BEHAVIOR OF ONTARIO-TYPE SKEW BRIDGE DECKS

온태리오형 교량상판의 거동에 관한 연구(사교의 경우)

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요 약

사교의 경우에 있어서 온태리오형 상판의 거동에 대하여 실험 및 해석적으로 연구하였다. 텍사스주에서 수정 제안된 온태리오형 상판의 상세에 따라 실물크기 모형을 제작하여 상판의 양단부와 중앙에서 상판이 파괴될 때까지 수행하였다. 실험모형은 현행 AASHTO 설계하중에서 뿐만 아니라 설계하중의 3배에 달하는 초과하중에서도 만족스러운 거동을 하였다. 상판의 양단부는 전단, 중앙부는 펀칭전단에 의하여 파괴되었으며 실제파괴강도는 아치현상을 고려하여 계산한 휨파괴강도보다 훨씬 작았다. 실험결과를 예측하고 다른 경우에 대해서도 사용할 수 있도록 해석모델을 구축하였으며 실험결과와 매우 근사한 해석결과를 얻었다.

ABSTRACT

An experimental and analytical investigation was conducted regarding the behavior of reinforced concrete skew bridge decks with Ontario-type reinforcement. A full-scale model representing the essential behavior of a full skew bridge was built and tested. The test specimen had details similar to those required by the Ontario Highway Bridge Design Code, modified as recommended by the Texas State Highway Department.

The skew bridge deck performed satisfactorily under the current AASHTO design load levels as well as the overload conditions(about 3 times the current AASHTO design wheel load). The skew edges failed by shear ; the center by punching shear. The calculated flexural capacity considering arching action always far exceeded the actual failure load (shear or punching shear) at each test location.

To check the experimental results a detailed finite element model of the specimen was developed using a general-purpose structural analysis program. Analytical predictions and experimental results agreed closely.

1. Introduction

A current trend in the design of reinforced concrete bridge decks is to consider the effect of in−plane membrane forces which significantly increase the flexural capacity of the deck. This phenomenon, referred to as "arching action" in much of the literature, is the basis for the semi−empirical design provisions of the current Ontario(Canada) Bridge Design Code

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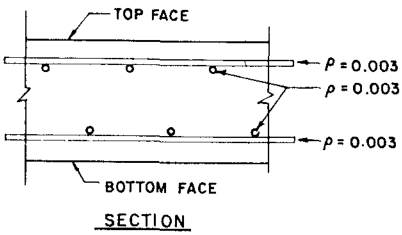
[1]. According to the empirial design method, design of the deck slab involves prescribing 0.3 % reinforcement in each direction at the top and bottom of the deck as shown in Fig.1[1]. This required reinforcement is considerably less than(about 60% of) that required by the current AASHTO design code[2]. Reduced flexural reinforcement can lead to reduced construction as well as maintenance costs, because the reduced steel area has less tendency to cause popouts and spalling of the deck surface. The research described here concerns the investigation of the performance of Ontario−type skew bridge decks.



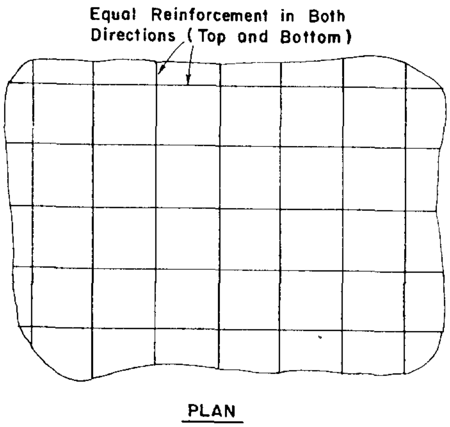


Fig. 1. Reinforcement layout prescribed by empirical method

2. Background

In a reinforced concrete beam with fixed supports at both ends arching action can be developed after flexural cracking. The neutral axis of the cracked beam is shifted toward the bottom fiber at the supports, and toward the top fiber at midspan. Under vertical loads, each uncracked portion of the beam rotates about the point where its neutral axis intersects the support(Fig. 2). Because of the eccentric location of the neutral axis, compressive membrane forces are developed even with small deflections of the beam. Bridge decks, which span transversely and are supported by girders, are analogous to the cracked beam discussed above.

Historically, the effect of in−plane membrane forces on the load carrying capacity of reinforced concrete slabs has been investigated for several decades[3, 4, 5, 6]. Since 1969, many field tests have been conducted by the Structural Research Section of the Ontario Ministry of Transportation and Communications [7]. It was found that the reinforced concrete deck slabs carried loads much greater than the loads predicted by traditional analysis methods, even if the deck had been considerably deteriorated, or if a large percentage of the reinforcing steel had been lost due to corrosion.

To investigate the behavior of such bridges, a series of studies were conducted, under the sponsorship of the Ontario Ministry of Transportation and Communications[8, 9]. Based on

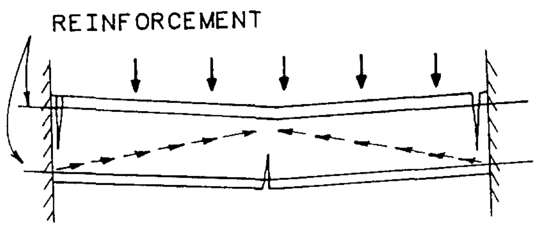


Fig. 2. Arching action in cracked beam

these studies, the empirical design method was developed. In the United States, States of New York and Texas conducted studies of strength of modified Ontario−type highway bridge decks to employ the empirical design method[10, 11, 12].

3. Tests and Analysis

3.1 Tests

A full scale test specimen detailed according to the modified Ontario−type decks was constructed and tested. Instead of buiding a full bridge, a skew bridge test specimen that would behave like the full skew bridge was developed after several analytical trials were conducted using a finite element analysis program. Three dimensional and plan view of the specimen are shown in Fig. 3 and 4 respectively. Three series of tests were conducted : 45−degree skew edge tests ; 20−degree skew edge tests ; and center tests. The load location used for each test series is shown in Fig. 4. At each location, the specimen was first loaded up to about three times the current AASHTO design wheel load and unloaded. Then the specimen was tested to failure.

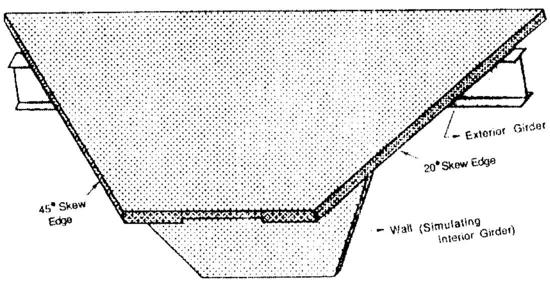


Fig. 3. Three dimensional view of skew bridge test specimen

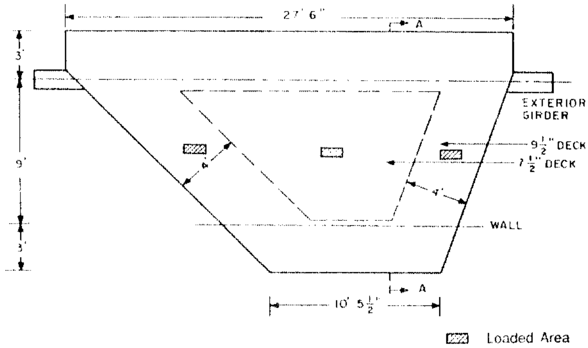


Fig. 4. Plan view of skew bridge test specimen

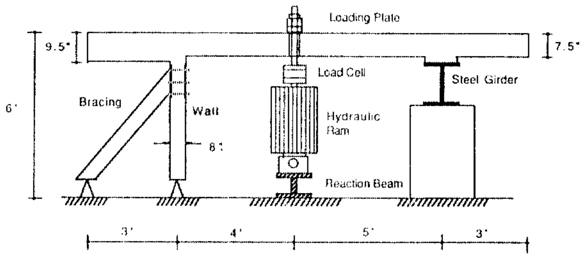


Fig. 5. Cross section of test sctup

The cross section of the test setup is shown in Fig. 5.

The behavior of the specimen was monitored at 5− or 10−kip intervals during the test through instruments located at various points on the test specimen. Locations of the instruments are shown in Fig. 6.

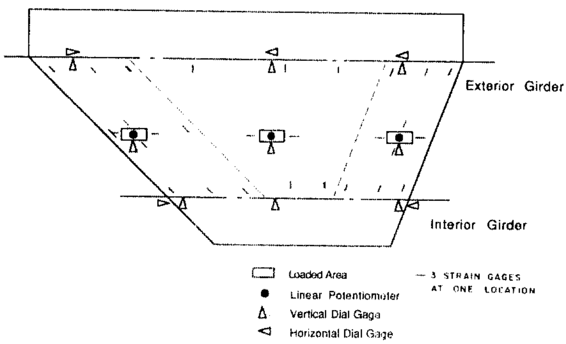


Fig. 6. Instrumented locations

3.2 Analysis

Finite element models of the test specimen were developed using an existing structural analysis program(SAP4), to check the experimental results and permit their extention to bridge decks other than the one studied experimentally. Fig. 7 shows the finite element mesh for skew bridge test specimen. The bridge deck and the wall were modeled using two layers of 16-node thick shell elements(Fig. 8). Composite action of the deck slab and the girder was modeled using a combination of thick shell elements and three-dimensional beam element connected with rigid links.

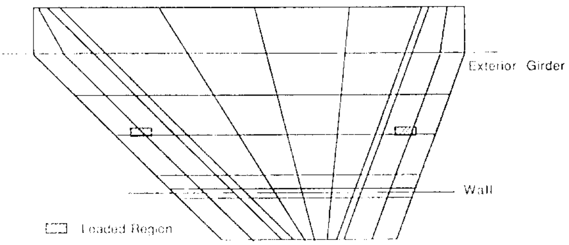


Fig. 7. Finite eement mesh for skew bridge test specimen

Since the primary objectives of the research was to study the effect of the compressive membrane action developed in the deck after cracking, a good representation of deck cracking was necessary. For crack representation, smeared crack models are used. Nonlinear behavior due to cracking was modeled using a sequence of lenear elastic analyses. A schematic representation of this sequential approach is presented in Fig. 9.

The modeling concept and analytical approach described above were verified by analyses and tests in the previous research[11].

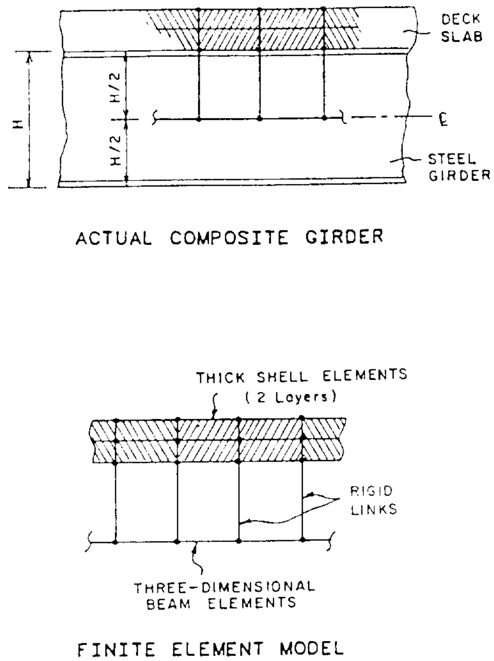


Fig. 8. Schematic representation of finite element model of composite girder

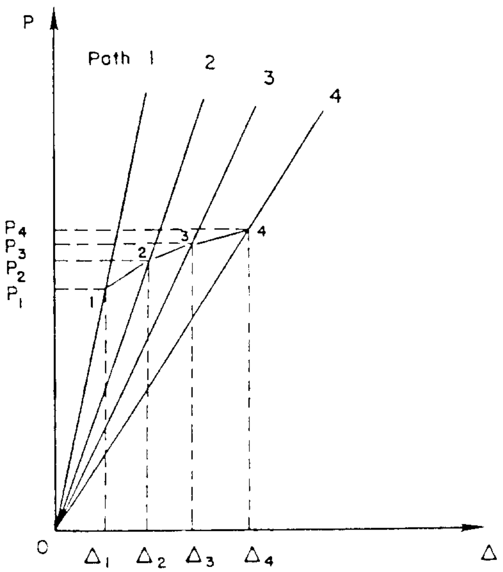


Fig. 9. Schematic representation of sequential linear approach

4. Discussion of Test Results and Analysis

4.1 Overall Behavior

The test specimen was analyzed using program SAP 4, a general purpose finite element analysis program and these analytical results were compared with experimental observations. Load−deflection relationships from tests to failure are shown in Fig. 10. The 45−degree skew edge failed by combined shear and torsion near at the interior support wall ; the 20− degree skew edge, by shear ; and the(Wall) center, by punching shear.

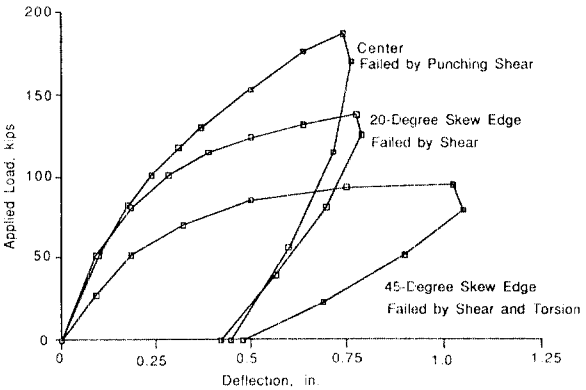


Fig. 10. Load−deflection relationships at loaded points, tests to failure.

The cracking patterns are shown in Figs. 11 and 12. The first bottom crack direction at each edge was almost perpendicular to the edge. This implies that the principal tensile stress is oriented parallel to the skew edge, and that using the skew span length is reasonable in the design of skew bridge decks. Maximum crack width was about 0.003 in. at service load level of 20.8 kips which smaller than the implied maximum allowable crack width of Ref. 2, even after the deck had been severely cracked by prior overload tests.

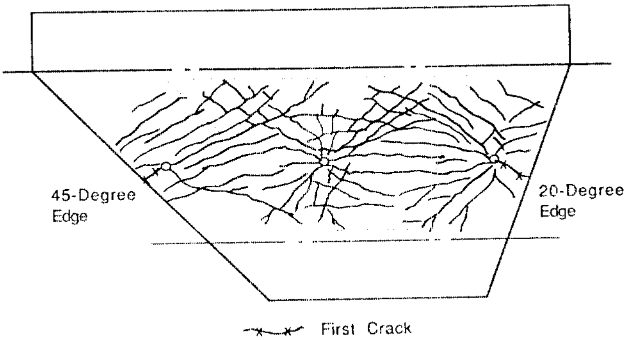


Fig. 11. Final cracking pattern on bottom surface after tests to failure.

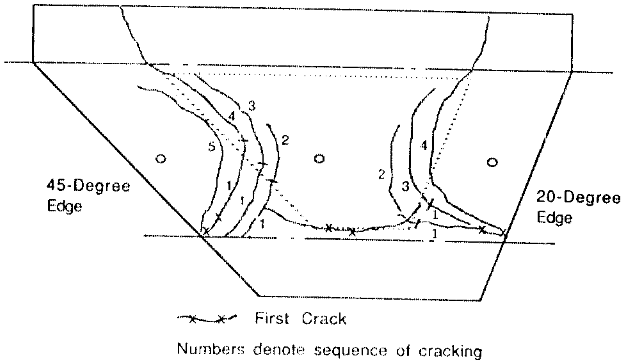


Fig. 12. Deck top cracking after failure testes.

At the 45−degree skew edge, most bottom cracks propagated perpendicular to the edge. However, many fan−type cracks were found at the bottom of the 20−degree skew edge. This implies that beam−type behavior was dominant at the 45−degree skew edge, while there was combination of beam action and slab action at the 20−degree skew edge. Crack propagation at the center was typical of a slab with a concentrated load. At each edge, top cracking consisted of a series of arcs around each loaded point.

In Figs. 13 and 14, the typical transverse moments and in−plane membrane forces calculated from test results are compared with analy tical results. In those figures, two calculated values are presented : one from the full skew bridge model ; and the other from the test specimen. The experimental and both calculated values agree closely, which proves the validity of the test specimen as well as the analytical model.

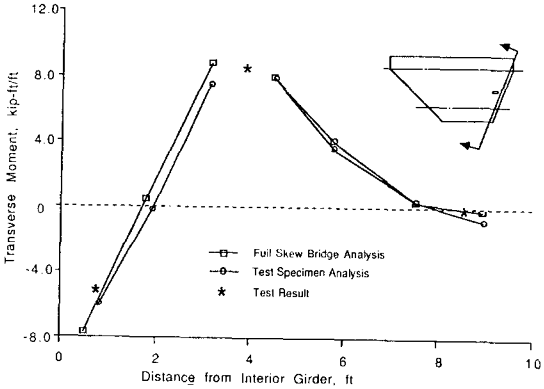


Fig. 13. **Transverse moments along 20－degree skew edge(after cracking, P＝40kips)**

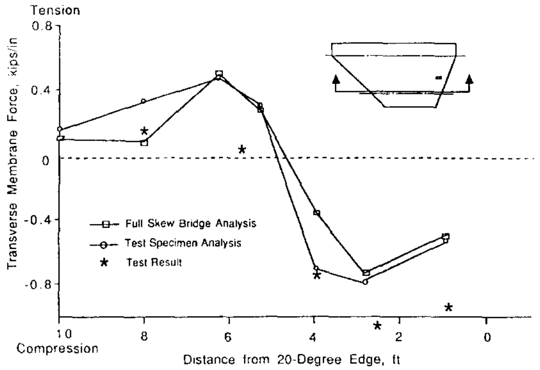


Fig. 14. **Transverse membrane force at interior girder, 20－degree skew edge test, (after cracking, P＝40kips)**

4.2 Observed versus Calculated Capacities

Capacities of the test specimen were calculated according to the current provisions of ACI 318－83 assuming different failure modes and compared with the observed actual failure loads. The results are shown in Figs. 15, 16 and 17. For each edge, the partial effective width means the measured actual failure length and the full effective width means the total width of the thickened edge of the deck which is the design width of the current AASHTO and Ontario Bridge Design Code. Flexural capacities with or without arching actions were calculated using yield－line analysis. When considering the arching action, flexural capacies of a deck increase due to the presence of the in－plane compressive membrane forces. This phenomenon could be interpretated using the moment－axial force interaction diagram as shown in Fig. 18. Flexural capacities considering arching action always far exceed the actual failure loads, which proved the validity of the Ontario empirical design method. It is noticeable that the actual failure load of the 20－degree edge is greater than the predicted flexural capacity neglecting the effects of arching action. This indicates that the flexural capacity of the deck increases with arching action, since the calculated

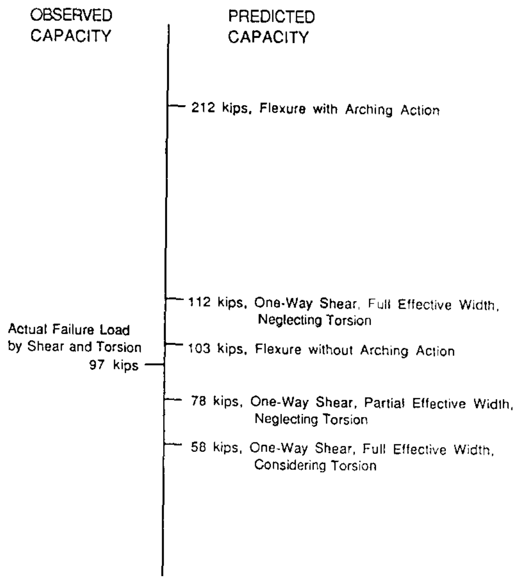


Fig. 15. **Observed vs. calculated capacities at 45－degree skew edge.**

flexural capacity without arching action is less than the actual failure load by shear, even though the calculated capacity by yield—line analysis is the upper—bound value.

Examining the figures from 15 to 17, it can be concluded that the current ACI shear formulars give very conservative estimations of the deck's shear capacity.

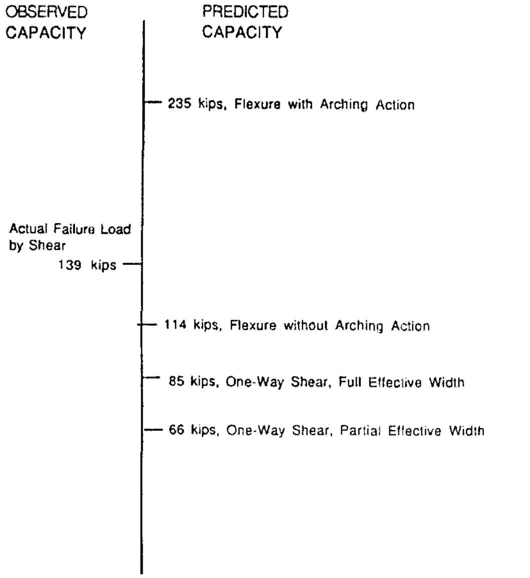


Fig. 16. Observed vs. calculated capacities at 20—degree skew edge.

5. Conclusions

1) An Ontario—type skew bridge deck, detailed in accordance with Texas Highway Department proposed provisions, performed satisfactorily under the current AASHTO design load levels as well as the overload conditions(about three times the current AASHTO design wheel load).
2) Analytical predictions and the experimental results agreed closely, which proved that the analytical model of the test specimen was satisfactory.

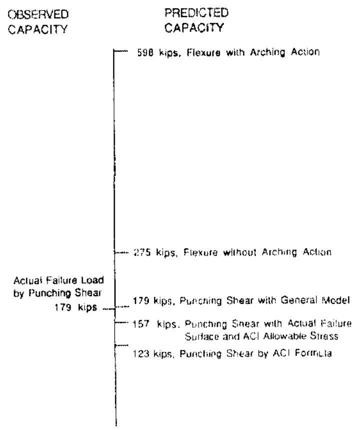


Fig. 17. Observed vs. calculated capacities at center.

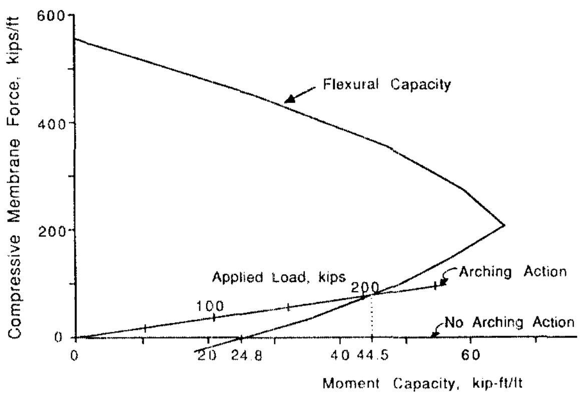


Fig. 18. Increase in flexural capacity of 4S—Deg skew edge due to compressive membrare force

3) Compressive membrane forces did exist in the Ontario—type skew bridge decks and significantly increased the flexural capacity of the deck. The ultimate flexural capacities of the bridge decks were much larger than the actual failure load.
4) Current AASHTO and ACI shear provisions give very conservative estimation of the deck's shear capacities.

6. Acknowledgement

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