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Behavior of Carbon Fiber-Reinforced Prestressed Concrete Skew Bridges

by Nabil F. Grace and George Abdel-Sayed

A new design and construction technique using carbon fiber-reinforced polymers (CFRP) prestressing tendons for skew highway bridges is presented in this paper. Two multiple double-T (DT) skew bridge models with 30 and 15 degree skew angles were constructed and tested. CFRP reinforcing rods and stirrups were used for flexural and shear reinforcement of the deck slab and the DT-girders. Internally bonded and externally unbonded draped CFRP tendons were used for prestressing in the longitudinal direction. CFRP tendons were also used for prestressing in the transverse direction. Conventional DT girders were modified by adding tendon deviators and cross beams through which the transverse prestressing was applied. The two bridge models were tested under static, repeated (7 million cycles), dynamic, eccentric, and ultimate loads. The effects of repeated load on the static and dynamic responses of the bridges and load distribution were examined. The influence of grouting the transverse CFRP prestressing tendons on the load distribution was also investigated.

The skew bridges designed and constructed using the described technique performed well during all phases of testing. The repeated load had no adverse effect on the dynamic and static characteristics of the tested skew bridges, and an insignificant effect on the load distribution in the transverse direction. None of the externally draped prestressing tendons experienced rupture under repeated or ultimate loads. Transverse load distribution exhibited the same characteristics whether the transverse prestressing tendons were bonded or not.

Keywords: bridges; carbon; fiber-reinforced concretes; girders.

INTRODUCTION

Skew bridges are frequently needed in a modern highway network because of geometrical considerations. Innovative designs, improved construction materials, and technologies have been combined to achieve significant economic and aesthetically pleasing profiles in skew bridge structures. The usual corrosion problems caused by steel reinforcement in these bridges, however, still exist. In coming years, thousands of skew bridges will be demolished and replaced. The cost of replacing these deteriorating skew bridges is enormous.

Fiber-reinforced polymer (FRP) reinforcements may be used in skew bridges to solve corrosion problems. These materials have characteristics that include a high resistance to corrosion, a high strength-weight ratio, low relaxation, and outstanding fatigue resistance. Significant research addressing the use of FRP in civil engineering has been conducted in Europe, Japan, and North America.[1,2] Applications have included reinforcing and prestressing beams, strengthening beams, walls, and columns. An extensive literature review has revealed no work addressing the use of FRP in reinforced or prestressed skew bridges.

In this study, a new design and construction technique for skew bridges using carbon fiber-reinforced polymers (CFRP) is presented. Both internal and external prestressing tendons were used. In addition, the conventional precast/prestressed double-T (DT) girders were modified by adding tendon deviators and cross beams through which transverse prestressing forces were applied. In the early stages of this research, it was determined that to fully exploit the advantages of CFRP prestressing tendons, a combination of internally bonded tendons and externally draped (unbonded) tendons should be used. This combination circumvents known shortcomings of CFRP prestressing tendons, that is, linear stress-strain behavior, low elastic modulus, and limited strain at failure. The effect of bonding the transverse prestressing tendons on the load distribution was also examined.

RESEARCH SIGNIFICANCE

The technology transfer of this new design and construction technique to practical applications requires comprehensive laboratory evaluation. To achieve this goal, two skew bridge models with two different skew angles were constructed and tested under different loading conditions. These loading conditions resembled various traffic load effects such as static, dynamic, and repeated loads. The findings of this investigation are essential for the construction of the planned Bridge Street bridge in the city of Southfield, Mich. This three-span skew bridge will be the first precast pretension/post-tensioned prestressed concrete bridge in the U.S. using internal CFRP tendons and external CFRP strands.

EXPERIMENTAL WORK

Construction of bridge models

Two CFRP prestressed concrete skew bridge models were constructed and tested under static, repeated (7 million cycles), dynamic, eccentric, and ultimate loads. The first Model DT-30 had a 30 degree skew angle, whereas the second Model DT-15 had a 15 degree skew angle. CFRP tendons were used for prestressing and flexural reinforcement.

Bridge Model DT-30 consisted of two modified precast DT girders, two tendon deviators, and two cross beams (Fig. 1). The two DT girders were precast and post-tensioned away from the testing area. CFRP prestressing tendons (10 mm in diameter) were used for prestressing in the longitudinal direction. Prestressing the DT girders internally placed the entire cross section in compression. After prestressing, the rods were grouted with a cement-based grout. The DT girders were then transported to the testing area and placed adjacent to one another using shear keys located at the cross beams and tendon deviators (Fig. 1). These keys ensured that no slippage occurred at the interface between the two DT girders during the application of the transverse and external prestressing. A mixture of epoxy and silica sand was poured into the interface between the two girders. This epoxy filled the 12 mm (0.5 in.) gap between the flanges of the two DT

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girders. Transverse prestressing at the cross beams and tendon deviators was applied after the epoxy cured, using 10 mm CFRP tendons. This prestressing ensured complete interaction between the two DT girders. After post-tensioning, the transverse rods were grouted with epoxy. A mesh of 8 mm CFRP rods was formed and was placed 25 mm (1.0 in.) above the top flange of the DT girders, for deck

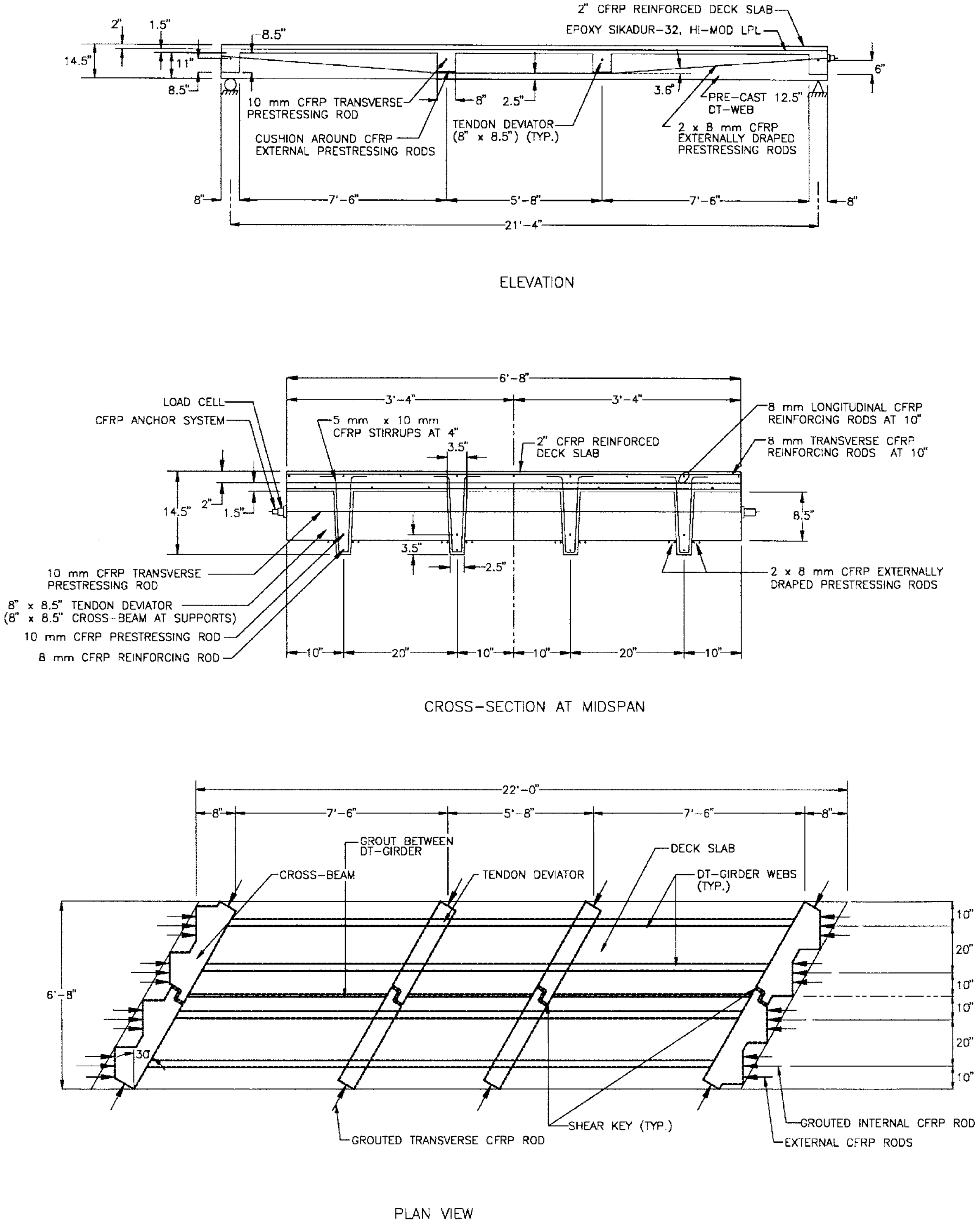
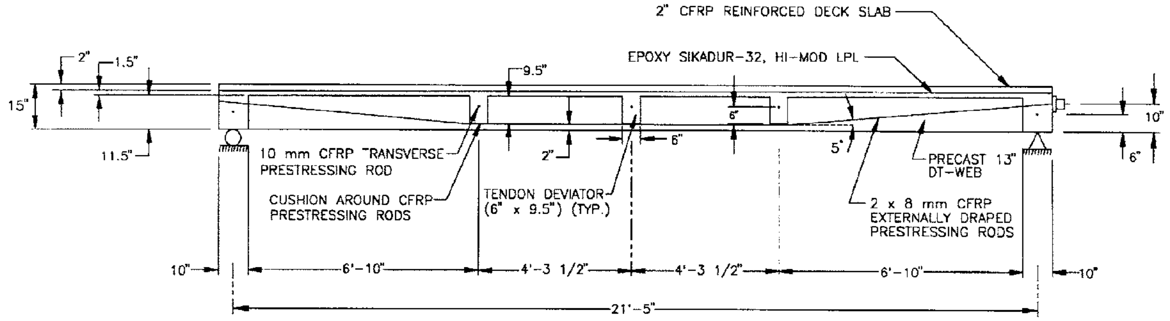
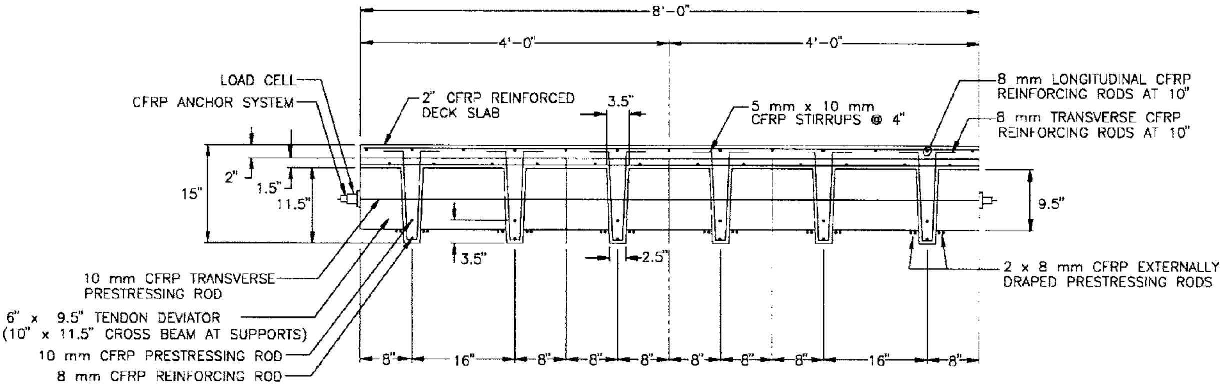


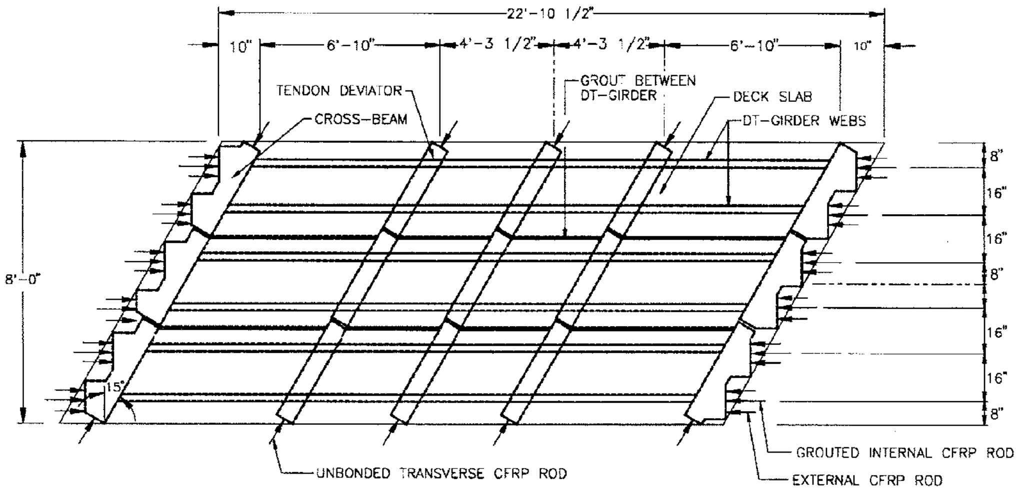
Fig. 1—Details of Bridge Model DT-30.



ELEVATION



CROSS-SECTION AT MIDSPAN

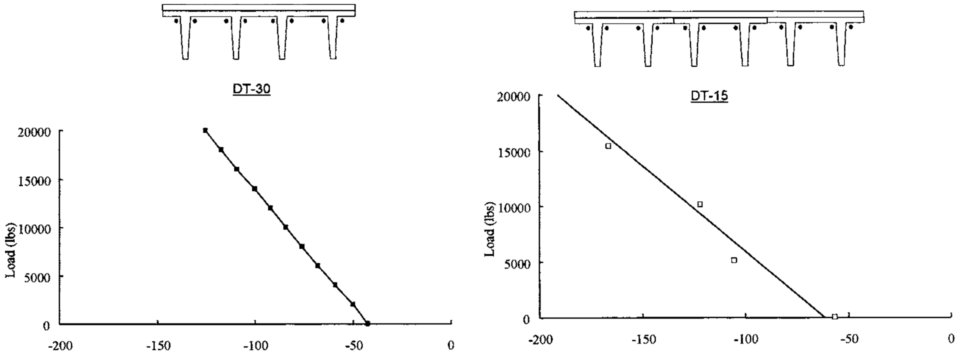


PLAN VIEW

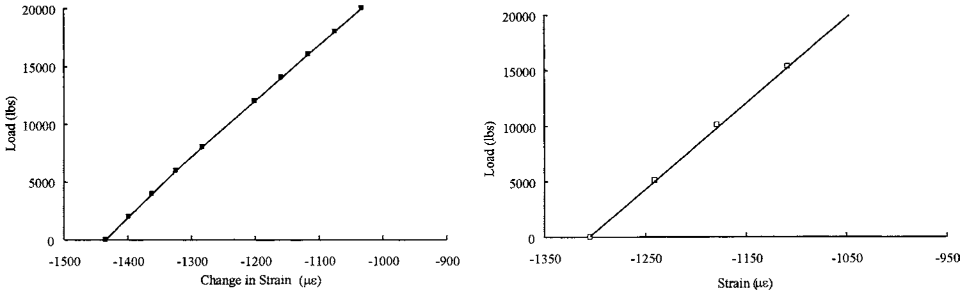
Fig. 2—Details of bridge Model DT-15.

slab flexural reinforcement. Prior to placing the concrete for the deck slab, a thin layer of epoxy was brushed onto the top surface of the flange of the two DT girders to provide bonding between the girders and the deck slab. This was necessary because the projected CFRP stirrups from the DT webs into the deck slab are weak in shear and may not provide adequate resistance to the horizontal shear. After the deck slab cured, the external prestressing tendons were positioned and tensioned. Two 8 mm CFRP tendons were externally draped and used for prestressing on either side of the DT girders webs. The external tendons were tensioned in an alternating sequence, beginning from the center and progressing outward from the cross section of the model. This was essential to avoid serious eccentric stressing on the cross section.

Bridge Model DT-15 consisted of three modified precast DT girders, three tendon deviators, and two cross beams (Fig. 2). Because this model had a smaller skew angle, shear



(a) Top Strain



(b) Bottom Strain

Fig. 3—Average change of strains at: (a) top strain; and (b) bottom strain due to static loading.

keys were not used in the construction. The model was constructed in a manner similar to Model DT-30. The three DT girders were precast and internally post-tensioned. After the girders were placed on their supports, grouting material was injected under pressure from one end of the girders to the other. Only the longitudinal internal tendons were grouted. The transverse prestressing forces were applied at the cross beams and tendon deviators. This linked the DT girders transversely without inducing a significant moment. After application of the transverse prestressing forces, the deck slab was poured. Finally, the externally draped tendons were post-tensioned. Additional details of construction can be found elsewhere.[3-7] As in Bridge Model DT-30, CFRP stirrups of 5 x 10 mm (0.2 x 0.4 in.) in cross section were used for shear reinforcement of the DT webs, cross beams, and tendon deviators. The stirrups were placed 100 mm (4 in.) apart and projected 25 mm (1 in.) above the top flange. This 1 in. projection was necessary to ensure adequate shear transfer and full interaction between the deck slab and the DT girders.

TESTING PROGRAM

The two bridge models underwent static, dynamic, repeated, eccentric, and ultimate load testing. In addition, Bridge Model DT-15 was held at a 2 in. deflection at midspan for 22 days to examine any losses that might be experienced by external prestressing tendons due to permanent deflection. A detailed discussion of this test can be found elsewhere.[7]

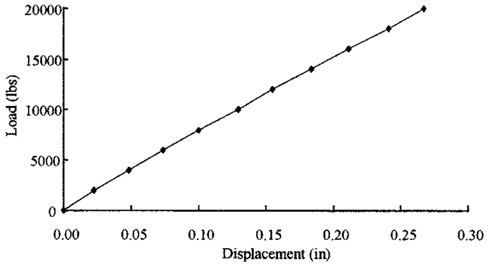
Static load testing was conducted using an eight-point loading incrementally applied at the midspan of Bridge Models DT-30 and DT-15. This eight-point loading was designed to simulate the loads of two scaled-down HS-25 trucks located at the midspan of the bridge model. In addition, bridge model DT-30 was tested using a four-point load simulating a scaled-down truck. Loads were applied in 8.9 kN (2 kips) increments to a maximum of 88.0 kN (20 kips) during testing of DT-30 and in 44 kN (10 kips) increments to a maximum of 222 kN (50 kips) during testing DT-15. The dynamic loading test was carried out using an impact force of 22 kN (5 kips) generated with a servo-hydraulic actuator. This maximum impact force can be generated using the available hydraulic equipment. The bridge's free vibration signature was measured using six accelerometers placed at different locations on the deck slab. The repeated loading test was conducted using a static set-point load of 35.2 kN (8 kips), which was then sinusoidally oscillated between 8.90 and 61.6 kN (2 and 14 kips) at a frequency of 2.0 Hz for 7.0 million cycles. The scaled-down working load level was estimated at 61.6 KN (14 kips); that is, the limits of oscillation were set between 14 to 100% of the working load.

Following the static, dynamic, and repeated loading tests, eccentric loading tests were conducted on the two bridge models. The objective of these tests was to determine how well the bridge system distributed transversely eccentric loads to the rest of the structure. This was essential to examine and compare the influence of bonding the transverse prestressing rods on the load distribution. The eccentric load was applied with a four-point load truck positioned on two webs at a time. The eccentric loading tests were carried out before and after the completion of repeated loading tests. This was done to determine the influence of the repeated load on the load distribution characteristics.

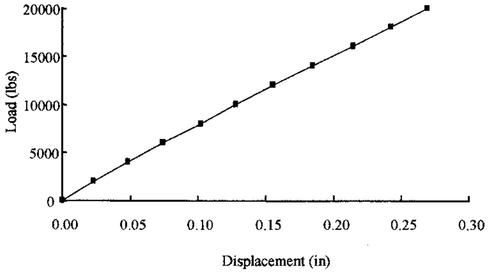
Upon completion of all the previously discussed tests, each bridge model was subjected to an ultimate loading test. This test was carried out in the same manner as the static loading test, with increased incremental loading until complete failure occurred.

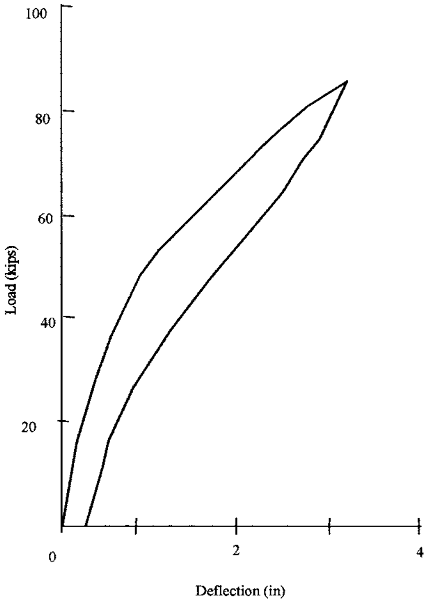
DISCUSSION

The behavior of the two bridge models during different phases of construction is discussed elsewhere.[5] In addition, the response of the external prestressing forces under static,



(a) Mid-span Deflection of DT-30 Due to 8 Point Load





(c) Mid-span Deflection of DT-15 Due to 8 Point Load

Fig. 4—Deflection response under static loading.

repeated, and ultimate loads is discussed in detail in Reference 7. In the following sections, the behavior of the two skew bridge models under the various loading conditions is addressed.

Static loading test

The concrete strain response under static loading of Models DT-30 and DT-15 is shown in Fig. 3(a) and (b), respectively. At the top of their cross sections, DT-30 and DT-15 experienced increases in compressive strain of approximately 85 and 120 $\mu\varepsilon$, respectively. At the bottom of their cross sections, DT-30 and DT-15 experienced decreases in the compressive strain that was developed during prestressing of approximately 400 and 275 $\mu\varepsilon$, respectively. This was expected due to the positive moment applied, which was within the design load limit. At no time were the bottoms of the two bridge models placed in tension; thus, no tensile cracks could form.

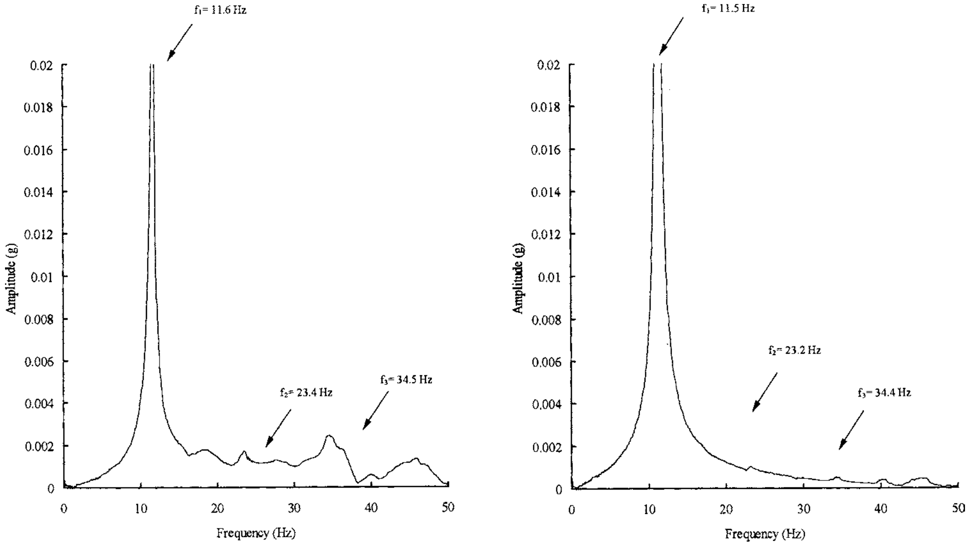
The deflection at midspan of DT-30 due to four-point loading was similar to the deflection due to eight-point loading. Figure 4(a) and (b) show the load-deflection response for both cases. Under four-point loading, a midspan deflection of 6.8 mm (0.270 in.) was noted, while under eight-point loading, a midspan deflection of 6.8 mm (0.268 in.) was noted. In both cases, the response was linear. This was expected, as the working load limit was designed to be less than the cracking load. For bridge model DT-15, it was decided to increase the load until cracking was observed in the webs of DT girders. The reason behind loading this model to 378 kN (85 kips) was to investigate the effect of repeated loading on the cracked section. Figure 4(c) shows the load-deflection response of Bridge Model DT-15. It experienced a deflection of 82 mm (3.2 in.) under 378 kN (85 kips) of applied load. The curve clearly shows cracking occurring at approximately 169 kN (38 kips). Upon release of the load, a residual deformation of 5 mm (0.2 in.) remained and the developed cracks closed.

Dynamic loading test

The first three natural frequencies of Bridge Models DT-30 and DT-15 were determined experimentally by impacting the bridge with a 22.0 kN (5 kips) force. The impact force was applied using a servo-hydraulic actuator. The bridge's free vibration signatures were measured using six accelerometers placed at critical locations on each of the two bridge deck slabs. The accelerometer data was scanned at a rate of 500 samples/s and recorded in acceleration-time history domains. The data file was then transferred from the data-acquisition system to a personal computer, where a fast fourier transform (FFT) was performed. This converted the acceleration-time history data into an acceleration-frequency domain. When these data were plotted, the fundamental frequencies appeared as peaks. A typical response spectrum is shown in Fig. 5. This figure indicates that the first three natural frequencies of the two bridge models, DT-30 and DT-15, were almost identical. This suggests that a 30 degree skew bridge may experience the same dynamic characteristics as a 15 degree skew bridge. Likewise, the addition of a third DT girder and a midspan cross beam has no effect on the dynamic characteristics of the bridge system.

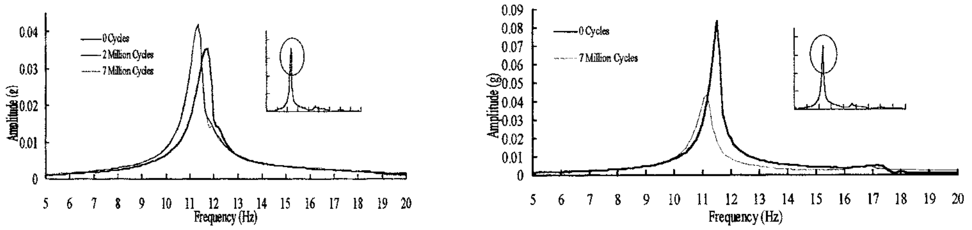
Repeated loading test

Models DT-30 and DT-15 experienced insignificant changes in their natural frequencies due to repeated loading. Figure 6 shows the results from a FFT analysis of the dynamic response of two bridges at different stages of the repeated loading test. Between 0 and 2 million cycles, the natural frequency associated with the first mode dropped only 0.3 and 0.5 Hz for Models DT-30 and DT-15, respectively, and was not measurably changed at 7 million cycles. At the same time, the natural frequency associated with the second mode dropped 0.6 and 0.75 Hz for DT-30 and DT-15, respectively, after 7 million cycles. Shifts of these magnitudes are insignificant, indicating that the dynamic response of the bridge is maintained under repeated loading conditions. The

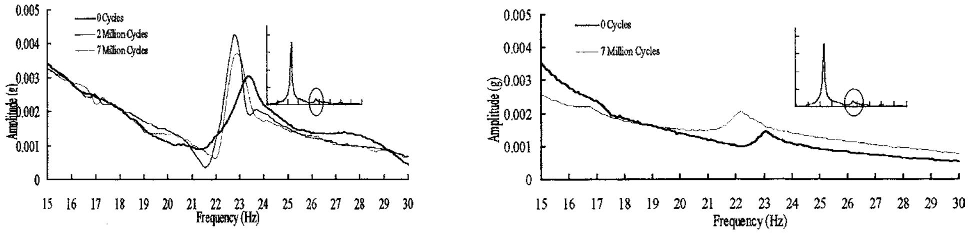


(a) Bridge Model DT-30 (b) Bridge Model DT-15

Fig. 5—Frequency spectrum response of tested bridge models: (a) Bridge Model DT-30; and (b) DT-15.



First Natural Frequency



Second Natural Frequency

(a) Bridge Model DT-30 (b)Bridge Model DT-15

Fig. 6—Changes in first two natural frequencies due to repeated load: (a) Bridge Model DT-30; and (b) DT-15.

damping ratio of each model was also evaluated at the beginning and end of the repeated loading test, using the logarithmic decrement method. It was found that the damping ratios increased over the course of the repeated loading. For example, between 0 and 7 million cycles, Model DT-15 experienced a 53.5% increase in damping, while Model DT-30 increased only 10.7%. The large increase in the damping ratio of Model DT-15 can be attributed to the increase in width and depth of existing flexural cracks. These cracks were formed during the static loading test, as discussed previously.

Variations in strain at the top of the deck slabs and at the bottoms of the DT webs in Model DT-30 were monitored during the repeated loading test and are shown in Fig. 7. From the data, maximum, minimum, and average strains were determined. These measurements represent the range of strains experienced by the bridge under simulated traffic load conditions. Because the measurements were taken under repeated loading, the average strains represent the strains induced by the static set point load of approximately 35.2 kN (8 kips). Similarly, the maximum and minimum strains occurred at approximately 61.6 and 8.9 kN (14 and 2 kips), respectively. In Fig. 7(b), it can be seen that Bridge Model DT-30 experienced an increase in compressive strain at the bottom of the webs at the midspan. This increase was linear throughout the repeated load test. Interestingly, the rate of increase tapered off as the testing progressed. Figure 7(a) shows the variation in strain measured at the top of the deck slab of Model DT-30. This strain remained compressive throughout the repeated loading test and became more compressive after 7 million cycles of repeated loading.

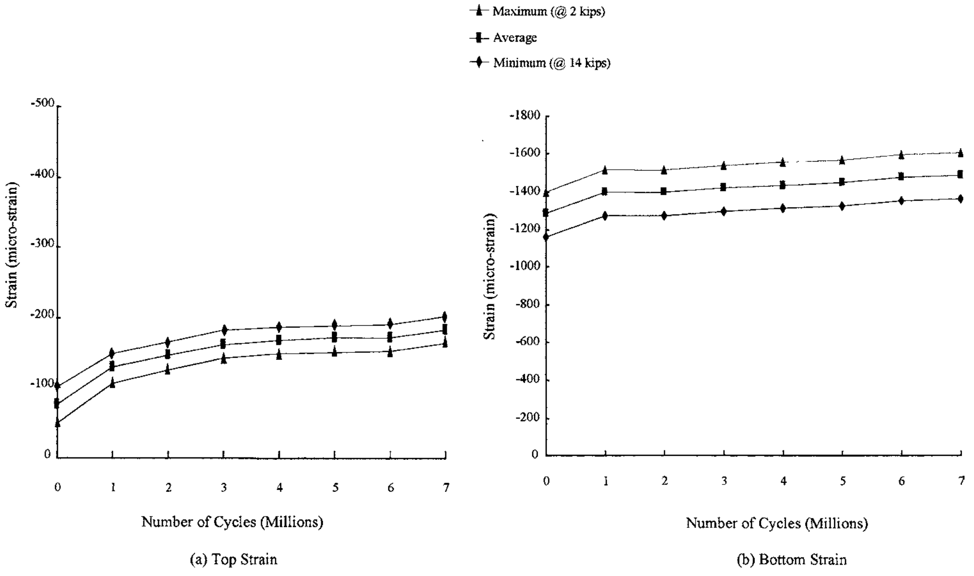


Fig. 7—Concrete strain variation of Bridge Model DT-30 during repeated loading test: (a) top strain; and (b) bottom strain.

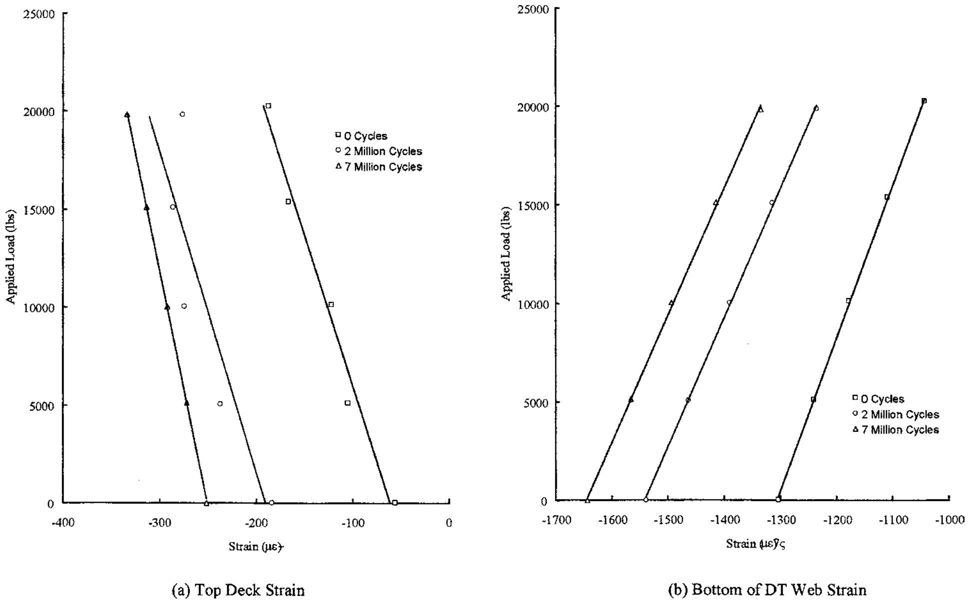


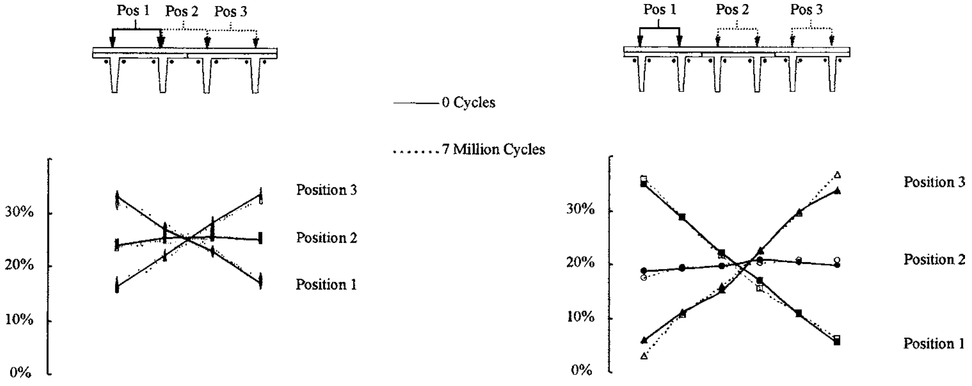
Fig. 8—Concrete strain response of Bridge Model DT-15 due to static loading: (a) top deck strain; and (b) bottom of DT web strain.

The repeated loading test was interrupted every 1 million cycles to conduct static loading tests. Figure 8 shows the strain-load responses at the top and bottom of Bridge Model DT-15. The strains became slightly more compressive over 7 million cycles of repeated loading. Similar to Model DT-30, the rate of increase tapered off as the testing progressed, perhaps indicating concrete creep effects. Figure 8(b) indicates that Model DT-15 experienced an increase in compressive strain at the bottom of the webs at midspan. This increase was linear throughout the repeated loading. The static load responses, indicated however, that the bridge model behaved linearly during and after the repeated loading test.

Both Fig. 7 and 8 indicate a gradual increase in compressive strain throughout the entire sections of Models DT-30 and DT-15, suggesting that creep induced by prestressing was present in the system. The results of these measurements imply that Models DT-30 and DT-15 experienced long-term creep due to prestressing. Furthermore, it can be concluded that repeated loading has an insignificant effect on uncracked or precracked skew bridges (DT-30 and DT-15), provided that the range of repeated loading is below the cracking load. This is expected since none of the internal or external prestressing rods were affected by the repeated loading.

Eccentric loading test

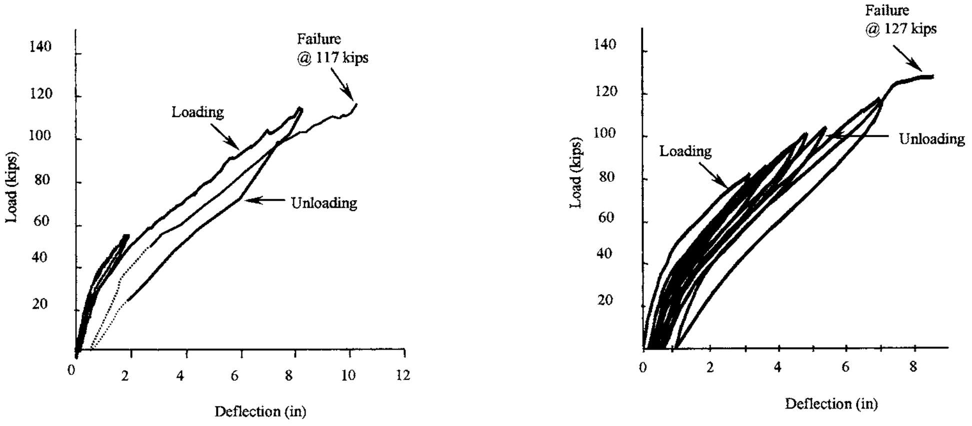
Deflections and longitudinal strains at midspan were used to determine the load distribution in the transverse direction. Eccentric loading tests were performed before and after the repeated loading tests to determine if any changes in load distribution occurred due to repeated loading. Figure 9 shows the distribution of load at each web



(a) Bridge Model DT-30

(b) Bridge Model DT-15

Fig. 9—Load distribution in transverse direction: (a) Bridge Model DT-30; and (b) DT-15.



(a) Bridge Model DT-30

(b) Bridge Model DT-15

Fig. 10—Deflection response during ultimate loading test: (a) Bridge Model DT-30; and (b) DT-15.

of Bridge Models DT-30 and DT-15 under different eccentric loading conditions. Full eccentricity (truck located in Position 1) caused a distribution in load at the outer webs of Model DT-30 of 33 and 16% of the total load. Similar distribution factors between two adjacent DT girders were experienced by Model DT-15. This suggests that grouting the transverse prestressing rods has an insignificant influence on the load distribution. Similar measurements were taken at the conclusion of the 7 million cycles repeated load test. Minimal changes suggested that repeated loading had an insignificant impact on the load distribution of Bridge Models DT-30 and DT-15.

Ultimate loading test

Deflection measurements were obtained at midspan during ultimate loading tests of Bridge Models DT-30 and DT-15. The midspan load-deflection responses are shown in Fig. 10(a) and (b). Loading/unloading cycles were conducted for each bridge model before failure. After each cycle of loading, residual deflections were measured. For example, after unloading from 511 kN (115 kips), Bridge Models DT-30 and DT-15 experienced residual deflections of 8 and 24 mm (0.35 and 0.95 in.), respectively. The load deflection relationships were linear up to 135.5 and 155 kN (30 and 35 kips) in Models DT-30 and DT-15, respectively. The maximum midspan deflections at failure were 261 and 213 mm (10.27 and 8.39 in.) and occurred at 515 and 565 kN (117 and 127 kips) for DT-30 and DT-15, respectively.

Figure 11 shows the longitudinal cross sections and plan views for both bridges at failure. Bridge Models DT-30 and DT-15 experienced extensive cracking and very large deflections before failure. It is apparent from Fig. 11 that the cracking was uniform and widely distributed throughout the spans of both bridge models. Bridge Model DT-15, however, experienced less cracking than Bridge Model DT-30. Flexural cracks that developed at stirrup locations were the primary type of cracks present in both models. Horizontal cracks at the internal prestressing rods also developed and continued for up to 1 ft in length in some locations. One interesting observation was that the tendon deviators caused cracks to grow near their inner edges where they intersected with the sides of the DT webs. This can be attributed to the fact that no corner reinforcement was provided to address the development of such cracks.

Figure 12 shows Bridge Models DT-30 and DT-15 after failure. Failure of both bridge models was initiated by the crushing of concrete followed by rupture in the internal prestressing rods. It can be seen that failure occurred perpendicular to the longitudinal centerline, originating at the tendon deviator and extending to the midspan of the opposite side. Some of the CFRP reinforcing tendons in the deck slab also experienced rupture at the line of failure. None of the external

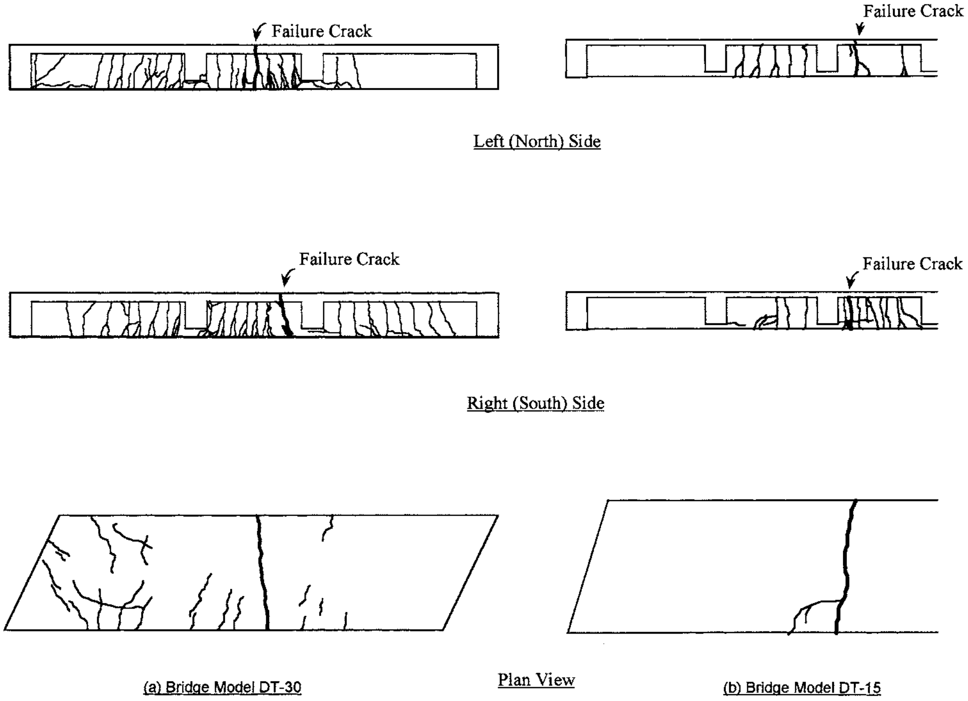
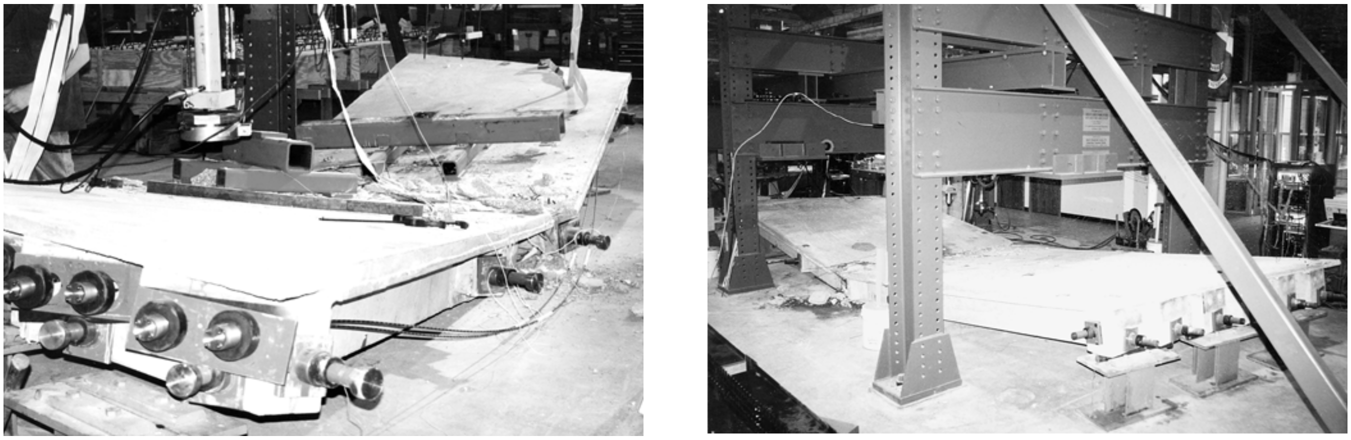


Fig. 11—Cracking pattern at failure: (a) Bridge Model DT-30; and (b) DT-15.



(a)

(b)

Fig. 12—Bridge models after failure: (a) Bridge Model DT-30; and (b) DT-15.

prestressing tendons, however, ruptured or pulled free of their anchor attachments.

After the conclusion of the ultimate loading tests, the cushioning materials (polyethylene tubes) were removed and the externally draped tendons were examined, which was to determine any changes on the surface of the rods due to the application of the 7 million cycles of repeated load. Examination of the tendons' exterior surfaces indicated that no serious changes occurred where the rods were deviated. Therefore, the cushioning materials were effective in reducing the friction between the tendon deviators and the prestressing tendons.

CONCLUSIONS

Results obtained from testing 30 and 15 degree skew bridge models under static, dynamic, repeated, eccentric, and ultimate loading indicate that:

1. A 30 degree skew bridge has the same fundamental natural frequencies as a 15 degree skew bridge, if both bridges are internally and externally prestressed using the design and construction technique proposed in this paper. Moreover, repeated loading has no effect on the dynamic and static characteristics of the tested skew bridge system;

2. Bonding the transverse prestressing tendons does not alter the load distribution characteristics. Furthermore, a repeated load has an insignificant effect on the load distribution in the transverse direction, if the repeated loads are applied within the working load limits of the bridge;

3. Internally bonded CFRP prestressing tendons in a precracked DT concrete cross section experienced no rupture after 7 million cycles of a repeated load that was below the cracking load;

4. A combination of internally bonded and externally draped (unbonded) CFRP tendons resulted in concrete crushing failure followed by rupture in the internal tendons. This type of failure forces the concrete to undergo inelastic deformation. Adequate reinforcement, however, should be provided at the intersections between the tendon deviators and the webs of the DT girders to avoid the development of cracks; and

5. None of the externally draped prestressing tendons experienced rupture under static, repeated, and ultimate loads. In addition, no changes in the surface condition of the tendons was noted at the locations of the tendon deviators after the repeated loading. Cushioning materials at the tendon deviators were effective in protecting the tendons.

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