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論文 Flexural Behavior of Two Span Continuous Segmental PC Beams with Exeternal Tendons

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ABSTRACT: Precast segmental concrete bridges with external prestressing have become popular in the current construction trend due to their advantages such as reduced web thickness and possibility of repairs. The use of continuous beams could be a remedy for reducing the number of expansion joints, thus providing a better driving conditions. However, the inherent structural behavior of such beams is not well understood especially at the ultimate limit state. This paper describes the experimental investigation conducted to examine the flexural behavior of two spans continuous beams with external and combined prestressing, with unsymmetrical loading.

KEYWORDS: confinement reinforcement, continuous beam, external prestressing, moment redistribution, precast segments, prestressed concrete

1. INTRODUCTION

One of the latest developments in the construction technology has been the use of external prestressing, which may be defined as a method of prestressing where major portion of the tendons is placed outside the concrete section. The concept of precast segmental construction with external tendons have been developed extensively in the past two decades. One of the important factors that favors this type of construction is the considerable economical and time saving. The use of continuous span structures is gaining popularity since the number of expansion joints are reduced, resulting in better driving conditions. However, questions have been raised on how these bridges will behave when subjected to loads greater than service loads because continuous reinforcement is not always provided across the match cast joints between segments. Concerns have been expressed that adequate ultimate behavior and sufficient strength could not be obtained. Moreover, lack of ductility of precast segmental bridge girders is another big issue that had to be addressed when such bridges are built as a frame structure in earthquake areas.

It has been shown by Matupayont [1] and Alkhari [2] that the eccentricity variations could have a marked influence in the ultimate strength of externally prestressed beams. In externally prestressed continuous beams, the presence of secondary moments due to prestressing, moment redistribution and plastic hinge rotation after yielding are some inherent structural behavior that had to be clearly understood. To obtain an insight of the ultimate flexural behavior of such beams, an experimental program was conducted on precast segmental two span continuous beams. In a previous investigation, the flexural behavior of such beams was studied with symmetrical loading conditions, whereas in the present study, the loading pattern was unsymmetrical to increase the moment ratio at critical sections. The results of this investigation are presented in this paper, with emphasis on the influence of confinement reinforcement and combined prestressing on strength and ductility. The experimental results are compared with the predicted ones based on the non-linear analytical program developed for the analysis of continuous beams with external prestressing.

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2. EXPERIMENTAL METHODOLOGY

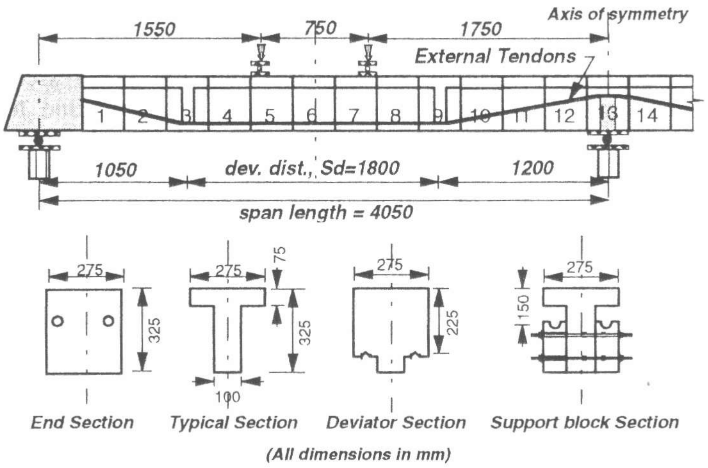
2.1 TEST VARIABLES AND SETUP

Three specimens with equal span length of 4.05 m having a T-shaped section were cast to study the flexural behavior. The span to effective depth ratio is 18.0 for all the specimens. The layout of test specimens is shown in Fig. 1. Specimen No.1 and No.2 are with external prestressing while specimen No.3 is prestressed with combination of internal and external prestressing. The difference between No.1 and No.2 is the provision of confinement in the compressive zone of concrete at critical locations. This was provided in view of increasing the rotational capacity at critical sections, thus improving the ductility of the structure, as shown in a previous study [3]. The confinement reinforcement is of D10 at 50 mm spaced rectangular hoops. This was provided in the top flanges in segments Nos. 5, 6, & 7, and in the bottom of web in blocks Nos. 12, 13 & 14 (see Fig.1). The segments are of 300 mm in length, provided with multiple shear keys. The specimens were concreted by long line match cast technique to have a good fit at the joints. These blocks were assembled and joined by epoxy resin.

Strain gages were attached to all the reinforcements (main, stirrups and confinement) at critical locations before concreting. Strain gages were also attached to the concrete surface of the cast specimen along the depth of the beam at desired points. To measure the strain variation in the tendons, gages were fixed at various locations along the length. Strain gages in the form of π-gages were mounted at critical locations where joint opening was expected. Load cells were placed at the anchorage ends of the external cables to measure the cable force. They were also set below the beam at each support to obtain the support reactions. The applied load was measured by the load cells put below the jacks. Displacement transducers installed placed at the mid span and deviators to measure the vertical deformation of the beam.

Table 1: Test variables and materials used

Specimen No.	Concrete strength (kg/cm^2)	Tendon type	Introduced prestress		Reinforcement		
			Force (tf)	% of f_{pu}	longitudinal	confinement	
						midspan	center-support
1. External prestressing, without confinement	384	SWPR7A 2-12.4 mm	18.01	55%	top: 2-D10, 2-D 6 bottom: 2-D10	-	-
2. External prestressing, with confinement	401		18.32			D10@50mm	D10@50mm
3. Combined prestressing, without confinement	436	SWPR7A 3-10.8 mm	12.03+ 6.32	50%		-	-



(All dimensions in mm)

Fig. 1 Layout diagram of 2-span continuous beam

2.2 TEST PROCEDURE

For specimens No.1 and No.2, two steel cables of type SWPR7A with 12.4 mm diameter were used as external tendons. For specimen No.3, which has combined prestressing, three cables of the same type with 10.8 mm diameter were used, two as external tendons and one as internal. All the specimens were subjected to a design prestress of 18.0 tf that was the maximum allowable value without allowing cracking. This force corresponds to approximately 55% and 50% of the ultimate tensile strength of the tendons for 12.4 mm and 10.8 mm diameter tendons respectively. Teflon sheets were inserted between the tendons and deviators to reduce friction. The joints were epoxied about a week before the testing and then a prestress force of 3.0 tf was introduced to fix the segments together. After hardening of epoxy, the beam was placed on the supports and further prestressed up to 18.0 tf. A clamping force of 1.0 tf was applied in the center support to prevent from uplifting during the prestressing, as uplifting was expected when the prestressing force exceeded 10.0 tf. In case of specimen No.3, that has combined prestressing, after epoxying, a force of 3.0 tf was applied through external tendons. Then, the internal tendon was stressed up to 6.0 tf, and grouted. Before testing, the balance force of 9.0 tf was applied to the external tendons.

Two point static monotonic loading was applied at a distance 0.75 m apart in each span, as shown in Fig. 1. However, the left span was heavily loaded compared to the right span, thus having an unsymmetrical loading arrangement. By doing this, the moment ratio at midspan to center support was increased, so that the mid span region would yield much earlier than the center support region. The loading in the right span was set to 30% of the applied load of left span. To achieve this it was necessary to control the two jacks independently. It was observed that the loading in the right span automatically increased when the left span was loaded. As such it was necessary to release some load on the right span at frequent intervals. After loading up to about 3.0 tf, the claming force at the mid-support was released, since the applied load was sufficient to prevent the beam from uplifting. At linear behavior, the measurements were taken approximately at 0.2 tf intervals. After yielding of the specimen, observations were recorded approximately at increments of 2.0 mm of mid-span displacement. The loading was stopped when crushing of concrete occurred in the left midspan, in specimen No.1. However, in specimens No. 2 and No.3, the loading was continued even after crushing of concrete at midspan section until crushing took place in the center support region.

3. TEST RESULTS AND DISCUSSION

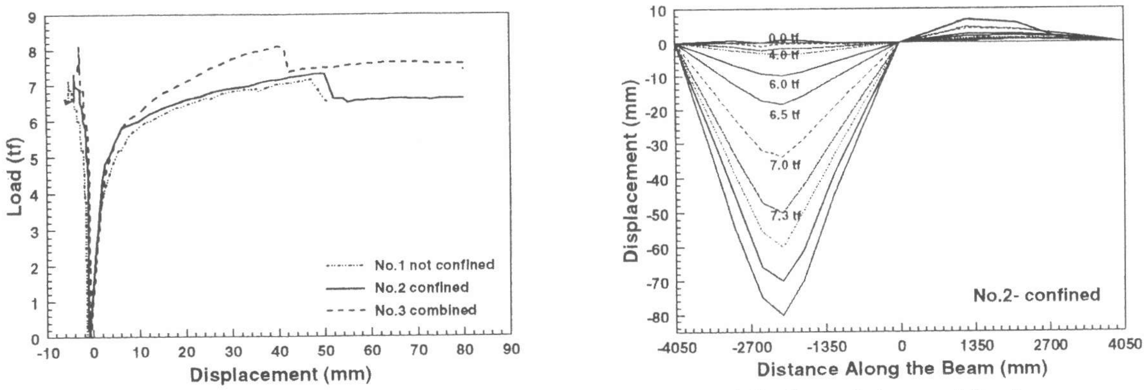
The experimental results of important parameters such as, concrete strength, applied prestress, ultimate loads, maximum deflection and mode of failure are summarized in Table 2, for the three specimens. Cracking was observed in the vicinity of the joint interface at the critical sections. The failure mode was due to crushing of concrete at the midspan region for all the specimens and crushing at center support for specimens No.2 and No.3. There was no yielding of external tendons. However, in specimen No.3, internal tendon yielded at a load of approximately 7.2 tf.

Table 2: Summary of experimental results in comparison to analytical results

Specimen No.	Load at first cracking (tf)				Maximum load (tf)		Max. deflection (mm)		Ultimate force in ext. tendons (tf)		Failure mode
	midspan		center support								
	test	analysis	test	analysis	test	analysis	test	analysis	test	analysis	
No. 1-Not confined	4.00	4.17 (0.960)	5.78	5.76 (1.003)	7.16	7.15 (1.002)	47.11	48.96 (0.962)	22.28	22.50 (0.990)	crushing of concrete *
No.2 - Confined	4.58	4.17 (1.100)	5.80	5.76 (1.007)	7.33	7.15 (1.025)	80.09	82.11 (0.975)	24.44	25.55 (0.957)	
No.3 - Combined	4.50	4.17 (1.080)	6.21	6.34 (0.975)	8.11	8.49 (0.955)	80.05	61.20 (1.308)	16.90	15.75 (1.073)	crushing of concrete * yielding of inner cable

Note: The values in ( ) represent the correlation of Experimental/Analysis

* The expected failure mode for all the specimens were the same as the observed failure mode



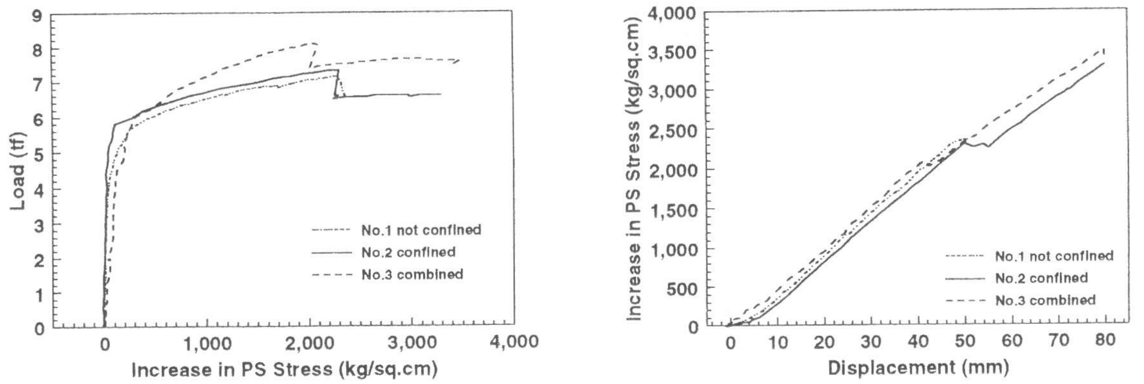
(a) Load-displacement characteristics **(b) Deflected shape of the beam**

Fig. 2 Variation of displacement with applied load

3.1 LOAD-DISPLACEMENT CHARACTERISTICS

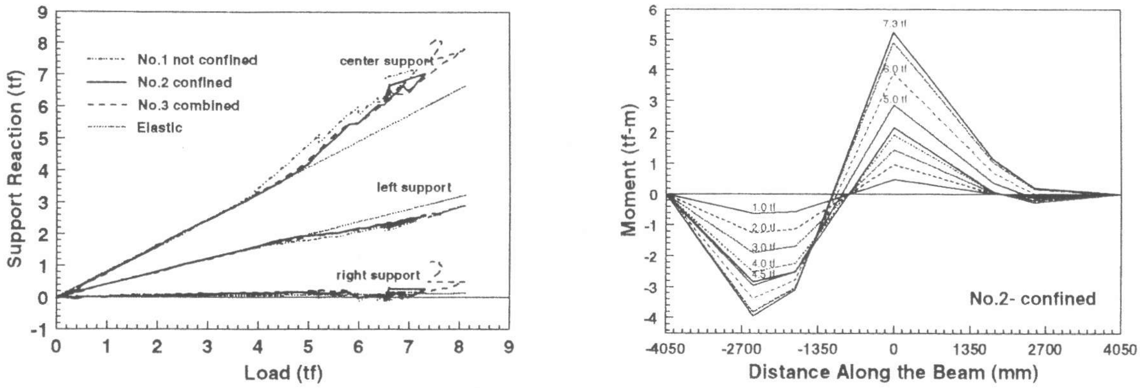
The observed load-displacement behavior for the left and right spans is given in Fig. 2(a). The displacement along the beam with increasing loading is shown in Fig.2(b) for specimen No.2. It could be seen that the right span had an upward displacement since the load on this span was approximately 30% of the left span load. The maximum load of the specimen No.3 with combined prestressing is the highest, 13% higher than that of No.1. Considering the final displacement, it can be seen that both the specimens No.2 and No.3 show 70% larger than specimen No.1. It should be noted that the load displacement characteristics of No.1 and No.2 followed almost the same path until crushing of concrete occurs at midspan. In addition, the displacement characteristics of No.2 and No.3 are similar except that No.3 has a higher load carrying capacity. From the above observations, it can be concluded that regarding ductile behavior, providing confinement reinforcement or combined prestressing produces similar results. As such, it can be expected that a mixture of combined prestressing and confinement reinforcements provide the best solution in view of strength and ductility. However, it is suggested that further research is should be carried out in this area.

Increase in external tendon stress with applied load and midspan displacement are given in Fig.3(a) and (b) respectively. From Fig.3(b), it could be seen that the stress increased in a nearly linear manner following almost the same path for all the specimens. In specimen No.2 and No.3, there was a slight drop in the stress after crushing occurred. However, it increased gradually with further loading.



(a) Variation with applied load **(b) Variation with midspan displacement**

Fig. 3 Variation of stress in external tendons



(a) Variation of support reaction with load

(b) Distribution of moments along the beam

Fig. 4 Effect of moment redistribution in continuous beam

3.2 MOMENT REDISTRIBUTION

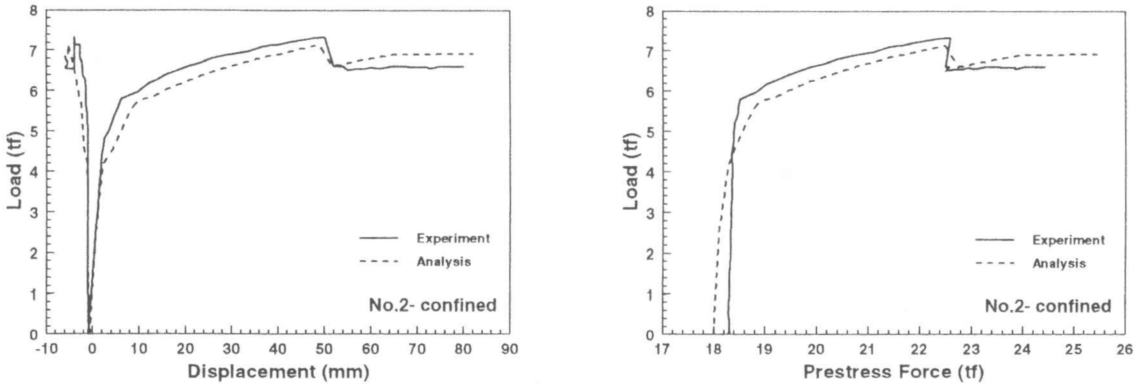
When the moment at a critical section reaches the yield moment, redistribution of moments takes place in continuous beams. This phenomena was discussed in detail in a previous investigation [4]. This will result in change of support reaction in a non-linear manner after reaching the plastic moment. Fig.4(a) shows the variation of observed support reaction with loading. From the variation of load with observed support reactions, the redistribution of moments was calculated. The moment distribution along the beam is shown in Fig.4(b) for specimen No.2. Similar pattern was observed for the other two specimens. It was observed that there is a clear change in support reactions after cracking at midspan section. In all the specimens, the center support reaction showed an increasing value compared to the calculated elastic behavior while the end supports reactions showed a decreasing value. The observed and calculated elastic moments are summarized in Table 3. It is noted that the midspan section has a positive redistribution with an average of 15% while the center support section shows a negative value with average of 55%. It may be concluded that the externally prestressed continuous beams have the ability of redistributing the moments when the critical section reaches the yield moment.

Table 3: Summary of ultimate moments and percentage of moment redistribution

Specimen No.	Calculated elastic moments, M_e (tf-m)		Observed plastic moments, M_p (tf-m)		Moment redistribution (%) $[1-M_p/M_e]$	
	mid of left span	center support	mid of left span	center support	mid of left span	center support
1-Not confined	4.450	3.352	3.751	5.414	+17.4	-61.5
2- Confined	4.648	3.432	3.984	5.168	+14.3	-50.6
3- Combined	5.142	3.797	4.449	5.610	+13.5	-47.8

3.3 COMPARISON WITH ANALYTICAL RESULTS

A non-linear analytical approach was adopted to predict the flexural behavior of precast segmental continuous beams with external prestressing based on existing methodology [1, 2, 5]. Both material and structural non linearities have been taken into account [1,5]. Modified Kent-Park model was used to calculate the effect of confinement reinforcements [6]. The moment redistribution was also incorporated based on the ultimate moment capacities of the two critical sections. The comparisons of experimental to analytical results are given in Table 2. The load-displacement characteristics and variation of tendon force are shown in Fig.5(a) and (b) for specimen No.2. There is very good agreement between the analytical and experimental results. Similar agreement was obtained for the other two specimens. However, the difference of 30% in the ultimate deflection of specimen No.3 can be attributed to the unexpected spalling of cover concrete at an early stage compared to the other specimens, thus having a larger deflection than estimated at a slightly lower load.



(a) Displacement characteristics **(b) Variation of force in external tendons**

Fig. 5 Comparison of experimental results with analytical prediction

4. CONCLUSIONS

The experimental investigation on flexural behavior of two span continuous beams with unsymmetrical loading was carried out using precast segmental beams with external prestressing. The effect of confinement reinforcement and combined prestressing on strength and ductility of the beams was also observed. The followings can be concluded from this study.

- The beam containing the combined prestressing has a higher load carrying capacity than the beams with fully external prestressing.
- The ductility of precast segmental beams could be improved further by providing confinement reinforcement. It could be also improved by having some internal bonded tendon together with external tendons.
- All the beams showed a significant moment redistribution. The left midspan location showed a positive redistribution while the center support sections showed negative redistribution.
- It is proposed that further investigation should be carried out to study the influence of combined prestressing on strength and ductility of precast segmental beams. It would be useful to conduct an investigation varying the ratio of internal to external prestressing.

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