Japan-Bangladesh Joint Seminar on Advances in Bridge Engineering ISBN: 984-32-2520-6
Dhaka, Bangladesh. 10 August 2005

Vibration serviceability requirement in the design of arch-supported suspended footbridge

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Abstract

Several cases of vibration serviceability problems with footbridges have been reported in the recent past from all over the world. In these cases, the respective designs failed to consider the so called 'footfall action mechanism' where human movement induces large amplitude lateral vibrations in the deck system. This prompted the code authorities to revise the code provisions for this class of bridges. According to the revised code provisions (BS 5400: Part 2, amended vide BD 37/01 on August 2001), the footbridges need to satisfy the vibration serviceability requirements indicated by the eigen frequencies of the system for first horizontal mode (1.5 Hz) and first vertical mode (5 Hz). With this background, the paper presents the design steps that were followed in a recent footbridge project in Bangladesh. In the design process, parametric studies were carried out to study the effect of different geometric parameters on the eigen frequencies of the bridge deck system. The study clearly shows that for addressing the problem, the lateral dynamic stability of the deck system can be effectively improved by increasing the lateral stiffness of the deck system. The lateral stiffening of the supporting system of the deck, two double curved arches in this case, further improves the performance. Attempts are also made to explore the possibility of improving the vertical dynamic stability of the system by incorporating additional deck-lake bed ties.

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1. Introduction

Footbridges are now becoming an integral part of the of modern city infrastructures. These bridges allow safe transfer of pedestrians over the urban roads, city waterways or highways by providing a segregated grade separated transportation facility in walking mode. Furthermore, in some applications, the bridges of this class also connect urban installations at different elevations. In the current trend, the architects, in the design process carefully consider the aesthetic appeal of these bridges to maintain a harmony with the surrounding infrastructure of the neighbourhood while the structural engineers

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follow the current design codes to ensure the stability, safety and durability of the structure. The construction of 332m long three-span Millennium bridge having a notable architectural appearance built over the Thames at London is a recent example. However, on the eventful opening day of the bridge with a large crowd trying to use it, the Millennium Bridge oscillated significantly due to vibration induced by pedestrian movement. On the eve of a new millennium, the event made the scientific and engineering community over the world realize the necessity to further sharpen their views about the nature that interacts with our built environment. The dynamic stability of the structures due to human movement induced vibration came into focus. Following that event, several studies have been carried out that led to significant modifications of the code provisions for the footbridges. Nevertheless, the efforts of the architects and structural engineers in coming up with new and innovative designs have not ceased in the recent days. Very recently, a similar footbridge has been designed and constructed over the Crescent Lake at Dhaka, Bangladesh by considering the recently improved code provisions. This paper discusses different intrinsic aspects of the analysis and design of the bridge from the structural engineers' viewpoint.

2. Pedestrian-induced lateral vibration problem

2.1 Early case studies

Early technical information regarding human movement induced lateral vibration is known from the work of Bachmann (1992). It presents several valuable case studies and reports serviceability problems due to vibration in footbridges. In one case, vertical vibration problem occurred in a steel bridge that had a fundamental frequency of about 4 Hz. In addition, Bachmann (1992) records the report of having lateral vibration problem in another case of 110m long steel footbridge that had the frequency in the lowest lateral mode in the range of about 1.1 Hz. However, his work could not explain the cause that triggered such a phenomena.

2.2 Identification of the footfall action mechanism

The credit of the identification of the mechanism of synchronized footfall action goes to the work of Fujino et al. (1992 and 1993). The work was initially based on addressing the lateral vibration problem of T-bridge (Toda Park Bridge, Toda City, Japan), a pedestrian cable stayed bridge that was completed in 1989. Immediately after it was opened, the bridge suffered from lateral vibration induced by high number of pedestrians trying to pass over it in a peak-time. The detail study done by Y. Fujino and his associates mentions that people usually walk with a frequency of about 2 Hz, it is not commonly known but about 10% of the vertical loading works laterally when people walk (Nakamura and Fujino 2002). The gravity of center of human body moves laterally when person steps with his right and left foot in turn, which induces this lateral dynamic force. The frequency of this lateral dynamic force is about 1 Hz. So he mentions that the lateral dynamic forces induced by pedestrians can be a resonant force for the bridge-deck system whose natural frequencies are closer to this frequency (1 Hz).

However, all these works and reports were mainly available in the scientific and technical literatures and the professional design engineers were unaware of such problems as the design codes did not take these works into consideration. The problem struck once again in the Millennium bridge London, UK on its opening day (June 2000).

2.3 The problem with the Millennium Bridge, London, UK

In September 1996, a design competition was organized by the *Financial Times* newspaper in association with the London Borough of Southwark to design a new footbridge across the River Thames. The design of the present three span Millennium Bridge won the competition. The lengths of the three spans are 81m for the north span, 144m for the main span between the piers and 108m for the south span. The structural form of the bridge is a shallow suspension bridge, where the cables are as much as possible (Dallard et al. 2001a,b) below the level of the bridge deck to free the views from the deck. On the opening day (10 June 2000), the bridge experienced unexpected excessive lateral vibrations when pedestrians with a maximum density of 1.3 and 1.5 persons per square meter tried to cross the bridge. The movement took place at the south span at a frequency of about 0.8 Hz, at central span at frequencies just under 0.5Hz and at the north span just over 1 Hz. The number of pedestrians allowed onto the bridge was reduced on 11 June 2000 and movement occurred more rarely. On 12 June it was decided to close the bridge and it had to be retrofitted before opening to the traffic once again.

3. Recent codes on pedestrian bridges

Following the incident of the Millennium Bridge, London, the engineering community started to appreciate the necessity of revising existing codes for pedestrian bridges and take the vibration serviceability problem into consideration. This led to some major code revisions.

The recent code (BS 5400: Part 2, amended vide BD 37/01 on August 2001) states that for pedestrian bridge superstructures for which the fundamental natural frequency of vibration exceeds 5 Hz for the unloaded bridge in the vertical direction and 1.5 Hz for the loaded bridge in the horizontal direction, the vibration serviceability requirement is deemed to be satisfied. However, in the cases where these conditions are not satisfied, the code suggests for field vibration tests for determining the maximum acceleration of movement. The method for estimation procedures must have to be agreed upon with a competent authority.

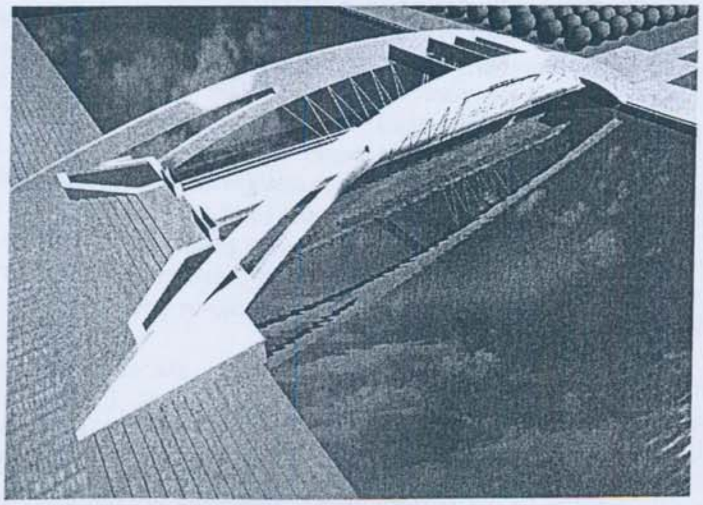

Fig. 1. A three dimensional view of the bridge as per initial architectural design

4. Architectural design and structural solution strategy in Crescent lake bridge

The study of the dynamic behavior of the arch-supported suspended-span footbridge presented in this paper originates from a development project initiated by the Public Works Department (PWD), Government of the Peoples' Republic of Bangladesh. The footbridge was constructed over the Crescent Lake, Dhaka, Bangladesh to facilitate movement of the pedestrians from adjacent roads to the nearby Mausoleum Complex of former Bangladesh President. Since the footbridge was to be constructed within the Master Plan area of well-known Bangladesh National Parliament Building Complex designed by famous Architect Louis Isadore Kahn, the architectural design of the footbrdige needed to be in harmony with the masterpiece creation of Architect Kahn. With this motivation, the architectural drawing suggested the construction of the pedestrian bridge with a special physical system where the hanging steel-framed deck (57.3m in length) fitted with tampered glass panels gets its support from two shallow reinforced concrete arches through hangers made of cables. The arches are connected at the top through reinforced concrete and steel ties. The arches have curvatures both in plan and elevation and are supported on 90 piles to bear the large lateral thrusts. Figure 1 presents a complete three dimensional view of the bridge as per the initial architectural design.

In such a system presented in Figure 1, the lateral and vertical stabilities of the arches and the deck system were considered to be quite vital. Hence, based on the conceptual design, a structural solution strategy had to be drawn so that the dynamic stability of the arch-deck system of the bridge can be ensured in accrodance with the recent code requirements mentioned in Section 3. To this end, fundamental natural frequencies of the bridge for a number of stiffening systems are considered. To identify the most effective stiffening system, a parametric study has been conducted to ascertain the major geometric parameters that govern the dynamic stability of the bridge system. Based on this parametric study, an arch-deck system that meet the most recent code requirements for eigen frequencies has been determined. Final part of the paper gives results obtained from a number of trial systems that can provide a better dynamic performance.

5. Finite element model of the bridge

In order to perform static and dynamic analysis of the arch-deck system, the three dimensional finite element model of the arches was developed using Strand Version 6.1- a general purpose finite element software. The arches were idealized as 3-dimensional beam. The supporting steel hangers that connect the steel girder with the arch were modeled as link (tension-compression) elements. The bridge girder made of steel sections was modeled as 3-dimensional beam elements. In order to check the design adequacy of the bridge, the available design codes/guides were consulted to ascertain the self weight of the bridge, the expected pedestrian load and the expected wind load on the arch and deck system. Within this notion, different geometric arrangements of deck, tie and bracing system were considered. Figures 2 and 3 presents two of these arrangements while the further details of all the options are presented in Section 6.

After modeling the arch, hangers and the deck system, the arch was analyzed for dead loads, live loads due to pedestrians and lateral wind forces. In general, for the design loads and assigned sections, the model was found to be numerically adequate. In view of the code requirements, the models developed here are used in the following Sections to study the dynamic stability of the system under pedestrian movement.

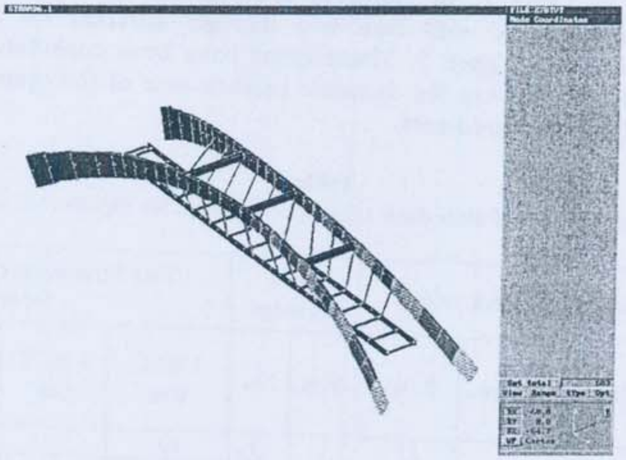

Fig. 2. Finite element model of the footbridge (Option B, Table 1)

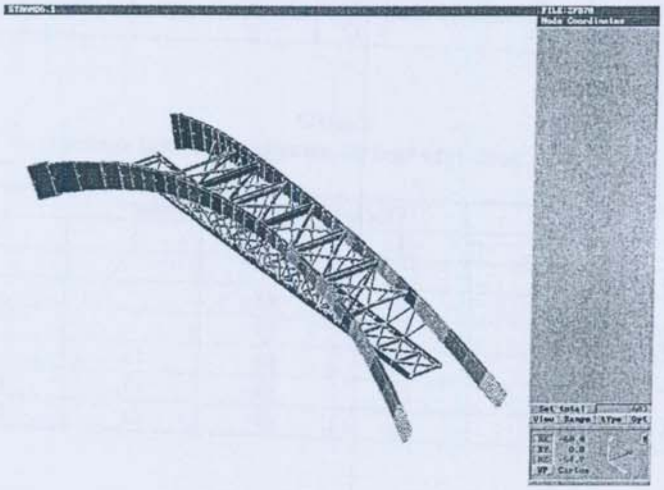

Fig. 3. Finite element model of the footbridge (Option E, Table 1)

6. Dynamic stability of the arch-deck system

6.1 Eigenvalue analysis

The recent code requirements regarding the vibration serviceability requirements are presented in Section 3. Section 4 has provided an overview of the structural system of the bridge. There it is observed that to achieve an adequate system, the fundamental vibration modes and natural frequencies of the structure with different stiffening systems need to be studied in details. Once studied, this would reveal the performance of the structural system against pedestrian movement. To this end, a parametric study was carried out to investigate the effect of different stiffening systems on the vibration modes and the fundamental natural frequencies of the arch-deck system using the developed finite element model (Section 5). Eigenvalues were calculated up to five modes for eleven possible combination options for choosing the most suitable arch-deck system. Among the eleven options, first five options (A-E) are based on the variation of the hanger system, deck width, deck bracings and number of ties connecting the arches at top as presented in Table 1. In addition, another six options (F-K) consisting of connecting the bridge deck with lake bed through different tie arrangements are presented in Table 2 and Figure 5. These cases have been considered to explore the possibility of further improving the dynamic performance of the system in accordance with the stipulated code requirements.

Table 1
Different options of arch-deck system considered for eigenvalue analysis

	Hanger system		Deck width		Deck bracings		Ties between arches at overhead locations		
	Straight	Inclined	4.27m	7.9m	Yes	No	3 RCC ties	5 RCC ties	5 RCC ties, 7 steel ties and bracings
A	O			O		O	O		
B	O		O			O	O		
C	O		O		O		O		
D		O	O		O			O	
E		O	O		O				O

Table 2
Different deck-lake bed tie arrangements trial systems

	Deck-lake bed tie number						
	1	2	3	4	5	6	7
F	O						
G				O			
H	O			O			
I			O	O	O		
J		O	O	O	O	O	O
K	O	O	O	O	O	O	O

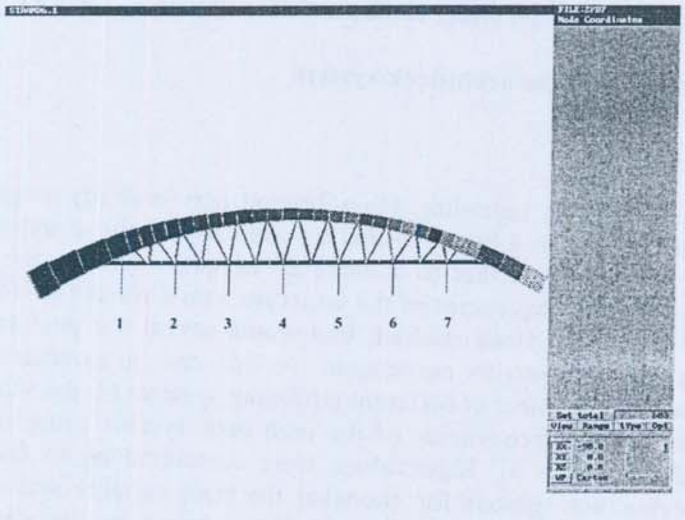

Fig. 4. Numbering scheme for deck-lake bed tie arrangement options

6.2 Mode shapes ascertained from the modal analysis

Figure 5 presents the typical mode shape for the first horizontal mode as computed for Option A or B. However, with the addition of deck bracings, the lateral stiffness of the deck system is increased. Due to this change, no true horizontal mode shape for the lowest frequency could be obtained. Rather it takes a complex mode shape, a horizontal sway coupled with a torsional mode. Figure 6 delineates the fact. However, there was no change in the mode shape for horizontal mode in options (F-K) of adding ties between the deck and lake bed. Figure 7 presents a typical shape.

In spite of changing geometric configurations, in all cases it was possible to obtain a true vertical mode shape. Figure 8 presents a typical shape.

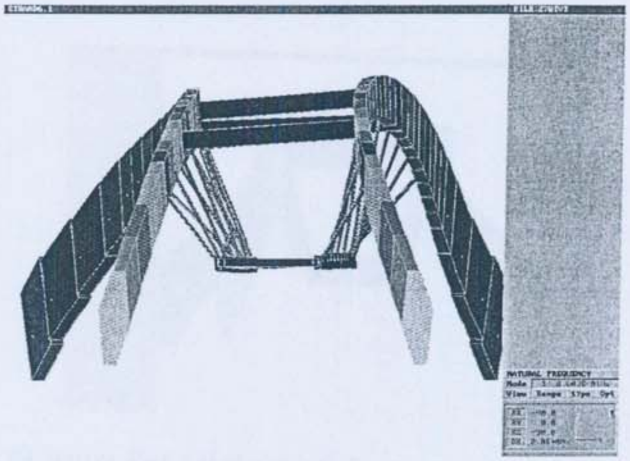

Fig. 5. First horizontal mode of vibration in the deck system for Option B

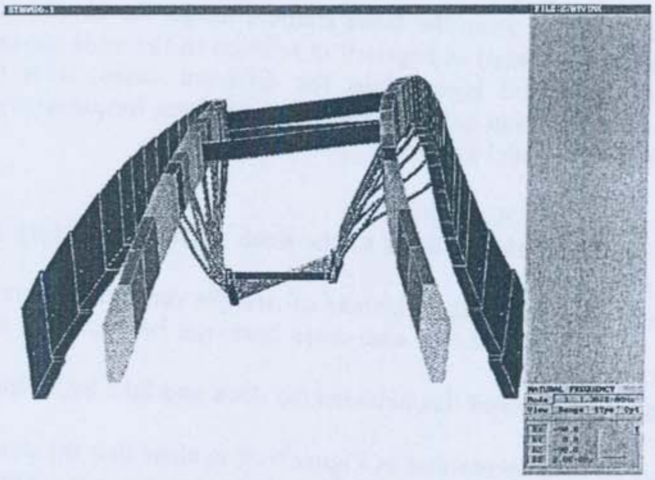

Fig. 6. First horizontal mode of vibration in the deck system for Option C

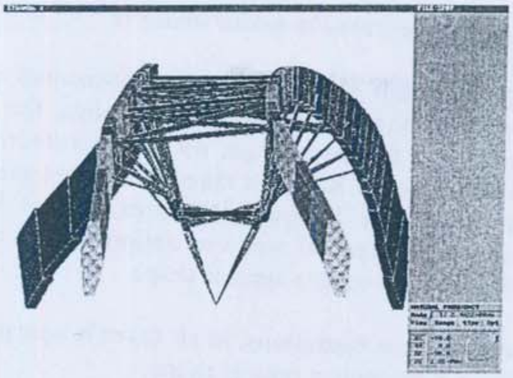

Fig. 7. First horizontal mode of vibration in the deck system for Option K

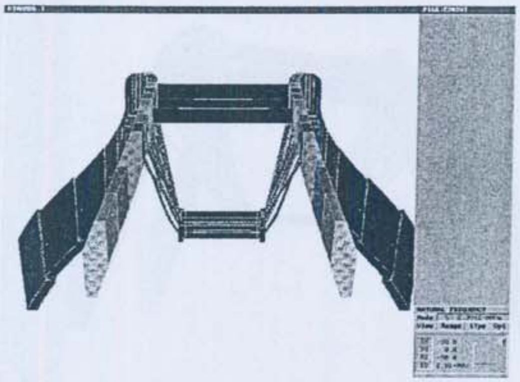

Fig. 8. Typical first vertical mode of vibration in the deck system for all options

6.3 *Eigenvalues computed from the finite element model*

The eigenvalues determined from the finite element model for first horizontal mode and first vertical mode are presented in Figure 9 in relation to the code recommended values. By comparing the computed eigenvalues for different cases, it is evident that the dynamic stability of the system expressed in terms of eigen frequencies improves for the following changes in the model geometry:

1. Decrease of deck width (Option B)
2. Increase of the lateral stiffness of the deck system by adding additional cross-bracings (Option C)
3. Adoption of inclined hangers instead of straight vertical hangers (Option D, E)
4. Increase the number of ties and cross bracings between the arches at the top (Option D, E)
5. Incorporating additional ties between the deck and lake bed (Option F-K)

Among all the eleven cases presented in Figure 9, it is clear that the dynamic stability of system can be improved if proper attention is paid to the above mentioned aspects. As a matter of fact, the first three aspects indicated above increases the lateral stiffness of the deck while the fourth aspect increases the lateral stiffness of the supporting arches. The fifth option attempts to increase the vertical stiffness of the deck. However, when compared with the code requirements, it is evident that the lateral stiffness of the system indicated by the frequency of the first horizontal mode can be attained in all the options above Option D whereas none of the cases could satisfy the vertical stiffness requirement indicated by the frequency of the first vertical mode. When compared between the cases, it is evident that the Option K with the deck connected to the lake-bed at seven different locations (Fig. 4) give the best possible performance in the light of the code but at the cost of aesthetic beauty.

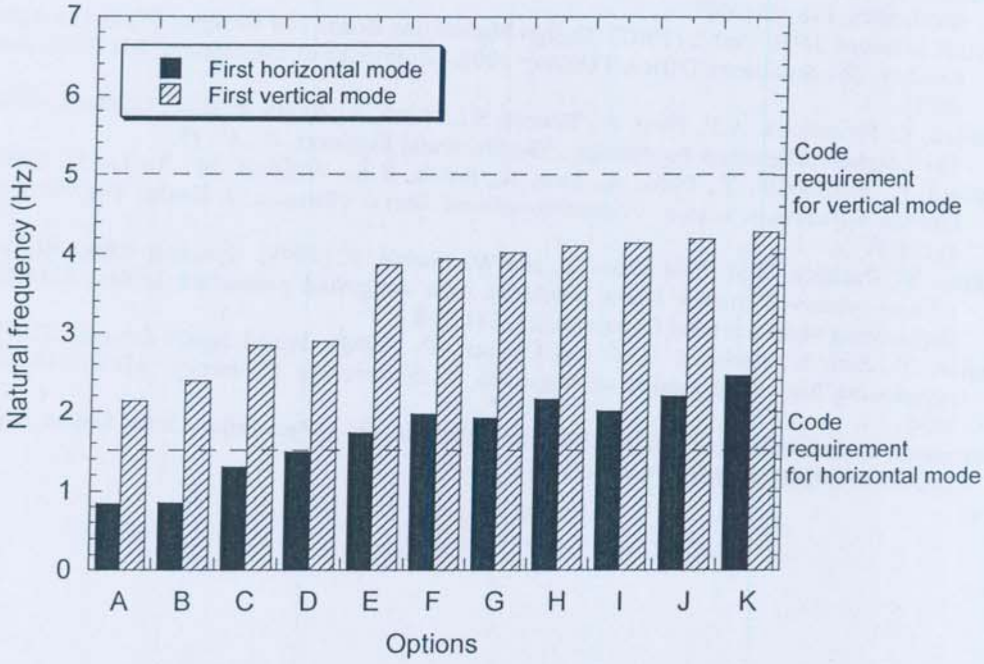

Fig. 10. Eigen frequencies determined for different Options and presented against the code requirements.

With a view to preserving the architectural view of the project to the best possible way, it was decided to go for constructing the bridge along with a provision of installing the deck-lake bed ties and perform a field test on the completed bridge without installing the ties. To this end, a field test involving an adequate number of volunteers crossing the bridge in both arbitrary and regular fashions was performed. The perception of users on its use was noted to have a more clear understanding of the behavior of the completed bridge under dynamic excitation. During the field test, the bridge was found to perform well and no perceivable vibration problem took place. The bridge was opened to pedestrian traffic.

7. Conclusions

In accordance with the recent code provisions, the footbridges need to meet the vibration serviceability requirements. To this end, in the recently completed Crescent lake footbridge project in Dhaka, Bangladesh, detail eigenvalue analyses were carried out on different finite element models with varied geometric parameters. The parametric study shows the necessity of having a careful consideration in choosing a geometric configuration that is most stable from vibration serviceability viewpoint. Furthermore, it is clear that a design not even completely satisfying the code stipulated eigen frequency(s) may also perform satisfactorily in the field level. However, in such cases, a full scale field test should be carefully performed before opening the facility to the traffic and in the event of failure of satisfying the performance requirements in field tests, the designer must maintain other clear provisions in his design for improving the system performance through adjustments in the field level.

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