AMBIENT VIBRATION TESTING OF BRIDGES - STATE OF THE ART

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ABSTRACT
Vibration testing of bridges can give very helpful information based on the behavior and performance during its service life. Ongoing researches are carried out based on the vibration based assessment of the bridge structure to evaluate the structural condition and overall integrity. A structural distress, locally or globally leads to decreasing in stiffness and free energy stored in the system or structure. Under the influence of the ambient and force excitation, vibration response is influenced by system parameters (stiffness, mass and damping), changes in these parameters may lead to changes in the vibration response such as natural frequencies, mode shapes and modal damping. The dynamic response of the bridge structure is measured. With this measured response modal parameters as well as system parameters can be obtained. These identified parameters can be used to monitor the performance of the bridge structures. Analytical models can also be used to validate using these parameters. In this paper, detailed review of the ambient vibration testing of bridge is given.

KEYWORDS: *vibration testing, ambient vibration, health monitoring, bridges.*

I. INTRODUCTION

Bridges are playing a vital role in transportation systems. Many of the earlier studies of bridge vibration were begun after bridge failures were notified due to vibration. A number of reports and technical papers on dynamic behavior of bridge structure under moving loads reveal continuous effort of researchers in this field. The historical developments within the field of structural dynamic techniques including structural monitoring activity carry out during the different development phases. In the 19th century, the development of relevant structural dynamics took place, followed by which execution of simple tests at clearly defined structures was carried out during 1920's to 1945's. In 1960's to 1980's, analytical work based on linear FE method and forced vibration methods were developed by the researchers. In 1975's to 1995's, analytical studies were carried out on integration of the linear and non-linear FE analysis. While during the 1980's to 2000, Introduction of the ambient vibration method and computer measuring technology for data extracting has come into existence. Also, since 1994, application of the ambient vibration methods, the development of smart monitoring methods and commercial utilization of monitoring equipments are taking place to study behavior and performance of the structures [1]. Due to the development of significant advances in experimental techniques along with theoretical techniques, yielding data from field tests is used to study the dynamic behavior of structures. Highway bridge tests have been conducted in many countries since few decades [2].
In the design of bridges, the vibration caused due to moving vehicles plays a very important role as the interaction between the moving vehicles and the bridge structures. Vehicle-bridge interaction is a complex dynamic phenomenon, which is a non-linear problem depends on many parameters. These parameters include the type of bridge and its vibration characteristics, vehicle characteristics and their relative positions on the bridge and roadway surface irregularities etc.

The arrival of high-speed digital computers and vibration measuring instrument made it possible to analyze the interaction problem with more bridge and vehicles. Full scale dynamic field test of bridges was also performed under the influence of the ambient or force excitation, to measures the dynamic response to extract the dynamic parameters for monitoring the performance of the bridge. Although extensive studies have been done in this field, high-performance analysis methods are still required for accurate prediction of dynamic response of bridges under ambient loads.

II. BRIEF OVERVIEW ON ANALYTICAL DYNAMIC STUDIES ON STRUCTURE

Dynamic response of bridges has been attracting researchers around the globe since last few decades. Willis [3] suggest an approximate solution for a single constant load over a beam of a negligible mass in 1851. In 1883, an exact solution of the equation was formulated by Stokes [4]. In 1922, Timoshenko [5] noticed that three major causes of vibrations in railroad bridges: the live load effect of a smoothly rolling load, the impact effect of the balance weights of the locomotive driving wheels, and the impact effect due to irregularities of the track and fiat spots in the wheels. Later on he illustrated two possible extreme cases of the live load effect: that the mass of the moving load is either large or small in comparison to the mass of the beam, for a simply supported beam using the method of expansion of the eigen functions. The case with the aid of Green's function was solved by Lowan [6]. Timoshenko also solved the problem of the effect of the balance weights by using a harmonic force moving over a beam at a constant speed. Jef cott [7] studied the problem involving both the load mass and the beam mass, being more complicated, was examined much later by whose iterative method became divergent in some cases. In 1934, various approaches were used to solve several cases of dynamics of railway bridges traversed by motion of a concentrated force, sprung and unsprung masses and harmonic forces acting on a beam, etc. with harmonic analysis by Fryba [8] and Wen [9]. Inglis [10]. Firstly the vehicle had been idealized by a single mass point. However, around the early 1950's idealization of the vehicle as a sprung and unsprung mass was attempted. With the help of fourier's method and the method of numerical differences to obtain the solution of the motion of sprung masses on a beam firstly has successfully done by Hillerborg [11]. Later development were made possible by digital computers. The formulation involving both sprung and unsprung masses was solved by Biggs et al. [12] using Inglis' method and by Tung et al. [13] using Hillerborg's method and was applied to vibration of highway bridges.
The use of computers helps in research into the dynamic response of bridges. The vehicles as well as the bridge have been idealized as multi-degree-of-freedom systems, with using of d' Alembert's principle or Lagrangean energy equations, equations of motions having been derived and solved by finite element or other numerical methods. The work of Hathout [14], Chu [15] et al, Wuiyachai et al [16], and others are significant. Experimental work also followed the theoretical work. The first dynamic testing were conducted by Robinson [17] in 1883. Later the American Railway Engineering Association conducted extensive tests on railway bridges which were reported by Turneaure [18] in 1911 and Hunley [19] in 1936. Until that time all the tests were on steel bridges. Now testing work has been extended in highway bridges also.

III. NECESSITY OF VIBRATION FIELD TESTING OF BRIDGE

There are several purposes for performing the full scale vibration testing of bridge. Which are described as follows:
With full scale vibration testing of bridge structure, it is easy to assess the overall integrity of the structure and understand the actual behavior of the structure.

1. Results of vibration test can be used to determine the type of loadings, dynamic load effects and load distributions. Therefore, to assess the integrity of a structure when higher loading levels are predicted either due to a change of use. Higher environmental loading or an increase in allowable loading. An example of such application is the current assessment of some highway bridges in the UK to check their ability to withstand 40 tons trucks to be introduced in 1999.Prouix et. al [20] dynamic testing is more reliable than other methods to evaluate the dynamic amplification factor since it (dynamic testing) produces information, on the dynamic properties of the structure, that can he used in structural assessment and design of repair work.

2. From the vibration data collected during the test are utilized to extract the modal parameters. These modal parameters are used to control and update numerical calculation methods and to validate theoretical models of structures. Mathematical models of real structures usually involve significant assumptions especially with regard to boundary conditions. Therefore, as the structural system becomes more complex and sophisticated, it becomes more difficult to understand its mechanisms. Therefore, to develop an appropriate model, this will give a good prediction of its dynamic responses. Comparison and updating of theoretical predictions with measured response will lead to a better understanding of the structure.
3. A vibration measurement on full scale bridges serves to increase the data base in a form of case studies on different type bridges. This database can be utilizes for performance information on the complete similar structures and also gives useful data for future designs.

IV. AMBIENT VIBRATION TEST

In ambient vibration testing, it does not require a external excitation of the structure. The Structures response to ambient excitation records in large number of points. According to Felber [21], the system identification technologies were applied to determine and analyse the frequency response functions from measured signal data. The loading could be from environmental, vehicular or pedestrian traffic or any other service loading. Nalitolela et. al. [22] shows that ambient vibration testing implicitly assumes response data alone could be used to estimate vibration parameters. This method is convenience of measuring the vibration response during the structure is under opertional condition. With the uses of data acquisition and storage systems, it provides wide range of measuring parameters.

In most cases, the nature of the ambient excitation can only be considered by statistical descriptions (for example wind loading, rain loading and traffic density based on the urbanization of region) or by assuming the excitation spectrum to be concentrated within a frequency range (for example. 2 - 4 Hz for vehicular excitation of bridges by Billing [23]. If the loading spectrum is limited to a narrow band of frequencies, only a limited picture of the dynamics of the structure can be monitored was suggested by Williams [24], A theoretical validation of ambient vibration testing has been proposed by James et.al. [25].

Frequency and mode shape data can be obtained by Srinivasan [26], estimated damping values are prone to errors. The errors in the damping estimates are due to a combination of factors such as the (possible) nonstationarity of the excitation process. Signal processing and data analysis procedures necessary to extract modal parameters and the insufficient excitation of some modes. Brownjohn [28] has discussed the problems of obtaining reliable damping estimates from ambient vibration testing.

The frequency response function changes depending on the amplitude of the input excitation. This leads to variation in damping estimates since damping depends on vibration amplitudes. Hence, results from low level excitation might not be appropriate to predict the dynamic response to high level excitation. Coupled with this is the considerable degree of nonlinearity exhibited by many real-life structures.

V. AMBIENT VIBRATION TESTING OF BRIDGES: SOME FIELD STUDIES

Much of the initial work in bridge vibration began with actual bridge testing. This enabled the researchers to identify the factors that most affected bridge vibrations. The initial tests involved simple span bridges only. This was followed by the study of multi-span bridges and then by more complicated bridges, such as suspension bridges.

K. H. Kinnier [29] and W. T. McKeel [30] studied at the influence of the bridge substructure on the dynamic behavior. In their first study, they had compared conventional and elastomeric influence bearings on a rolled - bean, composite bridge. In their second study, they compared tall and short piers on a composite bridge by measuring strains and deflections caused by a 3 - axle tractor - trailer.

J. M. Biggs and H. S. Suer [12] had been tested two steel stringer bridges and three plate-girder bridges with the load applied by a 2 - axle, 10 ton dump truck. They measured deflections with a deflectometer and accelerometers. The remaining study was by J. M. Biggs [31]. He tested two single medium span stringer type through girder bridges, with the load applied by a 2 - axle dump truck. The deflection was measured by deflectometers at midspan, and strains and accelerations were measured on the axles of the truck.

J. R. Billing and R. Green [32] reviewed three series of dynamic tests done in Ontario, Canada in 1956 to 1957, 1969 to 1971, and 1980. In the first two series, deflection was measured, while in the last series, acceleration was measured. In the last two series, test vehicles were used. R. Green [33] summarized 52 simple span bridge tests involving with both a test vehicle and normal traffic loading. He measured the deflections with a deflectograph.

C. P. Hems [34] tested 40 simple span bridges with five different types of vehicles obtaining stress versus time records at several locations along the bridge. C. G. Schilling, K. H. Klippstein, J. M. Barsom, and G. T. Blake [35] studied fatigue in bridges by summarizing 15 field bridge tests subject to traffic loading. Perhaps the most complete study was that by J. T. Gaunt and C. D. Sutton [44].They tested 62 bridges under normal traffic and a test vehicle. Both accelerations and deflections were measured. R.C. Edgerton and G. W. Beecroft [37, 38] studied two 3-span plate girder bridges with a tractor trailer combination. They measured strains for a variety of loading cases. Hayes and J. A. Sbarounis [39] tested a 3-span, continuous, I-beam Bridge by measuring strains due to vibrations caused by a test truck. G. M. Foster and L. T. Oehier [40] tested an 8-span plate Girder Bridge and a 6-span rolled beam bridge with 2-axle and 3-axle trucks and normal traffic. They measured deflections with a deflectoaeter.

The next study was by D. A. Linger and C. L. Hulabos [41] who tested four continuous span bridges. The loading was a van truck and a tractor trailer combination, and response was measured by strain gages. H. S. Ward [42] studied a 5 - span continuous, variable sized plate girder bridge with forced oscillation and a test vehicle. The vertical vibrations were measured with seisometers, i.e. velocity transducers. A study of strain measurements in an 11 - span composite bridge, subject to a 40 ton truck was done by J. B. Menzies [43]. In an extensive study W. H. Walker and J. S. Ruhi [44] tested two three-span continuous bridges and one two—span continuous bridge with normal traffic and a three axle tractor –semi-trailer combo, with strain and deflection gage measurements. At about the same time,R. Eyre and I. J. Snith [45] used deflection gages to study a two level, 20 - span steel box Girder Bridge with normal traffic and a test truck vehicle. R. S. Shepherd, H. E. E. Brown, and J. H. Wood [46], studied a 3 - span steel truss bridge subject to wind and normal traffic loading. Measurements were taken with dynamic displacement transducers and seisometers. Vibration response monitoring of bridge during ambient traffic was studied out by Creed [47] on a six-span concrete motorway bridge. To identified mode shapes and to check bearing motion at supports, total eight vertical accelerometers were used in pairs. The calculated natural frequencies also represent good agreement (within 3.5%) with finite element analysis predictions.

Extensive experimental tests have been conducted [48, 49] on the Golden Gate suspension bridge to determine effective structural damping, three-dimensional mode shapes and modal frequencies. Ambient Excitation was considered during test such as wind, ocean waves and vehicular traffic. 20 vertical, 20 longitudinal, 33 lateral and 18 torsional modes were identified between frequency range 0 - 1.5 Hz from simultaneous measurement of vertical, lateral and longitudinal vibration of the suspended structure. The estimated mode shapes and frequencies refect good conformity with the results of finite element analyses. V. R. McLamore [50] tested the Chesapeake Bay Bridge with the seisometers placed in five different patterns, with one seisometer always used as reference. V. R. McLamore, I. R. Stubbs, and G. C. Hart [51] tested the Newport Rhode Island Suspension Bridge in the same way. A. H. Abdel-Ghaffar and G. W. Housner [52, 53] tested the Vincent - Thomas Suspension Bridge in California. They used 16 different set ups of the eight seismometers with 4 of the seisometers always placed in the reference locations. P. G. Buckland, R. Hooley, B. D. Mogenstern, J. H. Rainer and A. M. Van Seist [54] tested the suspension bridge under ambient loading, with using accelerometers and seismometers to measure vibration. They used the Fourier spectra from their data to calculate damping, natural frequencies and mode shapes. Ambient vibration testing of the Tamar suspension bridge has been studied by Williams [55], which was excited by a wind of between 7 m/s and 12 m/s speed and a fairly continuous flow of traffic and dynamic response was measured. For measurements and identification of natural frequencies were done by sei mometers at 17 different locations. Yugoslavia [56] used seismometers to measure the wind induced vibrations of the Spilje lake bridge. The problem due to traffic induced noise [57] was encountered during the tests.

J. Tibor [58] who studied 3 and 5 span prestressed concrete bridges with two20 ton test trucks driven at varying speeds. The response was measured by deflectometers at the quarter and half points of each span. R. F. Varney [59] studied a 2 span prestressed concrete bridge by measuring strains, deflections, and accelerations when a tractor trailer crossed at varying speeds. P. J. Moss, A. J. Carr, and G. C. Pardoen [60, 61] studied three prestressed concrete I-beam bridges by accelerometers and seismometers during normal traffic, forced vertical loading produced by people jumping, and forced lateral loadings. R. Cantieni[62, 63] summarized 23 years of bridge testing by the Swiss.

Studies were also done on a railroad bridge, transit structures, pedestrian bridges, and pavement loads. V. Kolousek [64] tested a 3-span railroad truss bridge with a locomotive and measured strains deflections. The pavement load study was done by A. P. Whittemore, J. R. Wiley, P. C. Schultz, and D. E. Pollock [65]. They used both electronic scales embedded in the pavements and on board measurement systems to measure dynamic behavior. M. L. Silver and T. Venema[66] tested three elevated transit structures with accelerometers and three types of transit vehicles as loading. J. E. Wheeler [67] studied 21 pedestrian bridges using people jumping and people walking as the loading. The dynamic properties of Tinsley viaduct were identified under ambient traffic load and a 30 tonne vehicle load by Eyre and Smith [68] using cantilever deflection gauges and data are recorded. It was found that the superstructure deflected as a continuous beam and that the principal bending and torsional vibration frequencies were identified. A. Felber, R. Cantieni, and C. A. M. de Smet [69] describe an ambient vibration study of the Ganter Bridge. Which is an S shape bridge is an 8 span continuous, cable stayed, concrete box girder with an overall centre line length of 678 m. Test was carried out to identify natural frequencies and modes shapes of the structure. In results, 25 modes with natural frequencies below 4.0 Hz were identified. C.J. Black, C.E. Ventura [70] were conducted as a complimentary study to transient load tests conducted on the 24 m single span bridge. 8 accelerometers were used for ambient vibration measurement. From ambient vibration tests, the natural frequencies and corresponding mode shapes in the vertical and transverse directions, as well as the torsional modes of the bridge. Total 7 modes were identified below 50 Hz. J. Senthilvasan, D.P. Thambiratnam, G.H. Brameld [71] was tested the two-cell box girder bridge during the movement of a heavy vehicle at various speeds and strains and the deflections were recorded. The experimental results compare with analytical bridge–vehicle interaction model and by bridge design codes. Dongzhou Huang [72] was experimented Full-scale static and dynamic load testing of a curved box girder bridge with two Florida Department of Transportation (FDOT) test trucks. The understanding between test and analytical results supports the expectation that actual bridge responses can be well predicted through theoretical analysis with limited experimental data.

Martin Turek and Carlos E. Ventura [73] have been validating a computer model and a high density of vibration measurements was taken on the bridge. The data was then analysed using both a frequency domain analysis and a time domain analysis. These analyses were sufficient to determine ten modes of vibration below 20 Hz.C.W. Lina, Y.B.Yang [74] excites the bridge through movement of the truck. The response recorded using an accelerometer installed in the cart is processed by Fast Fourier Transform (FFT) to extract the "source" frequencies of the cart, which are exactly the frequencies of vibration of the bridge. Sean P. Brady and Eugene J. O'Brien [75] examines the dynamic amplification factor of a simply supported bridge being crossed by two loads travelling in both the same and opposing directions. An experimentally validated finite element model is used to examine the applicability of the conclusions to real bridge/vehicle systems. Magdy Samaan; John B. Kennedy and Khaled Sennah [76] are analyzed continuous curved composite multiple-box girder bridges, using the FEM, to evaluate their natural frequencies and mode shapes. Experimental tests are conducted on two continuous twin-box girder bridge models of different curvatures to verify and substantiate the FE model. Xinfeng Yin; Zhi Fang; and C. S. Cai, [77] studied on the bridge-vehicle coupled equations which are established by combining the equations of motion of both the bridge and vehicles. The accuracy and efficiency of the present method are verified by comparing the simulations and the field test results of a bridge under moving vehicle loads.

VI. CONCLUSION

Each structure has its specific dynamic behavior under applied loadings, which may be represented as vibration signature. Changes in a structure, such as damage, loading condition due to changes in heavy traffic vehicles loading as per present scenarios, ageing of the structure cause deteriorations etc. are leads to decrease of the load carrying capacity, which have an impact on vibration response of the structure. Hence, use of these dynamic response characteristics to evaluate overall behavior of structural integrity as well as performance of the structures.

To find out these vibration response measurements, there are two types of testing were carried out on field vibration test of bridges i.e. Ambient Vibration Test (AVT) and Forced Vibration Test (FVT). Out of which relatively AVT were reported most widely used into vibration testing of bridge. This is because of its advantages over of a FVT such as it is easier to perform to get structural response measurements, while the structure still in service. Under the operating condition, Structural response obtained from the measured test results data gives actual behavior of the structure. However, during ambient vibration testing measured response are small but it gives a better idea for actual operating conditions of the structure. Further, the loading is unknown and thus, the analysis becomes more difficult than in traditional modal analysis. These tests are required very sensitive equipment, careful data analysis to be done. Since last few decade development of sensing technology and analysis techniques provides better feasibility in testing and analysis of bridges.

VII. FUTURE SCOPE

Since past few years, there are noticeable development in sensing technology and different methods for estimation of dynamic properties of the structures have been carried out by researches. Therefore, Study based on sensing instruments and its technology such as wired sensor network and wireless sensor network can be carried out. Detail review study can be carried out based on the methods of modal analysis from time domain and frequency domain data for estimates the modal parameters of the civil engineering structures.

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