Structural adequacy of a deformed prestressed concrete girder in Khodarhat bridge: An assessment utilizing filed vibration data and FE computations

Conference Paper · August 2015

DOI: 10.13140/RG.2.1.1646.5122

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Structural adequacy of a deformed prestressed concrete girder in Khodarhat bridge: an assessment utilizing filed vibration data and FE computations

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ABSTRACT: The paper was aimed at evaluating the structural adequacy of a laterally deflected and twisted PC girder at the 2nd span of Khodarhat bridge utilizing vibration data and finite element (FE) computations. Total Station survey data and vibration measurements were taken respectively to model and evaluate the stiffness properties of as-built deformed girders. The design natural frequencies of the straight girder as obtained from FE analysis were then superimposed on those obtained from the vibration measurements to quantitatively estimate the variations in stiffness properties in two geometric conditions (straight and curved). From the analyses of the girders, the stiffness of the curved girder was estimated to be about 7.8% lower than the straight girder at design condition. The reduction in stiffness was considered insignificant for the structural strength, safety and serviceability condition of the bridge.

1 INTRODUCTION

The Roads and Highways Department (RHD), Bangladesh was constructing a 348.12m long prestressed concrete (PC) girder bridge over the Shangkha River at the 8th km of Fultoli-Kanchana-Khoderhat Road under Dohazari Road Division, Chittagong. The 42m long, 2.4m deep girder 2C of the 2nd span of the bridge reportedly got laterally deflected about 10 days after application of prestress and subsequent grouting. A total station measurement showed the girder to be laterally deflected in top plan together with some amount of twisting of the section. The deformation appeared to be highest near the mid span and lowest at supports.

To evaluate the stiffness properties of the PC girder in as-built deformed condition, on site measurement of natural frequency of the girders were taken. The idea behind conducting the investigation by field vibration measurement was based on the fact that natural frequency of a girder of any geometry is directly related to its stiffness. Whereas, the stiffness of a girder further depends on the modulus of elasticity, moment of inertia and length. Therefore, there lies an opportunity to compare the natural frequencies of the deformed girder with the adjacent straight one having similar mass and boundary conditions to determine the relative stiffness properties assuming that the adjacent straight girder is structurally adequate and meets the design requirement. This shall enable one to assess the relative change in the stiffness in as-built condition and compare the values with the theoretical design considerations as well. All these steps shall lead towards assessing the structural adequacy of a girder having geometric deformations. Thus, a comparison of stiffness values between the acceptable girders and the girder with geometric deformations were made. Furthermore, results of compressive strength tests, cable layouts, stressing records, tension test of the strand together with design drawings of the relevant girder were taken into consideration. FE analyses of the straight girder were conducted to determine the fundamental (theoretical) natural frequencies at design condition. Total station survey data were used to model the curved girder. FE analysis of a full span with curved girder showed that torsional moments are developed in the curved girder due to design loads. The paper presents the salient aspects of the study.

2 VISUAL OBSERVATIONS AND MEASUREMENTS

The data on geometric deformations of girders of the said bridge were gathered by conducting several site visits. During the visits the onsite measurement of natural frequency of the girders were taken to make a comparison of the stiffness values between the acceptable girders and the girder with geometric deformations. In addition, the total station survey of the girders was conducted to ascertain the sectional properties. From total station survey data it was found that the girders get laterally deflected on top plan of the order of about 190mm accompanied by some amount of twisting of the section. The deformation appeared to be highest near the mid span and lowest at supports (Figures 1 and 2). In addition, results of compressive strength tests, cable layouts, stressing records, tension test of the strand together with design drawings of the relevant girders as supplied by RHD were taken into consideration.

(a) (b).

Figure 1. Girders seen from the top. (Left to Right: 2A, 2B, 2C, 2D. (a) The lateral deflection of the girder 2C is visible. (b) Lateral deflection of the Girder 2C seen at the top near the mid span

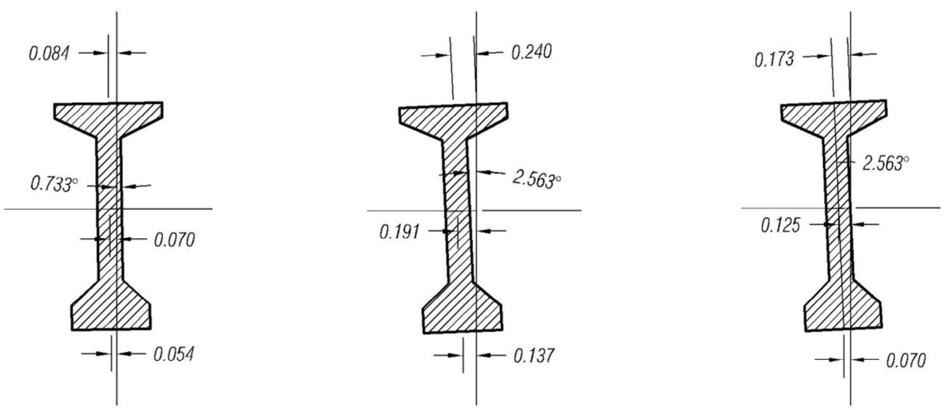

Figure 2a. Section at first quarter span.

Figure 2b. Section at mid span.

Figure 2c. Section at third quarter span.

3 FIELD VIBRATION MEASUREMENT

As a part of the work, the detail field vibration measurement of the said girder was taken by conducting free-vibration test (Chopra 1995; Clough and Penzein 2003; Yamaguchi 1992). In this method, the girder was excited by means of a free falling weight. The resulting free vibration responses of the curved girder were recorded using Profound Velocity Meter (Model Vibra+). Four sensors were placed at the Support, Quarter Spans and at the Mid-Span of deformed 2C girder. Excitations were applied both at mid-span and at quarter span. In every case, measurements were repeated for three times in each location. The same test methodology was also applied for the adjacent straight girder (2B). Trace vibration measurement were recorded on portable computers (1024 records per second). The recorded data were later processed using software to determine the natural frequencies in all the three orthogonal directions by means of First Fourier transformations (FFT) (Thorby 2008; Yamaguchi 1992; He and Fu 2001). The natural frequencies obtained from FFT were plotted and compared between the curved and the straight girder. Typical results of the vibration analyses are shown Figures 3 and 4 for the mid-span locations.

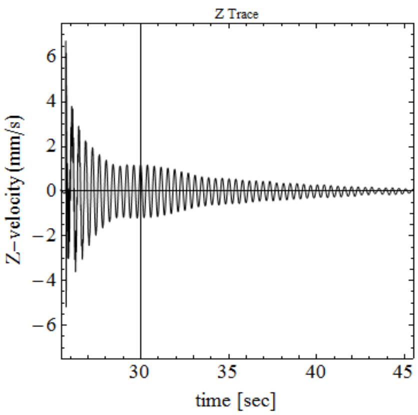

Figure 3(a). Typical decay of vibration at mid-span after impact. Trace velocity measurement in Z-direction is shown for 2B (straight) girder. Impact was also made at mid-span.

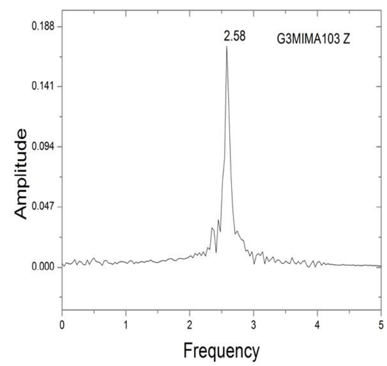

Figure 3(b). First Fourier Transform (FFT) of the Trace Data shown in Figure 2a.

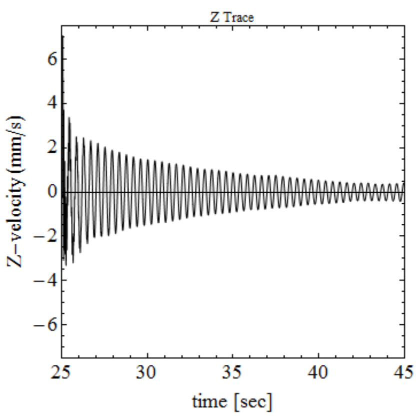

Figure 4(a). Typical decay of vibration at mid-span after impact. Trace velocity measurement in Z-direction is shown for 2C (curved) girder. Impact was also made at mid-span.

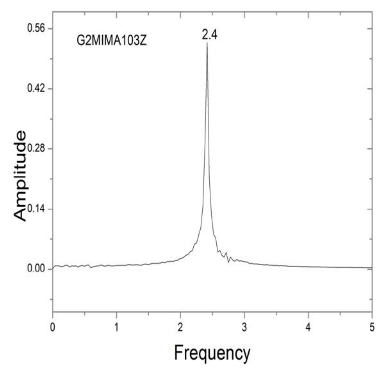

Figure 4(b). First Fourier Transform (FFT) of the Trace Data shown in Figure 3a.

4 FEM MODEL & ANALYSIS

FEM Analyses of the straight girder was conducted to determine the fundamental natural frequencies at design state. Total station survey data were used to model the curved girder. Due to curvature and twisting, sections of the girder in question has been shifted from the centerline as well as tilted. Typical positions of the girder sections as found from survey are shown in Figure 2. Theoretical natural frequencies so determined supplimented the test results. The casting record showed that the girder 2C was cast on 10 January 2012 and post-tensioning was applied on 20 January 2012. Therefore, the effects of actual concrete strength and the design concrete strength on the natural frequencies were investigated by incorporating the Young's modulus corresponding to the different concrete strength values. Figures 5-6 show the typical FEM models developed for the investigation.

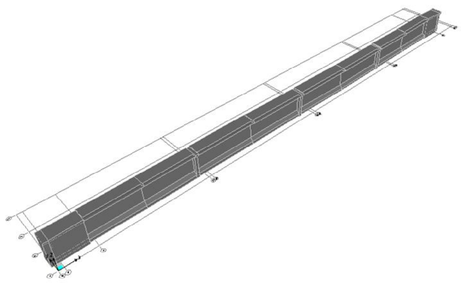

Figure 5. FE model of single girder

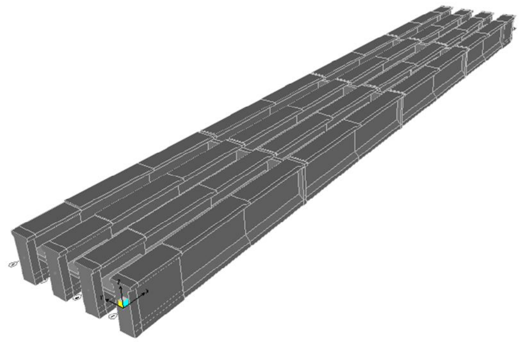

Figure 6. FE model of 2nd span.

5 VERIFICATION WITH DESIGN CONSIDERATIONS

A smaller magnitude of a natural frequency in a direction indicates lower stiffness characteristics. In addition, a twist in the geometry has the potential of developing torsional moments not accounted in the original design. To this end, the comparisons between the natural frequencies and torsional capacities are presented in the following sub-sections.

Table 1.Comparison of natural frequencies

	Natural Frequencies (Hz) in Vertical Direction		
	FEM (Design condition)	FEM (Test Condition)	Test Result
Straight Girder (2B)	2.5	2.59	2.58
Curved Girder (2C)	--	2.43	2.40
Ratio of Frequency (Curved: Straight)		2.4/2.5 = 0.96	
Ratio of Stiffness (Curved: Straight)		$(2.4/2.5)^2 = 0.922$	

5.1 *Natural Frequency (As-built Condition vs Design Consideration)*

Table 1 presents a brief comparison of the natural frequencies of the curved girder with adjacent straight girder obtained by different methods. A reasonable match between FEM and the Test Condition can be observed (Table 1). The concrete strength (28 days) achieved in January 2012 was about 41 MPa. This strength was used to estimate the concrete strength and resulting Young’s modulus in the Test Condition when the test was conducted in December 2012. About 10% increase in compressive strength has been assumed. The natural frequencies in the Design Condition were calculated using the design concrete strength of 40 MPa.

Stiffness of the girder is proportional to the square of the natural frequency. Therefore, the stiffness of the curved girder appeared to be about 7.8% lower than the straight girder at design condition. This difference in stiffness may be considered not significant in affecting the structural strength, safety and serviceability condition of the bridge. It is expected this difference will be further minimized with time due to natural ageing of concrete. Strength gain in concrete through this process is higher in concretes made with composite cements.

5.2 *Torsional Capacities*

The digital survey record of the curved geometry of the girder shows permanent twisting of girder sections (Figure 5). This twisting accompanied with eccentricity due to lateral curvature shall induce additional torsional moment which needs to be accounted for in considering the structural adequacy of the girder. The torsional capacity of the as-built girder section was checked. FE analysis of a full span with curved girder (Figure 6) shows that torsional moments are developed in the curved girder due to design loads. However, it is found that the torsional capacity of the curved girder is higher than the developed torsional moments. Therefore, no additional considerations are needed for this eccentricity.

6 CONCLUSIONS AND RECOMMENDATIONS

A thorough investigation on the structural safety and adequacy of the curved girder has been performed in this work where field vibration test, analysis of construction records and numerical finite element analysis were used to derive the following conclusion:

i. The structural adequacy of the curved girder (Girder 2C) has not been affected significantly due to geometric deformation. Therefore, construction of the said span may be continued.
ii. Construction of the remaining works of the bridge should preferably be supervised by a competent engineer to avoid repetition of construction problems.

7 ACKNOWLEDGEMENT

The authors gratefully acknowledge to the Bureau of Research, Testing and Consultancy (BRTC), Bangladesh University of Engineering & Technology (BUET) and the Roads and Highway Department (RHD), Bangladesh for their support and cooperation for taking field vibration measurement by conducting free vibration test of girders of the bridge.

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