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Vibration Analysis of Vertically Curved Concrete Flyover Bridges: Analytical Model Study

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ABSTRACT

By there gemeotry, vertically curved reinforced concrete flyover bridges (VCRCFBs) are expected to provide parabolic profiles for smooth passage of traffic. Conventional use of straight precast beams in producing such profiles has consistently resulted in polygonal profiles with persistent expansion joint problems, causing discomfort to users and reducing public confidence. Geometrical influence of three profiles on the dynamic characteristics of this type of bridges as well as bridge-vehicle response at varying vehicular speed with respect to human perception to vibration have been presented. Modal analysis was conducted on three VCRCFB models using CSiBridge (2015); a profile achieved using horizontal beams, a profile using slightly curved beams and a profile using a combination of straight and curved beams. Three vehicles were simulated, each passing the bridge for a period of 10 seconds per lane at the same speed of 10, 20, 30, 40 and 50 km/h and at varying vehicular speeds of 45, 50, 60 km/h and 60, 65,70 km/h, respectively. Response spectrum from time history analysis conducted for the three (3) vehicles moving on each of the models was plotted. Vertical component of acceleration at corresponding frequencies was compared with Irwin (1979) base curve for human perceptibility threshold. Profile with combination of straight and curved beams was found to induce less vibration compared to profile with straight and that with slightly curved beams. The results indicate that profiles of VCRCFBs with combination of straight and slightly curved beams at the cusp induced less vibration compared to profiles with straight or slightly curved beams. As such, the use of combined geometry precast beams should be encouraged in achieving vertical profiles for this class of bridges.

KEYWORDS: Vertically curved reinforced concrete flyover bridge (VCRCFB), VCRCFB profiles, Human perceptibility to vibration, Modal analysis, Time history analysis, Response spectrum analysis.

INTRODUCTION

The use of Vertically Curved Concrete Flyover Bridges (VCCFBs) at interchanges of highway systems is becoming increasingly popular because of increasing demand for curved roadway alignment for the passage of congested traffic as well as modern emphasis on aesthetic considerations. As such, health and performance of such bridges are very important considering the strategic roles they play in our cities.

According to David and Joanna (2014), vibration generated by vehicles traveling at speeds can be a significant issue in considering the design life of highway bridges. Dynamic effects can potentially become more serious if the bridge is old and has been subjected to increases in both magnitude and frequency of loadings during its working life.

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Determination of dynamic response of structures, especially bridges, has been the topic of numerous studies in recent years; however, the related question of user comfort on these vibrating bridges has received relatively little attention (Awall et al., 2012). The human body, however, is primarily sensitive to dynamic effects, such as acceleration and change of acceleration. Although not related to issues of safety, this may have the psychological effect of impairing public confidence in the structure, thus demanding consideration at the design stage (Awall et al., 2012).

Profiles of Vertically Curved Concrete Flyover Bridges (VCCFBs) are mostly constructed using straight precast beams with the aim of producing parabolic profile. This is almost impossible, as this method provides a polygonal profile instead of the desired smooth parabolic profile. Profiles of this type of bridges achieved using straight precast beams are mostly associated with problematic expansion joints, especially at the cusp of the curve, with conspicuous gaping of the parapet at such locations. By observing some of these types of bridges, the disparity in width of expansion gap at the cusp is due to the geometry of both the beam (straight) and the bridge as a whole (suppose parabolic). In some of such bridges, vehicles moving at a certain speed could bounce at each transition of the polygonal end formed by the straight beams. Also, vibrations or motion occurrences that often affect the comfort of bridge users are quite alarming. People without engineering training could easily spot pronounce gaping of parapet at varying elevations and ubiquitous expansion joint deterioration, resulting in unpleasant noise that lowers public confidence.

Understanding the dynamic properties of different profiles of VCCFBs achieved using beams of different shapes is timely. As such, models of VCCFBs achieved using straight beams, slightly curved beams and a combination of both (straight and curved beams) with the curved beams placed at the cusp of the curve, were studied with respect to modal behaviour, human perceptibility to vibration threshold and bridge-vehicle response to vehicular induced vibration. The outcome of this study will serve as a guide to provide a suitable means of achieving the best VCCFB profile.

This paper is aimed at conducting vibration analysis on different profiles of vertically curved concrete flyover bridges.

Objectives of the study are to:

(i) Conduct modal analysis on three (3) profiles of Vertically Curved Concrete Flyover Bridges.
(ii) Compare modal parameters of the bridge models with the profile achieved using horizontal beams, profile achieved using slightly curved beams and profile achieved using a combination of straight and curved beams.
(iii) Analyze bridge-vehicle response of the three models at varying vehicular velocities.
(iv) Identify human perceptibility to vibration for the models at varying vehicular speeds.
(v) Establish a suitable deck profile for such type of bridges.

Scope of the study involves an analytical study of the three (3) models stated above using CSiBridge (2015) software.

Human Perceptibility to Traffic-Induced Bridge Vibrations

People have high sensitivity to vibrations. So, human response to vibrations due to dynamic loads should be considered as a serviceability limit state. Several factors influence human sensitivity to and perception of vibration; namely, position of the human body, health condition, age, type of activity, excitation source characteristics, exposure time, direction of motion, floor and deck system characteristics and level of expectancy (Murray et al., 1997; Naeim, 1991).

The acceptable level of vibration also depends on the kind of structure; for instance, a higher level is acceptable on bridges, with respect to residential buildings, due to the awareness of the presence of wind and traffic and for the limited in time exposure (Wiss and Parmelee, 1974).

METHODOLGY

CSiBridge software (2015) is used in this study. The software is an ultimate, easy-to-use, integrated finite element software program for modelling, analysis and design of bridge structures.

Description of Bridge Model

The proposed bridge model is made up of 16 spans of 18m each. The total length of the bridge is 288m. The superstructure consists of eight (8) precast concrete T-beams with a section of 1160 mm depth x 350 mm web width x 17950 mm length. The carriageway is 8m wide flanked by a 0.7m safety kerb with a precast parapet wall on both sides. It is overlain with a 50mm-layer of asphaltic concrete surfacing. Figure 1 shows the section of the bridge superstructure.

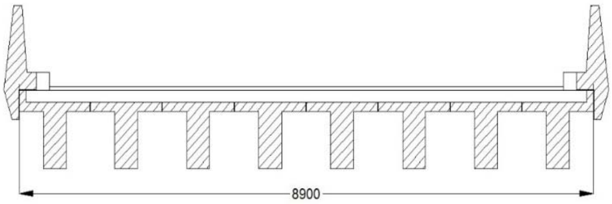


Figure (1): Section of bridge superstructure

METHODS

Steps in Creating Bridge Object Model in CSiBridge Software

CSiBridge model is parametrically defined. The modelling process begins by specifying the basic layout of the bridge (that is, length, bearing, alignment, spans, number of lanes, lane widths and slopes). Bridge components are then defined: deck sections, abutments, diaphragms, bents, foundation springs and so on. These components are located relative to the layout. Applied loading, load cases, superstructure, substructure design and load ratings are defined for the assembled bridge object.

In order to analyze the modal parameters of the adopted bridge (Kawo Flyover Bridge) as built, information provided in the bridge approved drawing obtained from Design and Implementation Office of Kaduna State Ministry of Works and Transport (Nigeria) was used to model and analyze the bridge.

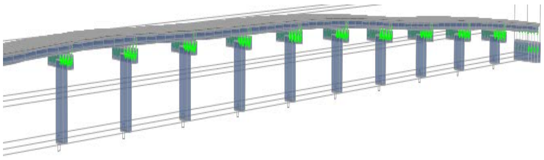


Figure (2): 3D view of updated bridge model

Analysis of Model

Load case analysis type was selected, which includes modal analysis and time history analysis.

Modal Analysis

Eigenvector type of modal analysis is adopted in this work. It involves the solution of generalized eigenvalue problem as shown in Equation (1).

$$([k] - \omega^2[M])[\emptyset] = 0 \qquad (1)$$

Time History Analysis

This is a step-by-step type of analysis used for the determination of dynamic response of a structure under specified loading as presented in Equation (2) (CSI, 2013).

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t) \qquad (2)$$

Response Spectrum Analysis

It is a statistical type of analysis used for the determination of the likely response of a structure under seismic loading as represented in Equation (3), which is a dynamic equilibrium equation associated with the response of a structure to ground motion (CSI, 2013).

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = m_x\ddot{x}_{gx}(t) + m_y\ddot{x}_{gy}(t) + m_z\ddot{x}_{gz}(t) \qquad (3)$$

where:

m_x, m_y and m_z are the unit acceleration loads.

$\ddot{x}_{gx}\,, \ddot{x}_{gy}\ and\ \ddot{x}_{gz}$ are the components of uniform ground motion.

Bridge Response to Varying Vehicular Speed

The bridge model was simulated for various speeds and in each case, three vehicles were allowed to pass in the following sequence:

(i) First vehicle accesses the bridge on lane 1 at 10km/sec at a starting distance of 0m.
(ii) Second vehicle accesses the bridge on the same lane with the same speed after 2sec.
(iii) Third vehicle accesses the bridge with a starting distance of 288m on lane 2 at 10km/sec.

Time history analysis was run using a linear direct history analysis load case. The response of the following speed combination for the three vehicles was recorded.

(i) 20,20,20km/h,
(ii) 30,30,30km/h,
(iii) 40,40,40km/h,
(iv) 50,50, 50km/h,
(v) 45, 50, 60km/h,
(vi) 60, 65, 70km/h.

The model was simulated for a loading duration of 10sec and discreticized for 0.1 sec, with 100 output time steps having an output time step size of 0.1sec.

RESULTS AND DISCUSSION

Results of Modal Analysis, Time History Analysis and Response Spectrum Analysis

Twelve (12) modes were recorded, each with corresponding mode shape and natural frequency for each model of the three profiles. Vertical component of acceleration at varying vehicular speed and damping ratios were also recorded, including bridge- vehicle interaction for a period of 1 0 seconds at varying speed.

Modal Analysis Results

Relationship of natural frequency of the different profiles to number of modes is presented in Figure 3.

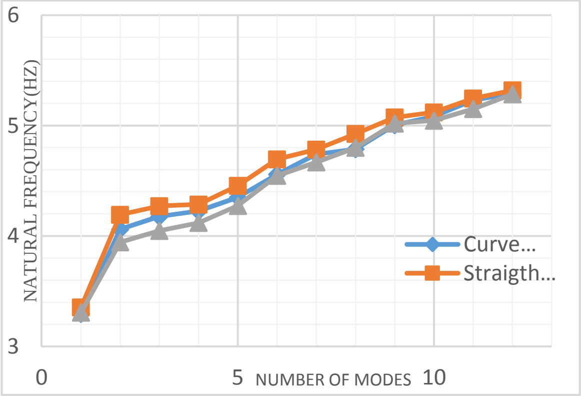


Figure (3): Relationship of natural frequency to number of modes for curved, straight and straight-curved beams

Differences in natural frequencies are presented in Tables 1 and 2 for models containing straight-curved beams and straight- straight/curved beams, respectively.

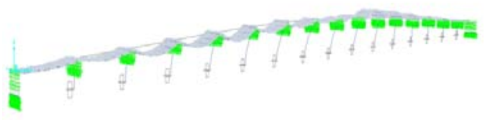
Table 1. Differences in frequencies between models with curved beams and straight beams

Mode No.	Frequency of curved beams (Hz)	Frequency of straight beams (Hz)	Difference in percentage (%)
1	3.296259	3.353384	1.733025
2	4.060484	4.193029	3.264266
3	4.176786	4.271131	2.258794
4	4.226323	4.28547	1.399491
5	4.349716	4.455593	2.434113
6	4.557598	4.694582	3.005618
7	4.740383	4.783542	0.910454
8	4.787311	4.924665	2.869126
9	5.005267	5.074043	1.374073
10	5.08293	5.120001	0.729323
11	5.228857	5.245227	0.31307
12	5.291043	5.319221	0.53256

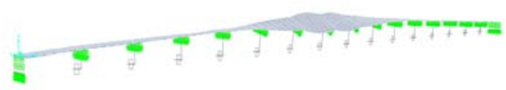
Table 2. Differences in frequencies between models with straight beams and combined curved and straight beams

Mode No.	Frequency of combined curved and straight beams (Hz)	Frequency of straight beams (Hz)	Difference in percentage (%)
1	3.3074	3.353384	1.390337
2	3.944	4.193029	6.314123
3	4.048	4.271131	5.512129
4	4.1197	4.28547	4.023837
5	4.2743	4.455593	4.241466
6	4.5459	4.694582	3.270683
7	4.668	4.783542	2.475193
8	4.8002	4.924665	2.592913
9	5.0202	5.074043	1.072527
10	5.0461	5.120001	1.464517
11	5.1511	5.245227	1.827318
12	5.2843	5.319221	0.660844

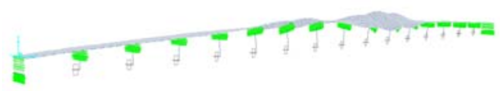
Mode shapes for models with curved and straight precast beams are presented in Figure 4.



Mode 1,f=3.30735Hz



Mode 2, f=3.94401



Mode 3, f=4.04796Hz

Figure (4): Mode shapes for models with curved beams and straight beams

Bridge-Vehicle Response at Varying Vehicular Speed

Response of the models based on vertical acceleration component at varying speed as well as response based on time of entrance into the bridge are presented in the response spectrum curves and plot functions for models with curved, straight and straight-curved beams.

Response Spectrum of Bridges with Curved Beams

Vertical component of Pseudo-Spectral Acceleration (PSA) and vertical response from FE simulation at varying vehicular speed and damping ratio are presented in Figures 5 to 14.

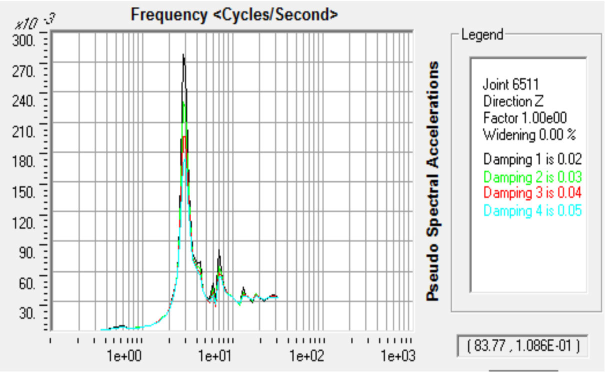


Figure (5): PSA spectrum from time history analysis at 10km/h

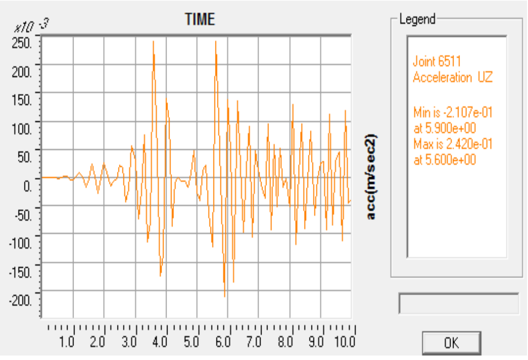


Figure (6): Vertical response of vehicles from FE simulation at 10km/h

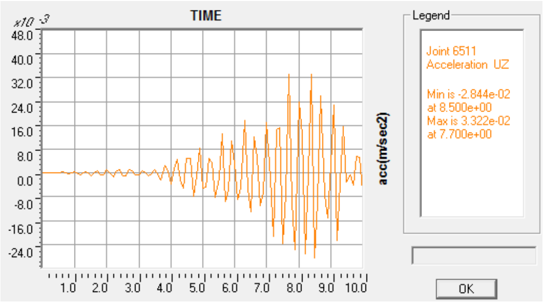


Figure (7): Vertical response of vehicles from FE simulation at 40km/h

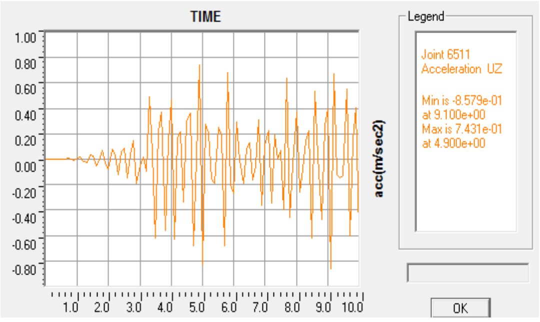


Figure (8): Vertical response of vehicles from FE simulation at 45, 50 and 60 km/h

Response Spectrum for Straight Beams

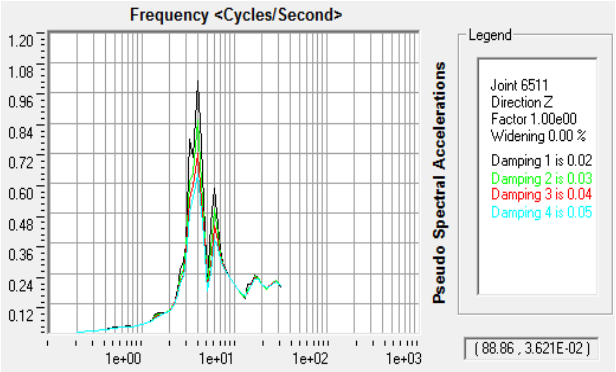


Figure (9): PSA spectrum from time history analysis at 10km/h

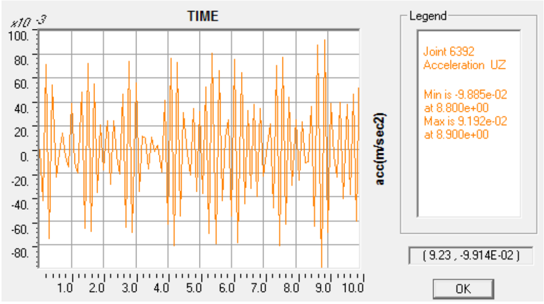


Figure (10): Vertical response of vehicles from FE simulation at 10km/h

For speed combinations of 20, 30, 40km/h, 45, 50, 60km/h and 60, 65, 70km/h response of bridge model is surprisingly the same. So, only 20km/h case is presented.

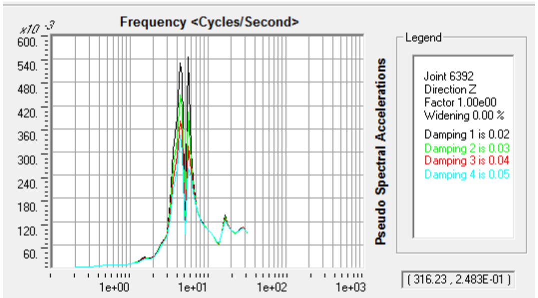


Figure (11): PSA spectrum from time history analysis at 20km/h

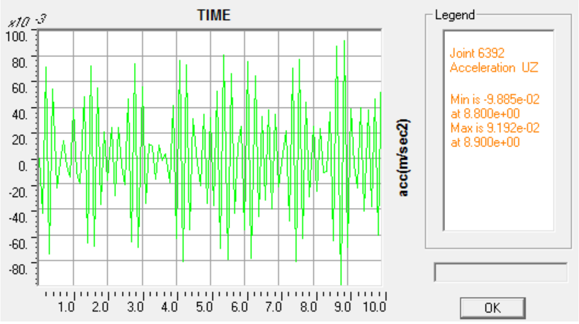
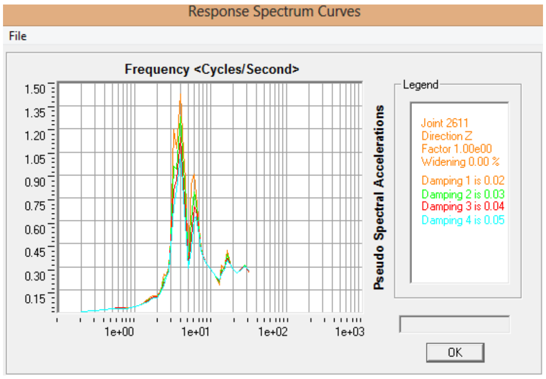


Figure (12): Vertical response of vehicles from FE simulation at 20km/h

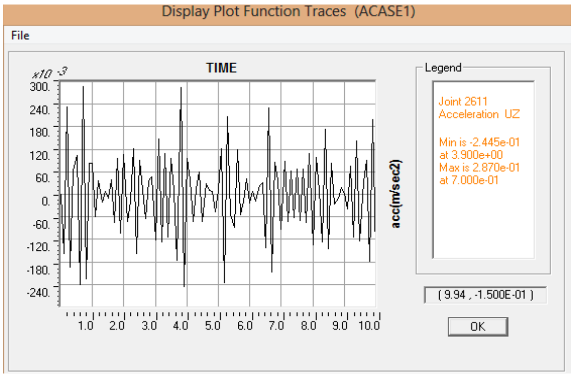
Response Spectrum for Combination of Straight and Curved Beams

Response of VCCFB model with profile achieved using a combination of both vertical and horizontal and curved beams is presented.



Joint 2611
Direction Z
Factor 1.00e00
Widening 0.00 %
Damping 1 is 0.02
Damping 2 is 0.03
Damping 3 is 0.04
Damping 4 is 0.05

Figure (13): PSA spectrum from time History analysis at 10km/h



Joint 2611
Acceleration UZ
Min is -2.445e-01
at 3.900e+00
Max is 2.870e-01
at 7.000e-01

(9.94 , -1.500E-01)

Figure (14): Vertical response of vehicles from FE simulation at 10km/h

Human Perception to Vehicular Vibration

Irwin (1979) base curve for human perceptibility to vibration is used as a basis in this work. The points recorded from the analysis are plotted in the curves presented in Figures 15, 16 and 17 for curved, straight and a combination of straight-curved beams, respectively.

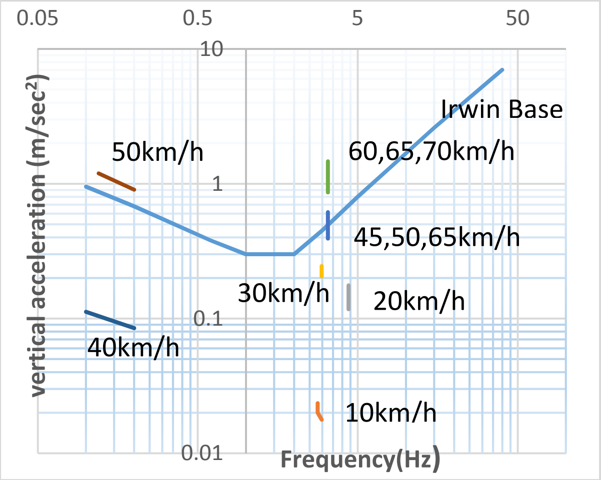


Figure (15): Human response to the vertical component of vibration for bridge with curved beams

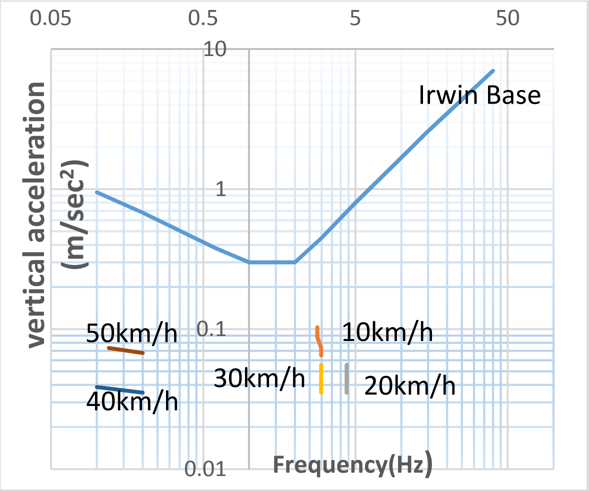


Figure (16): Human response to the vertical component of vibration for bridge with straight beams

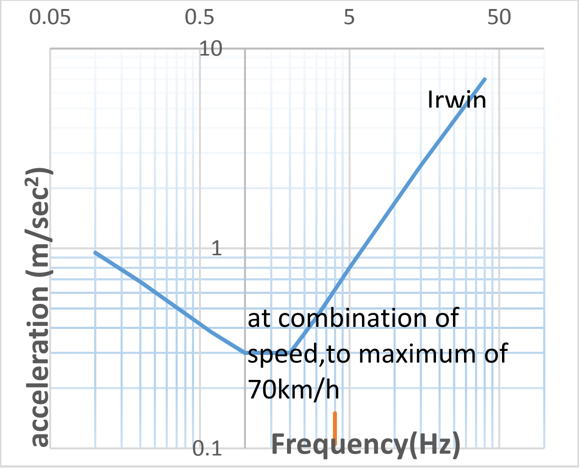


Figure (17): Human response to the vertical component of vibration for bridge profile achieved using a combination of curved and straight beams

DISCUSSION OF RESULTS

Modal Analysis

Results of modal analysis for the three models (curved, straight and combination of straight and curved beams) are presented. Mode shapes are presented for each model, with natural frequencies ranging from 3.34 to 5.32 Hz for straight beams, from 3.30 to 5.29 Hz for curved beams and from 3.31 to 5.28Hz for combination of straight-curved beams, respectively with increasing number of modes. For each mode, natural frequencies of the model with straight beams are found to be higher than those for profiles with curved beams and combination of straight-curved beams. Relationship between natural frequencies is presented in Tables 1 and 2. It is clear from the tables that for each mode, natural frequencies of the model with straight beams are higher with major differences in modes 2, 6 and 8, representing 2.26, 3.01 and 2.87% between straight and curved beams, respectively. For straight and straight-curved beams, differences in natural frequencies are more pronounced in modes 2, 3 and 5, representing 6.31, 5.51 and 4.24%, respectively.

Bridge-Vehicle Response to Vehicular Speed

The results of the vertical component of Pseudo-Spectral Acceleration (PSA) at various frequencies are presented, later converted into actual vertical acceleration values and compared with the Irwin (1979) base curve for bridge vibrations.

Response Spectrum Curves

For bridge models with curved beams, the vehicle response during the first few seconds after entering the bridge was only noticeable after some time ranging between 4.2, 4.5, 0.5, 1.2, 1.4, 1.2 and 1.1sec, respectively for vehicular velocities considered in the analysis. Also, the maximum accelerations recorded are 0.033m/sec^2 at 7.7 sec for 10km/h, 0.332m/sec^2 at 8.9sec for 20km/h, 0.165m/sec^2 at 7.7sec for 30km/h, 0.242m/sec^2 at 5.6 sec for 40km/h, 1.482m/sec^2 at 6.1sec for 50km/h, 0.743m/sec^2 at 4.9sec for 45,50,65km/h and 1.957m/sec^2 at 5.7 sec for 55,60,65km/h. This implies that VCCFB profiles achieved using curved beams will provide smoother entrance into the bridge.

For models with straight beams, it is clear that at all speeds, vehicle response at the first few seconds after entering the bridge is highly noticeable. The implication of this is that there will be an impact of wheels at the entrance which may be disturbing.

Also, for models with combined straight and curved beams at the cusp of the bridge, the property of straight beams still dominates; that is, the response of vehicles at all speeds is very noticeable at a few seconds after entering the bridge. This implies wheel impact at the entrance, but vibration is considerably reduced afterwards.

Human Perception to Vibration at Varying Vehicular Speed

Irwin (1979) suggested a base curve for acceptable human response to vibration of bridges under various forms of loading. In this study, Irwin's (1979) curve for vertical component of bridge motion in stormy wind conditions was selected as a base curve for the human-perceptible vertical component of vibrations on the footway of the bridge deck because of its wide range of frequency; from 0.2 to 80Hz. Vibration magnitude lower than the curve is considered as the acceptable limit according to his recommendation.

For bridge models with curved beams as presented in Figure 15, vehicular velocities from 10 to 40km/h are acceptable, while combined speeds of 45, 50 and 60km/h may be allowable, being right on the curve. But, velocity of 50km/h and combined speeds of 60, 65 and 70km/h will induce more vibration, being above the base curve considered and the corresponding vertical component of acceleration is from 0.9 to 1.5m/sec^2 for 50km/h and combined speeds of 60,65 and 75km/h.

For bridge models with straight beams as presented in Figure 16, vehicular speeds ranging from 10 to 50km/h fall below the base curve, which makes them within the acceptable limit specified by Irwin (1979).

For bridge models with combined straight and curve beams at the cusp as presented in Figure 17, at all speeds considered, the vibration threshold is quite lower than the base curve.

CONCLUSIONS

Based on the results obtained from modal analysis and time history analysis for different VCCFB profiles and vehicles passing at different speeds, the following conclusions are drawn:

(i) Modal analysis on three VCCFB profiles was conducted.

(ii) Natural frequencies and mode shapes for the profiles considered were compared. It was established that mode shapes are mainly coupled, consisting of longitudinal and torsional modes of vibration for all profiles.

(iii) Profiles with straight beams are considered more stable as a result of their higher natural frequencies.

(iv) Bridge–vehicle response at varying vehicular speed were simulated using time history analysis and response spectrum analysis.

(v) Vertical component of vibration, which is the major contributing parameter in structural vibration, reduces as damping ratio increases from 2% to 5% for all vehicular velocities considered.

(vi) Using straight beams at VCCFB entrance induces higher vehicle response.

(vii) Bridge-vehicle response results were compared with Irwin (1979) base curve for acceptable human response to bridge vibrations.

(viii) Profiles achieved with a combination of straight and curved beams at the cusp are more suitable for VCCFBs because of their lower vehicular induced vibrations recorded at varying speed.

From the result obtained, it can be noted that profiles achieved with a combination of straight and curved beams at the cusp have lower vehicular induced vibrations recorded at varying speed, which makes them more convenient for VCCFBs.

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