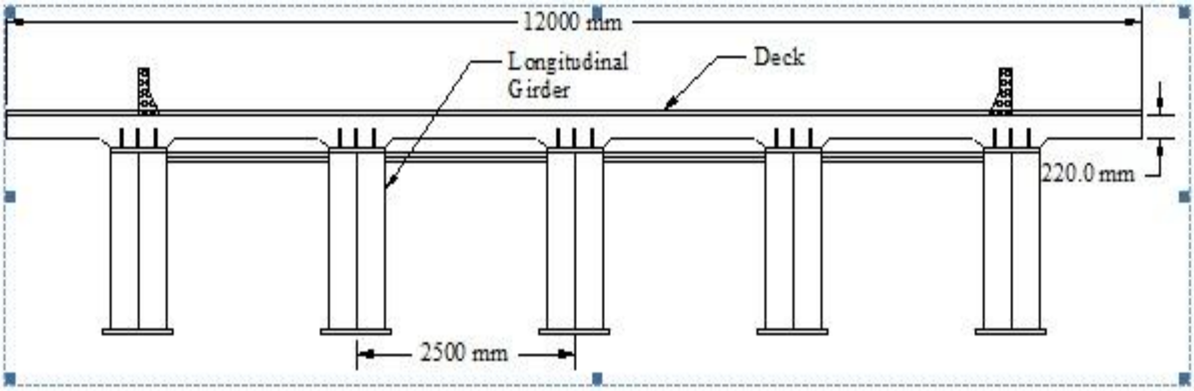

Fig. 3.a Cross Section of 5-Girders Composite Bridge

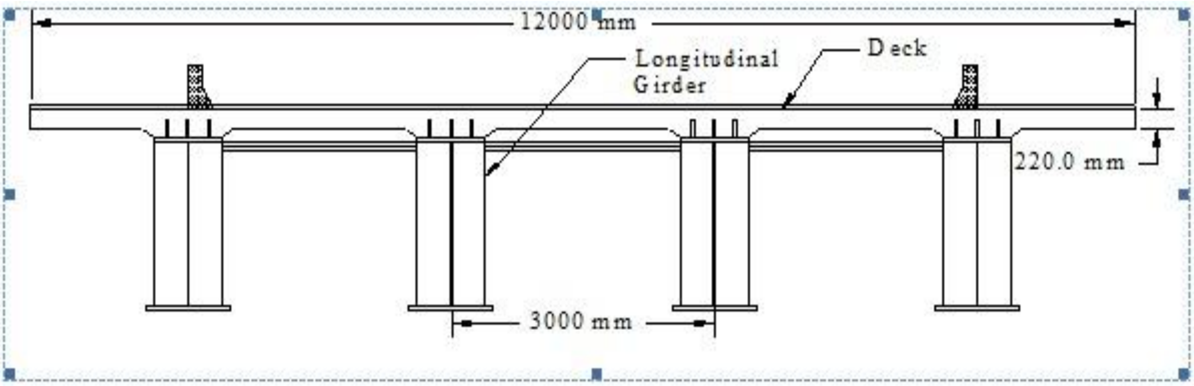

Fig. 3.b Cross Section of 4-Girders Composite Bridge

Various combinations of cross-section were generated to optimize the resulting bridge profiles keeping the maximum flexural stresses and maximum deflection at the mid span within the permissible limits. Resulting bridges were studied to investigate the influence of prestressing force and girder spacing.

III. DESIGN RESULTS

As per Indian Standards, Class 70R wheeled and tracked loads, two lanes Class A load, and Bogie load are considered for calculating the live load effects on the bridges. Maximum bending moment and deflection are computed using STAAD.Pro V8i software. Various results for different spans and girder spacing are calculated using MATLAB.

Summaries of resulting designs are presented in Tables I and II, for 5-girders and 4-girders composite bridge designs, respectively.

It may be noted that these designs were performed to observe qualitative trends between the variables described above. Changes in the design assumptions will naturally change the resulting design values. Following subsections provide summary comments regarding the influence of the variable parameters on bridge performance.

Changing the tendon force and eccentricity alters the vertical force exerted on the structure. Vertical component of prestressing force is transferred to the support through the vertical stiffener. Horizontal component of the prestressing force provides axial compression in the deck slab concrete.

Prestressing force for zero deflection under dead load and imposed load eliminate shrinkage cracks and increase the stress level in the deck slab, Further, higher stress level in the deck slab results in its better performance under fatigue loading.

Table-I. Summary of Study: 5 Girder System Composite Bridge

Span (m)		20	40	60	80	100
Girder web (mm)	Depth	1400	1800	2200	2600	3000
	Thickness	10	12	14	15	15
Girder top flange (mm)	Width	400	500	600	800	800
	Thickness	20	30	40	50	60
Girder bottom flange (mm)	Width	500	600	800	900	1000
	Thickness	20	30	40	50	60
Girder cross section area (mm^2)		32,000	54,600	86,800	124,000	153,000
Total Steel Area (5*Ag)		160,000	273,000	434,000	620,000	765,000
Without Hogging						
Total Prestressing force required in each cable (kN)		1080.5	2150.8	3423.2	4531.5	6000.3
Stresses in deck slab at mid section (N/mm^2)	Direct	3.27	6.31	6.86	6.26	7.19
	Flexural	5.84	7.33	7.48	7.20	7.04
	Total	3.27-9.12	6.31-13.64	6.86-14.35	6.26-13.54	7.19-14.22
Hogging with the 50% of LL deflection						
Total Prestressing force required in each cable (kN)		1322.3	2492.8	3819.5	4963.7	6457.9
Stresses in deck slab at mid section (N/mm^2)	Direct	5.31	8.24	8.38	7.55	8.31
	Flexural	5.84	7.33	7.48	7.20	7.03
	Total	2.39-8.24	4.57-11.90	4.64-12.12	3.95-11.15	4.79-11.83

Table-II. Summary of Study: 4 Girder System Composite Bridge

Span (m)		20	40	60	80	100
Girder web (mm)	Depth	1500	2000	2500	3000	3500
	Thickness	10	12	14	15	15
Girder top flange (mm)	Width	400	500	600	800	800
	Thickness	20	30	40	50	60
Girder bottom flange (mm)	Width	500	600	800	900	1000
	Thickness	20	30	40	50	60
Girder cross section area (mm^2)		33,000	57,000	91,000	130,000	160,500
Total Steel Area (4*Ag)		132,000	228,000	364,000	520,000	642,000
Without Hogging						
Total Prestressing force required in each cable (kN)		1170.4	2287.3	3549.3	4587.7	5959.4
Stresses in deck slab at mid section (N/mm^2)	Direct	2.90	5.47	5.71	4.91	5.55
	Flexural	5.96	7.20	7.23	6.91	6.72
	Total	2.90-8.87	5.47-12.67	5.71-12.94	4.91-11.82	5.55-12.27
Hogging with the 50% of LL deflection						
Total Prestressing force required in each cable (kN)		1441.8	2660.9	3975.4	5047.6	6442.6
Stresses in deck slab at mid section (N/mm^2)	Direct	4.87	7.29	7.13	6.11	6.60
	Flexural	5.96	7.20	7.23	6.91	6.72
	Total	2.01-7.85	3.69-10.89	3.51-10.74	2.65-9.56	3.24-9.96

3.1. Span Comparison for PSCC 5-Girder System Bridges

As the span length increases from 20.0 m to 100.0 m, the corresponding depth of girders required increases from 1400 mm to 3000 mm. The total cross-section area of girders required also increases from 160,000 mm^2 to 765,000 mm^2 with increase in the span length.

The prestressing force required in the cable increases from 1080.5 kN to 6000.3 kN for no hogging case, and from 1322.3 kN to 6457.9 kN for the 50% of LL hogging case. Thus, by marginally increasing prestressing force in the cables for the 50% of LL hogging case, the range of flexural stresses due to live load becomes half, which decrease the strain range in the concrete, so there will be very less fatigue in the deck slab.

Due to prestressing force the stresses in the deck slab are raised in the range of 3.27 N/mm^2 to 14.22 N/mm^2 for no hogging case, and 2.39 N/mm^2 to 11.83 N/mm^2 for the 50% of LL hogging case. The maximum stress in the hogging case is also lower than that of no hogging case. Higher stress level in the deck slab results in its better performance under fatigue loading. Shrinkage and creep, and prestressing losses are also taken care of by anchoring the cables into the deck slab.

3.2. Span Comparison for PSCC 4-Girder Bridges

As the span length increases from 20.0 m to 100.0 m, the corresponding depths of girders increase from 1500 mm to 3500 mm. With increase in the span length the total required cross-section area of girders increases from 132,000 mm^2 to 642,000 mm^2.

The prestressing force required in the cable increases from 1170.4 kN to 5959.4 kN for no hogging case, and from 1441.8 kN to 6442.6 kN for the 50% of LL hogging case. Thus, by marginally increasing the prestressing force in the cables for the 50% of LL hogging case, the range of flexural stresses due to live load becomes half, which decrease the strain range in the concrete resulting in lower fatigue in the deck slab.

Due to prestressing force the stresses in the deck slab are raised in the range of 2.90 N/mm^2 to 12.94 N/mm^2 for no hogging case, and 2.01 N/mm^2 to 10.89 N/mm^2 for the 50% of LL hogging case. The maximum stress in the 50% of LL hogging case is also lower than the no hogging case.

Higher stress level in the deck slab results in its better performance under fatigue loading. Shrinkage and creep, and prestressing losses are also taken care of by anchoring the cables into the deck slab.

3.3. Girder Spacing Comparison: 5-Girder System Vs 4-Girder System

For all the span length bridges the total area of steel required in the 4-girder system in nearly 20% lower than 5-girder system.

The required prestressing force in the cable is also marginally lower in the 4-girder system than 5-girder system.

The maximum stress (10.89 N/mm^2) in the deck slab is lower in the 4-girder system in comparison to the 5-girder system (12.12 N/mm^2).

IV. CONCLUSION

This study has presented the comparison of the total area of steel girder and prestressing force required in the cables, and stresses in the deck slab using various span lengths and girder spacings.

The following main conclusions are drawn from the study.

(1) 4-girder system is found to be beneficial and economical in bridge design as compared to 5-girder system for all the span length bridges.

(2) In comparison to no hogging case, in the 50% of LL hogging case, the range of flexural stresses due to live load is half, which decrease the strain range in the concrete, and hence results in reduced fatigue in the deck slab.

(3) Shrinkage strain can well be taken care of by anchoring the tendons into end block of the deck slab. Further, by doing so stress level of concrete deck is raised, resulting in its better performance under fatigue loading.

(4) In all cases, the 4-girder bridge case resulted in approximately 20% lower girder area (or weight) than the 5- girder bridge case.

(5) In all cases, the prestressing force required in the 4-girder system bridge is little lower than that of 5- girder bridge system.

(6) The maximum stress (10.89 N/mm^2) in the deck slab is lower in the 4-girder system in comparison to the 5-girder system (12.12 N/mm^2).

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