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Load Testing of Chicago's 100-Year-Old Mass Transit Structures

Essais de charge sur les structures centenaires du métro surélevé de Chicago

Belastungsversuche an Chicagos 100jährigen Hochbahnbauten

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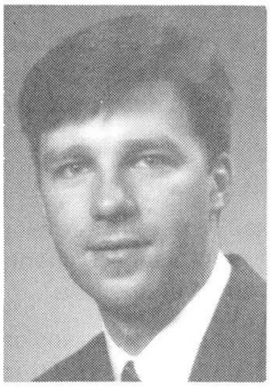

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SUMMARY

As part of an overall engineering assessment of the Chicago Transit Authority's elevated rapid transit system, a field load testing program was carried out to measure the response of the elevated steel structures to static and dynamic train loadings. This paper describes the structures tested, instrumentation and equipment used to obtain strain and deflection measurements, and test results. The study resulted in specific recommendations for future analytical analyses of the elevated structures.

RÉSUMÉ

Une évaluation globale du système ferroviaire surélevé en zone urbaine a été menée par la "Transit Authority" de Chicago. Un programme d'essais de charge a été effectué sur le site en vue d'enregistrer le comportement des structures métalliques soumises aux effets statiques et dynamiques de convois-types. L'article présente une description des ouvrages testés, l'instrumentation et l'équipement servant à mesurer les allongements et les flèches des éléments, ainsi que les résultats des essais. Cette étude fournit également des recommandations précises pouvant servir à des analyses futures sur des ouvrages ferroviaires surélevés.

ZUSAMMENFASSUNG

Als Teil einer ingenieurmässigen Gesamtbeurteilung des städtischen Hochbahnsystems der Chicagoer Transit Authority wurde ein Feldprogramm für Belastungsversuche durchgeführt, um das Verhalten der aufgeständerten Stahltragwerke unter statischen und dynamischen Eisenbahnlasten zu messen. Der Beitrag beschreibt die geprüften Tragwerke, die Instrumentierung und Ausrüstung für die Dehnung und Durchbiegungsmessungen sowie die Prüfergebnisse. Die Untersuchung ergab spezifische Empfehlungen für spätere Nachrechnungen solcher Hochbahnbauten.

1.0 INTRODUCTION

1.1 Background

The Chicago Transit Authority (CTA) operates and maintains the second largest mass transportation system in the United States: A system which comprises an asset base valued at over $15 billion (US dollars) and which serves 2.3 million passengers daily [1]. The largest portion of the system is an elevated rail structure, the majority of which was designed and constructed between 1895 and 1905. In order to determine the exact operating condition of every mile of the elevated rail system, the CTA conducted an exhaustive multimillion dollar engineering assessment. This assessment, the most comprehensive ever undertaken on a mass transit system, was carried out with the eventual goal of rehabilitating this vital infrastructure.

As part of the overall engineering assessment, a field load testing program was carried out to measure the response of the elevated steel structure under static and dynamic train loadings. To account for variations in the structural systems which comprise the elevated rail system, sixteen locations were selected for inclusion in the field testing program. Test results presented herein are specific to three tests conducted on the CTA's Loop Line. The Loop Line structures measure approximately 5 km in length and service the downtown business district of Chicago, Illinois. This paper describes the Loop Line structures, instrumentation and equipment used to obtain strain and deflection measurements, and test results. This study resulted in specific recommendations for future analytical analyses of the elevated structures.

1.2 Description of Tested Structures

The CTA's Loop Line is an open deck, elevated steel structure supporting two tracks. The structure was designed in late 1895 and early 1896 by renown bridge engineer, J.A.L. Waddell and put into service shortly thereafter. Medium steel corresponding to ASTM A-7 steel is used throughout the Loop Line structure.

The overall structure is comprised of multiple spans each having an average length of 15.2 m, with expansion joints located every third span. Each track is supported by two, open web truss stringers as shown in Figure 1. The stringer top chord is a built-up member consisting of two angles and a vertical plate. The stringer bottom chord and web members consist of double angles. Each stringer pair is braced laterally using angles in the plane of the top chord and diagonal cross bracing at stringer midspan and end supports. Stringers frame into riveted built-up cross-girders which span between riveted built-up columns. Riveted full-depth web angles are used to complete the stringer to cross-girder attachment. At expansion joints, the stringer is supported by a seated bearing connection.

Three representative segments of the Loop Line were selected for inclusion in the field testing program. Each test location included the instrumentation of two adjacent spans, one span having both stringer ends attached to the cross-girder and one span having one end attached to the cross-girder and the other at an expansion joint. Test locations were identified by the centrally located bent number, that is 0116, 0122, 0164. The segments were similar in construction except for their top chord flange angles. Test location 0122 represents construction with all components dating from 1897 while test locations 0164 and 0116 represent spans which have had their top chord flange angles replaced using riveted and bolted construction, respectively. Replacement flange angles were similar in size to the original angles.

2.0 INSTRUMENTATION AND FIELD TESTING

2.1 Objectives of Field Testing Program

A field testing program was carried out to measure the response of the elevated structure to static and dynamic train loadings. Strain and deflection measurements were recorded under static loading provided by a control train and dynamic loading using the control train and normal rush hour train traffic. Objectives of the testing program were as follows: Measure strains and deflections in stringers to verify the analytical analysis; Estimate the level of stringer end fixity at cross-girder connections; Develop influence lines for instrumented locations using the control train; Determine stress range experienced by tension members of the truss stringer; Measure longitudinal response to dynamic and braking loadings; and, Determine impact levels.

2.2 Description of Instrumentation

A total of 40 foil type, single element strain gages were installed at each of the three test locations. Gages were placed on the top and bottom chords at each stringer end and the midspan to monitor maximum negative and positive bending, respectively. Web elements expected to experience the largest tensile strains were instrumented. Gages were also placed at the column bases to measure maximum strains due to axial and bending forces. Deflections were monitored using seven linear variable displacement transformers (LVDT). LVDT's were positioned at the three supporting cross-girders and each midspan location to measure vertical displacements. Two LVDT's were positioned at the expansion joint to measure horizontal displacement of the cross-girder and relative bearing slip. To record the data, a van was equipped as a recording station. Lead wires from strain gages and LVDT's were routed to the recording station and connected to a data acquisition system.

2.3 Field Testing

An empty four-car CTA train was used as the control load for the dynamic and static testing. Each train car has a mass of approximately 24,500 kg or 6,125 kg per axle. For each car, individual truck axles are separated by 2 m with a distance of 10.3 m between truck centerlines. The truck centerline of adjacent cars is separated by 4.4 m.

For the control static tests, the test train was positioned at 1.2 m intervals along the structure and strains and deflections were recorded. A total of 90 intervals was used with the first and last interval location resulting in zero strain. For the control dynamic tests, the test train passed over the instrumented spans at various speeds ranging from a crawl, that is less than 8 km/hr, to a maximum speed of 56 km/hr. Dynamic braking tests were also conducted by having the test train obtain a speed of 56 km/hr then applying axle and track brakes simultaneously. This braking represents the most severe braking condition. Dynamic tests were also conducted under normal rush hour traffic. These tests were conducted to determine the influence of passenger loading on maximum stress levels. For CTA fatigue rating calculations, a passenger loading of 2,495 kg per axle is combined with dead load to obtain 8,845 kg per axle.

3.0 STRESSES UNDER CONTROL LOADING AND REVENUE TRAFFIC

3.1 Static Testing

Strains due to the control loading were plotted with respect to load position to develop influence lines for all gages at each test location. The ordinate and abscissa correspond to the calculated stress and load position of the train, respectively. Positive stress represents tension and negative stress represents compression. In general, data show five distinct humps as shown in Figure 2 for the two midspan locations at test location 0116. The first hump is the first truck (2 axles) of the leading car. The middle three humps represent pairs of trucks (4 axles) at the coupler connection between cars. The last hump is the rear truck (2 axles) of the last car. The middle humps show a larger magnitude because they represent the loading of four axles rather than two axles. Data plotted for other gaged locations and included in Reference [2] were similar to that shown in Figure 2.

Data from the stringer top chord revealed localized bending effects due to concentrated loads applied through the wood ties randomly located along the stringer length. Top chord flanges typically experienced compression while the base of the vertical top chord plate experienced tension.

A summary of the maximum stress ranges for test location 0116 is shown in Table 1. Data for the two other test locations were similar. The largest tensile stress range was 21.4 MPa and was measured in the end diagonal. The positive moment tensile stress range at midspan averaged 20.7 MPa while the negative moment tensile stress range averaged 10.3 MPa adjacent the stringer to cross-girder attachment.

Midspan deflections were corrected for support displacements and plotted with respect to load position for all test locations [2]. Maximum deflections did not exceed 4 mm. Both the deflection and stress plots indicate significant continuity at stringer end to cross-girder connections. The deflection plots show upward displacements of 1.8 mm when the train is positioned in an adjacent span. In general, upward deflections did not occur across expansion joints. Similarly, negative bottom chord plots in Figure 2 indicate continuity across stringer to cross-girder connections.

3.2 Dynamic Testing

Similar to the static testing, strains and deflections were plotted with respect to load position [2]. Dynamic stress levels under the control train increased from static measurements by approximately 15 percent for the three test locations. This is significantly less than the design impact level of 57 percent calculated using the requirements of the American Railway Engineering Association (AREA) specifications [3].

Data obtained under rush hour train traffic indicates increases in stress levels from the control test data of about 20 percent. The maximum stress range measured at midspan was 26.2 MPa compression and 28.3 MPa tension.

4.0 ANALYTICAL STUDIES

The deep riveted connections at the stringer ends provide a significant amount of fixity, affecting the stress levels and behavior of the stringers. Analytical models were developed to determine the level of end fixity by calibrating to field data. For spans with connections at each end, the effective end fixity was determined to be approximately 75 percent of the fully fixed end moment. At spans with an expansion joint at one end and assuming the expansion joint contributes no fixity, the riveted end connection was determined to contribute between 95 to 103 percent fixity. This finding indicates that some fixity must be provided at the expansion joint. Fixity at the expansion joint occurs as a force couple consisting of a tensile force in the rail and a shearing force transferred across the expansion joint at the steel-to-steel bearing.

5.0 CONCLUSIONS

Load tests of three separate segments of the Loop Line indicate similar results even though their top chord flange angle construction differs. Measurements obtained in spans having flange angles dating to the original 1897 construction were similar to those obtained in spans having replacement angles with bolted or riveted construction. Under rush hour trains, the maximum tensile stress range in the end diagonal and midspan bottom flange were similar and did not exceed 30 MPa. Comparison of static and dynamic data under control loading indicates 15 percent would be a realistic value for impact calculations. The riveted stringer end connection is such that significant continuity is provided at the stringer end support. By calibrating an analytical model to the field data, the relative end fixity was determined to be approximately 75 percent of the fully fixed end moment.

Research indicates that riveted bridge members are not likely to develop fatigue cracks in primary members when the stress ranges are less than 48 MPa [4]. Based on this research, it is projected that the primary stringer members used in the Loop structure as originally designed or currently reflanged, and under current loadings could be expected to have a remaining fatigue life of about 80 years. However, stringer connection angles and connection angle rivets may exhibit cracking or failure and require replacement before reaching this projected life.

The findings of this work resulted in the recommendation of guidelines for the analytical evaluation of the Loop structure. These recommendations include the more realistic impact and end fixity findings reported herein.

6.0 REFERENCES

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3. AREA, *Manual of Railway Engineering, 1990-1991*, American Railway Engineering Association, Washington, D.C.

4. FISHER, J.W., and et al., "Fatigue and Fracture Evaluation for Rating Riveted Bridges," *NCHRP 302*, December 1987, 86 pp.

TABLE 1 SUMMARY OF MEASURED STRESSES, TEST LOCATION 0116[1]

ELEMENT	CONTROL LOAD STATIC (MPa)	CONTROL LOAD DYNAMIC (MPa)	IMPACT (%)	RUSH HOUR DYNAMIC (MPa)
Midspan Bottom Chord	20.7	24.8	20	28.3
Midspan Top Chord Flange	-20.0	-23.4	17	-26.2
Midspan Top Chord Vertical Plate	10.3	11.0	7	13.8
End Diagonal	21.4	24.1	13	26.9
Stringer End Bottom Chord	-22.0	-25.2	-14	-27.8
Stringer End Top Chord Flange	10.3	11.7	13	13.1
Stringer End Top Chord Vertical Plate	-10.3	-11.0	7	13.1

Notes: 1. Measured stresses for Test Locations 0122 and 0164 were similar

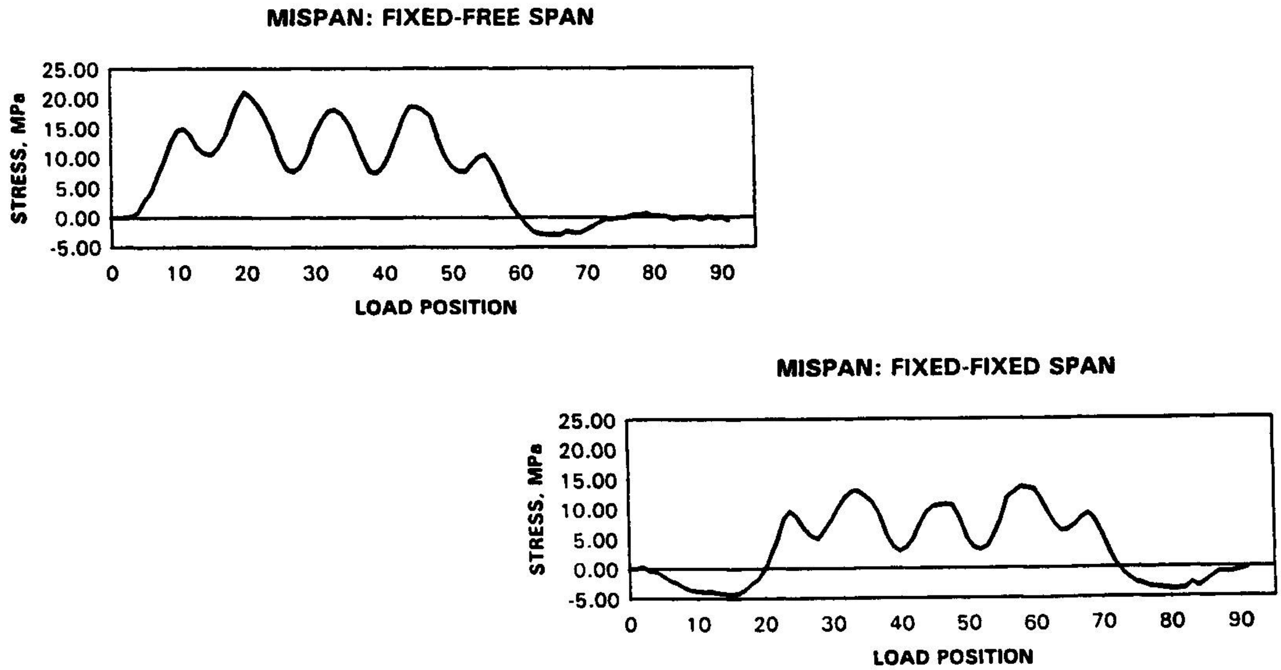

Figure 2 - Midspan stress response for midspan gages at Test Location 0116

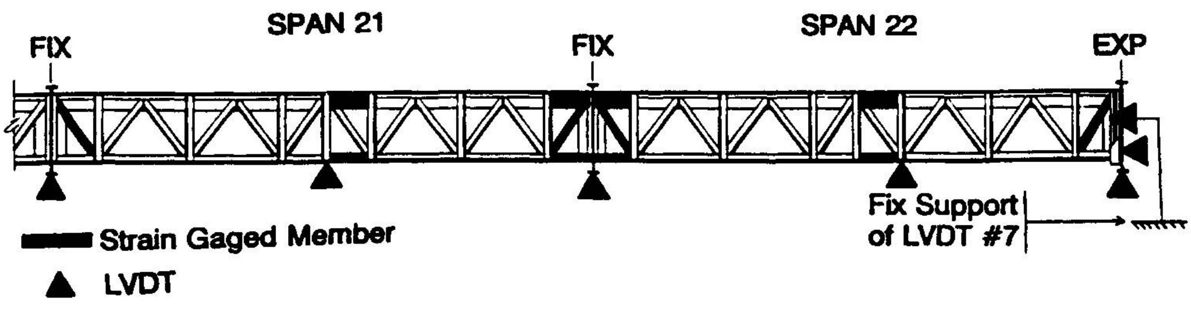

Figure 1 - Typical Loop structure and instrumentation plan

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