Fatigue of Curved Steel Bridge Elements

Ultimate Strength Test of a Curved Composite Box Girder

Fritz Engineering Laboratory

By

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November 1977
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ULTIMATE STRENGTH TEST OF A CURVED COMPOSITE BOX GIRDER

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This work has been carried out as part of an investigation sponsored by the Federal Highway Administration, and is part of the course requirements for CE 385.

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November 1977
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ABSTRACT

The development of the urban areas and the increasing interest in aesthetics has brought about the increased use of the horizontally curved composite steel bridge girder. A need exists therefore for research into both the fatigue strength and ultimate load capacity of curved composite steel bridge girders.

Following a brief theoretical analysis of a curved composite steel box girder assembly, an ultimate strength test is described in detail.

Excellent agreement exists between the theoretically computed value of maximum load and the experimental value of maximum load. It is concluded therefore, that the theoretical analysis used is valid for a horizontally curved, composite, cantilever, steel box girder.

The report closes with recommendations for further study.
1. INTRODUCTION

1.1 Background

The development of urban areas with their restricted site alignments, and an awareness of aesthetics has been partly responsible for the introduction of the horizontally curved box girder bridge. Although the use of curved box girder bridges has increased greatly, technical knowledge regarding the fatigue strength and the ultimate load capacity of such girders has lagged behind. A need therefore exists for research into both the fatigue strength and ultimate load capacity of curved steel box girders.

Project 398 is a four-year, multiphase investigation involving extensive analytical and experimental study of the fatigue of curved girder bridges. Included in the experimental study is the fatigue testing of three large-scale box girder assemblies. Following the fatigue tests, a limited ultimate strength testing program was established in order to obtain as much information as possible from each large-scale box girder assembly (Daniels, et al., 1976; Herbein and Daniels, 1977; Batcheler, 1977).

1.2 Objectives and Scope

The primary objective of this work is to obtain information on the ultimate strength behavior of horizontally curved, composite, box girder assemblies.
One composite box girder assembly, designated Box Girder No. 3 was tested to failure in Fritz Laboratory. A plan and side view of the test setup is shown in Figs. 1 and 2. The ultimate strength testing program is summarized in Table 1.

Following a brief discussion of the theoretical analysis of the box girder assembly under study, the ultimate strength test of Box Girder No. 3 is described in detail. The load-deflection behavior and governing failure modes are presented. The report concludes with a summary of significant conclusions and recommendations for further study.
2. **THEORETICAL ANALYSIS**

2.1 _Elastic Analysis_

The elastic response of the composite assembly was established by two methods. First, the uncracked characteristics were obtained then, the cracked characteristics. Results of both are shown in Table 2. A plot of load versus deflection for these elastic behaviors is shown in Fig. 3.

An elastic analysis by the finite element method using SAP IV (Bathe, et al., 1974) is planned during the spring.

2.2 _Plastic Analysis_

The development of models for determining the ultimate load of horizontally curved box girders is in the initial stages. Therefore a simplified approach is used to compute an estimated value of the ultimate load (Beedle, 1958).

A fully cracked concrete slab is assumed. All steel, webs, flanges and reinforcing bars as well, are assumed to reach yielding, thus the plastic moment capacity of Box Girder No. 3 was computed as 2459 k-ft.

The plastic load limit is then computed by assuming a straight section between the point of loading and the support. The distance between these points being the centerline span length. The plastic limit load is therefore estimated by statics to be 266 kips.

A more rigorous analysis of the failure modes and ultimate strength of the curved composite box girder is planned for the spring and summer.
3. EXPERIMENTAL PROGRAM

3.1 Modification of Box Girder No. 3

Following the fatigue tests of Box Girder No. 3, all detected fatigue cracks were repaired. Preparation of the box girder proceeded with the addition of the composite deck shown in Figs. 4 and 5. A plan and section view of the composite deck reinforcement is shown in Figs. 6, 7 and 8.

3.2 Test Setup and Instrumentation

After the deck had cured a minimum of 28 days, Box Girder No. 3 was tested in the Baldwin Universal testing machine as shown in Fig. 9. The box girder assembly was loaded by a concentrated load placed at the centerline of the cross section and applied to an essentially rigid loading beam (W14x730).

The test setup shown in Figs. 1 and 2 was designed specifically to investigate the buckling failure of the bottom flange under compressive loading. The 37'-0" long (measured along the centerline) horizontally curved box girder was supported at the east end and at the west quarter point. Figure 10 shows the special roller support. A hold-down frame shown in Fig. 11 was placed at the east end to carry the uplift force caused by the cantilever action. A detailed cross section of Box Girder No. 3 is shown in Fig. 12 and a typical plate diaphragm which is located at all quarter points is shown in Fig. 13.

Fifteen dial gages were placed as shown in Fig. 14 to measure movement of the girder during the test. Dial gages No. 1 and 2, No. 4 and 5, and No. 15 were used to measure the vertical deflection of the
box girder. These dial gages are located in section in Figs. 15, 16, and 17, respectively. No distortion of the bottom flange was measured at these points since diaphragms, which resist flange distortion, were at these locations. Dial gage No. 3 shown in Fig. 15, and dial gage No. 6 shown in Fig. 16 measured horizontal displacement of the box girder. No. web distortion was measured here since these measurements also were recorded at diaphragm locations. Figure 18 shows the remaining dial gages No. 7 through 14 which were used to measure distortion of the bottom flange along the centerline of the cross section.

Fifty-eight strain gages were placed at six locations along the length of Box Girder No. 3. These locations are shown in plan in Fig. 19. Figures 20 through 25 show the specific locations of all the strain gages at these six cross sections.

3.3 Test Procedure

The test procedure consisted of loading the box girder assembly with incremental loads until a maximum value was achieved. Upon reaching a maximum load the test continued by increasing the deflection under the cantilever end at approximately \( \frac{1}{2} \)" increments. The test was continued to failure of the box girder assembly, which was considered to be the point at which additional deflection was accompanied by a drop in the applied load. During the test, the dial gages, which measured vertical and horizontal deflection, were visually read at each increment of load. Figure 26 shows a graph of load versus total deflection at the cantilever end. This was plotted as the test proceeded. (Dial gages No. 1 and No. 2 measured the plotted deflections.)
Strain gage readings at each increment of load were recorded automatically through the use of a B&F 100 channel Strain Indicator with Teletype Output. The time of each reading was also automatically recorded by this unit.
4. **TEST RESULTS AND DISCUSSION**

The theoretical and experimental results of load-deflection behavior of Box Girder No. 3 are shown in Fig. 27. Initially, close agreement exists between the theoretical elastic behavior and the experimental behavior. However, upon reaching a load of 37.5 kips cracking of the composite deck begins as shown in Fig. 28. From this point on the curves describing theoretical and experimental elastic behavior diverge.

The ultimate strength test of Box Girder No. 3 continued uneventfully until the load reached 112.5 kips. At this time dial gages No. 7 through No. 14 were placed as shown in Figs. 14 and 18. They measured distortion of the bottom flange east and west of the western support. Upon increasing the load to 125 kips, buckling of the bottom flange on both sides of the western support was detected. The load was then incremented to 137.5 kips where it was noticed that the east end of the girder had lifted off its bearings by approximately $\frac{1}{4}''$ to $\frac{3}{8}''$. It was therefore deemed necessary to insert dial gage No. 15 (see Figs. 14 and 17) to record any further displacement. The test proceeded from this load to 237.5 kips uneventfully. The only noticeable change during this period was that the buckling of the bottom flange became more pronounced. Upon attempting to increase the load to 262.5 kips a loud report was heard at 260 kips. Investigation revealed that wood blocking in the hold-down frame at the east end had broken. It was then decided to reduce the load to zero, repair the hold-down frame, and restart the test.

The test was restarted and loading incremented by 50 kips until the total load reached 250 kips. Load was then incremented until a maximum value of 266 kips was achieved. This load agreed precisely with
the estimated theoretical value. The close agreement between experimental and theoretical values indicated that the plastic analysis might be an excellent method of computing the ultimate load for a cantilevered box girder. It was also noticed at this loading that web buckling east of the south-western support had begun. Increasing the deflection by approximately one inch caused this buckling or bulging to appear more pronounced in both webs east of the western support. The deflection was then incremented to a total vertical displacement of approximately 5½ inches at which time the test was halted. The resulting permanent web bulging and bottom flange buckling can clearly be seen in Figs. 29 and 30.
SUMMARY AND CONCLUSIONS

The results of a theoretical and experimental investigation of the ultimate strength of a curved composite box girder were presented. Following are the significant conclusions of this investigation:

(1) Theoretical and experimental behavior of load-displacement is shown in Fig. 27. Very good agreement between theoretical and experimental values exists which indicates that the plastic analysis procedure may be used to compute the ultimate load for horizontally curved, composite, cantilever box girders.

(2) The governing failure mode was the buckling of the bottom flange and buckling of the webs. Although the buckling reached a point of stable equilibrium in the test this would not occur under normal loading conditions since the load would not drop off. The load would remain constant under normal conditions thus causing a catastrophic failure unless the inherent redundancy in highway bridges arrested the unstable equilibrium condition.

Recommendations for further study include:

(1) A refined theoretical elastic and plastic analysis of the composite member should be undertaken.

(2) Reduction of the strain gage data should be completed so that a comparison of theoretical stress and experimental stress can be made in various structural elements.
6. ACKNOWLEDGMENTS

This study was conducted at the Fritz Engineering Laboratory, Department of Civil Engineering, at Lehigh University. Dr. L. S. Beedle is Director of Fritz Engineering Laboratory, and Dr. D. A. VanHorn is Chairman of the Department of Civil Engineering.

This study was undertaken as part of a multiphase investigation entitled, "Fatigue of Curved Steel Bridge Elements". Dr. J. H. Daniels is the Principal Investigator. The sponsor is the Federal Highway Administration (FHWA), United States Department of Transportation. The FHWA Project Manager is Mr. Jerar Nishanian.

The following members of the faculty and staff of Lehigh University made major contributions to the conduct of this work: Dr. J. W. Fisher, Dr. B. T. Yen, Dr. R. G. Slutter, Dr. J. H. Daniels, D. Abraham, R. Dales, R. Longenbach and M. Bennett.
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<td><strong>Box Girder No. 3</strong></td>
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<tr>
<td>Centerline span length</td>
<td>37 ft</td>
</tr>
<tr>
<td>Centerline radius</td>
<td>120 ft</td>
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<tr>
<td>Cross-section properties:</td>
<td></td>
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<tr>
<td>web depth</td>
<td>34-1/8 in.</td>
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<tr>
<td>web thickness</td>
<td>3/8 in.</td>
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<tr>
<td>flange width</td>
<td>38 in.</td>
</tr>
<tr>
<td>flange thickness</td>
<td>3/8 in.</td>
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<tr>
<td>Composite deck:</td>
<td></td>
</tr>
<tr>
<td>width</td>
<td>54 in.</td>
</tr>
<tr>
<td>thickness</td>
<td>6 in.</td>
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<td>Material properties</td>
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<td>Steel:</td>
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<tr>
<td>Specified tensile strength</td>
<td>36 ksi</td>
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<td>Concrete:</td>
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<tr>
<td>Specified compressive strength</td>
<td>3000 psi</td>
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<td>Reinforcement:</td>
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<tr>
<td>Specified tensile strength</td>
<td>40 ksi</td>
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<td>Box Girder No. 3</td>
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<tr>
<td><strong>Uncracked section:</strong></td>
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</tr>
<tr>
<td>Moment of inertia ($I_x$)</td>
<td>19834 in.$^4$</td>
</tr>
<tr>
<td><strong>Cracked section:</strong></td>
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<tr>
<td>Moment of inertia ($I_x$)</td>
<td>12965 in.$^4$</td>
</tr>
<tr>
<td>Cracking moment ($M_{cr}$)</td>
<td>5285 kip-in</td>
</tr>
<tr>
<td>Cracking load ($P_{cr}$)</td>
<td>42 kips</td>
</tr>
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Fig. 1 Plan View of Box Girder No. 3 Test Setup
Fig. 2 Side View of Box Girder No. 3 Test Setup (looking North)
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Fig. 19 Plan View of Strain Gage Locations
NOTE: GAGES NO. 1 & NO. 2 WERE NOT USED DURING THE ULTIMATE TEST

Fig. 20 Strain Gage Locations - Gage Section 1 (viewed from West)
Fig. 21 Strain Gage Locations - Gage Section 2 (viewed from West)

NOTE: GAGES NO. 14 & NO. 15 WERE NOT USED DURING THE ULTIMATE TEST
NOTE: GAGES NO. 27 & NO. 28 WERE NOT USED DURING THE ULTIMATE TEST.

Fig. 22 Strain Gage Locations - Gage Section 3 (viewed from West)
Fig. 23 Strain Gage Locations - Gage Section 4 (viewed from West)

NOTE: GAGES NO. 40 & NO. 41 WERE NOT USED DURING THE ULTIMATE TEST.
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Fig. 30 Permanent Web Bulging and Bottom Flange Buckling
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