Dynamic behavior of hybrid composite bridge girder

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ABSTRACT: Dynamic behavior of a hybrid composite bridge girder was investigated using experimental and analytical methods in order to understand dynamic performances of girders under operational loading conditions. The vibration response of the girder was measured using a single-point impact excitation. A dynamic analysis of the girder was performed using Euler – Bernoulli beam theory and Timoshenko beam theory for comparison. Also the girder's hybrid composite configuration was modeled and a detailed dynamic analysis was performed using finite element (FE) techniques on FE software STRAND7. It has been found that both FEA and analytical frequencies are at par with the experimental results. This paper outlines some conclusions on dynamic characteristics of hybrid bridge girders and the rationale of using engineering beam theories and FEA in hybrid beam analysis.

1 INTRODUCTION

Fibre Reinforced Polymer (FRP) shapes are being increasingly used in Civil Engineering applications. In particular there is a need of replacing the ageing concrete and wooden bridges in Australian country roads with strong and lighter composite beams and decks. The Centre for Excellence in Engineered Fibre Composites (CEEFC) of University of Southern Queensland together with Loklite Pty Ltd has recently tested a new type of fibre composite bridge that uses hybrid composite beams [Fig. 1].

Figure 1 Hybrid Composite Bridge Beams

The bridge girders will experience severe static and fatigue loading regimes during their operational life due to moving vehicles and mobile machinery. These moving loads generate cyclic stresses on the bridge's structural components. The moving loads are also capable of forcing bridge's structural components to vibrate in frequencies closer to their fundamental frequencies which will cause unexpected and catastrophic failures of the structure. As such, a detailed dynamic analysis of the bridge and its structural components are critical to maintain the integrity of bridge structure under operational loading regimes.

The conventional hybrid composite components comprise with concrete, fibre composite laminates and steel have been widely used in civil infrastructure construction. As a result of increased use of hybrid composite in infrastructure development, substantial amounts of research and development work have been done on design and analysis of hybrid composite beams (Van Erp 2002).

The hybrid beams are designed to achieve same level of strength as the concrete girders while reducing the weight of the beam to lower levels as much as possible. Because this reason the material properties of the beam varies along the beam's longitudinal axis. As such, rigorous analytical procedures are essential to analyse hybrid beams which are approximately fall in to the class of functionally graded beams (Thomas & Herbert 2006). However, some recent research work has reported that reasonably accurate results can be obtained using Finite Element Methods (FEM) (Lee et.al 2007, Avila 2007, Li et. al 2007, Backstrom & Nilsson 2007). In any case an experimental validation of the numerical results is an essen-

tial requirement of the present design process of hybrid composite beams.
This paper details a dynamic analysis performed on a hybrid bridge girder and the validation of the analysis by experimental results

2 ANALYSIS

The section of the beam consider in this study was 400 mm x 400 mm and the beam is 10 m long. The beam has a functionally graded type core material. Unfortunately due to confidentiality issues, more details of the beam can't be disclosed at this stage.

The analysis is performed using Euler – Bernoulli and Timeshenko Beam theory (Reddy 2004, Rao 2005) for comparison.

Using Euler – Bernoulli beam theory, for beam AB shown in Figure 2:

$$M(x,t) = EI(x)\frac{\partial^2 w(x,t)}{\partial^2 x} \tag{1}$$

Therefore it can be shown that the equation of motion for free lateral vibration of the beam;

$$EI\frac{\partial^4 w}{\partial x^4}(x,t) + \rho A(x)\frac{\partial^2 w}{\partial t^2}(x,t) = 0 \tag{2}$$

Using solution for equation (2) as;
w(x) = C_1 *Cos βx*+ C_2 *Sin βx* + C_3 *Cosh βx*+ C_2 *Sinh βx* (3)

where $\beta^2 = \omega\sqrt{\frac{\rho A}{EI}}$ and C_1, C_2, C_3, C_4,are constants which can be evaluated using boundary conditions, ω = natural frequency, ρ = the density of the material at the section, *EI* = the flexural rigidity of the beam and *A* = cross-sectional area. Please note that in this analysis *EI and ρ* of the beam material assumed to be constant along the beam.

For simply supported beam AB,

$$\omega_n = (n\pi)^2\sqrt{\frac{EI}{\rho A L^4}} \quad rad/s \tag{4}$$

Euler – Bernoulli theory considered as a thin beam theory as it does not consider rotary inertia and shear deformation of the beams cross-section. Using Timoshenko's beam approach, these effects can be included in the dynamic response.

For beam AB (Fig. 2),

$$\alpha^2\frac{\partial w^4}{\partial x^4} + \frac{\partial^2 w}{\partial t^2} - r^2\left(1+\frac{E}{kG}\right)\frac{\partial^4 w}{\partial x^2\partial t^2} + \frac{\rho r^2}{kG}\frac{\partial^4 w}{\partial t^4} = 0 \tag{5}$$

where $\alpha^2 = \frac{EI}{\rho A}$ *and* $r^2 = \frac{I}{A}$, *k* is Timoshenko's shear coefficient for a rectangular section, *k* is taken as 5/6. *G* is the shear modulus of the material.

Considering only the rotary inertia the equation (5) can be re-written as;

$$EI\frac{\partial w^4}{\partial x^4} + \rho A\frac{\partial^2 w}{\partial t^2} - \rho I\frac{\partial^4 w}{\partial x^2\partial t^2} = 0 \tag{6}$$

Using solution for this equation as

$$w(x,t) = C\,Sin\left(\frac{n\pi x}{L}\right)Cos(\omega_n t) \tag{7}$$

The natural frequency,

$$\omega = \sqrt{\frac{\alpha^2 n^4\pi^4}{L^4\left(1+\frac{n^2\pi^2 r^2}{L^2}\right)}} \quad rad/s \tag{8}$$

3 EXPERIMENTAL PROCEDURE

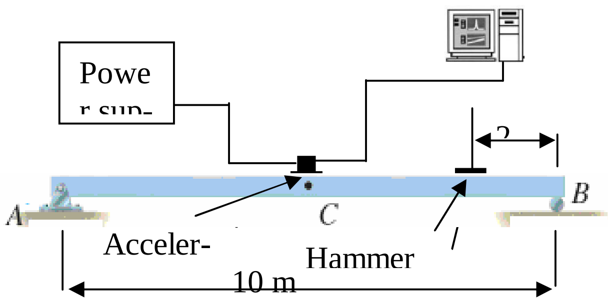

Figure 2 Schematic of experimental setup.

The 10 m long girder was placed as a simply supported beam as shown in Figure 3. Two thin steel plates were glued on the top surface of the girder where the locations of the accelerometer (mid point) and at the hamper point (2m from the left roller support). The single axis 2g button type accelerometer was attached to the mid point of the beam and an impact force was applied on the plate attached by a rubber head hammer. A National Instrument USB Dynamic Signal Analyser DAQ card was used to acquire acceleration data. The data files were stored in the attached computer for post processing..

4 ANALYSIS OF RESULTS AND DISCUSSION

4.1 *FEM Results*

Finite Element Model was created for the beam as shown in the Figure 3, using FEA software Strand 7. The model comprised of 13916 QUAD4 plate elements for laminates and 8922 HEXA8 brick elements for core/filler materials.

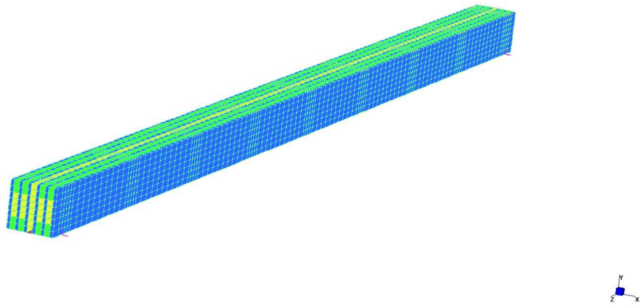

Figure 3. FE model of the hybrid beam.

The natural frequencies, and mode shapes were calculated using the FE model. Figures 4 to 6 inclusive shows some results of FE dynamic analysis.

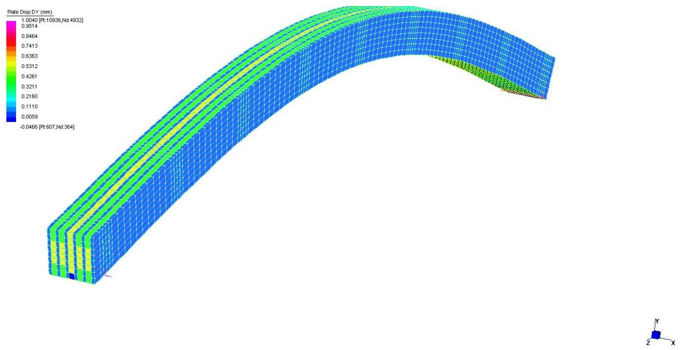

Figure 4 Mode1 @ 8.5 Hz

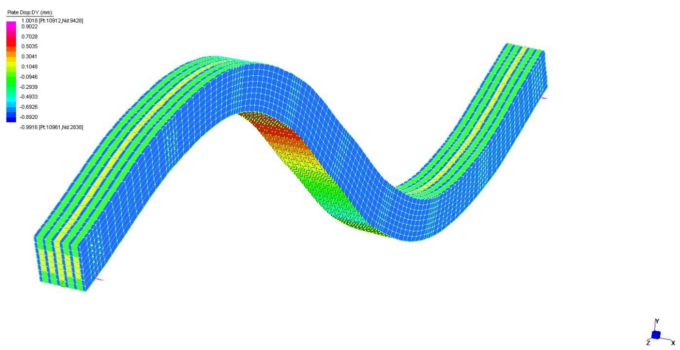

Figure 5 Mode2 @ 31.7 Hz

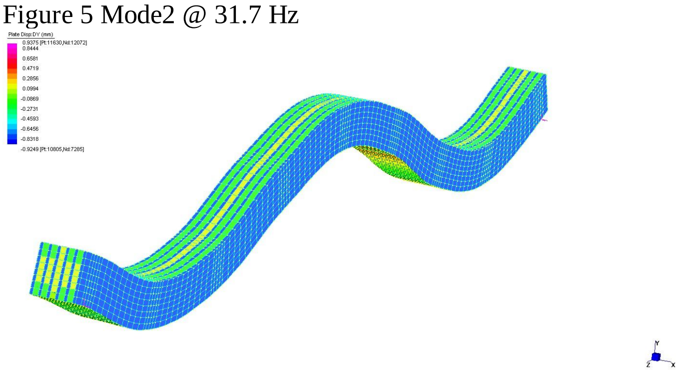

Figure 6 Mode2 @ 62.7 Hz

4.2 *Dynamic Test Results*

The acquired acceleration data were analysed using Fast Fourier Transformation (FFT). Several fundamental frequencies were extracted from the acquired acceleration data. Figure 7 shows a frequency spectrum of the girder that was obtained experimentally. Table 1 lists the natural frequencies extracted from the FFT analysis of experimental data.

4.3 *Calculated fundamental frequencies*

Fundamental frequencies were calculated using Equations 4 and 8 using average materialproperties. Following average material data have been used to calculate the frequencies.

Equivalent rigidity $EI = 5.66 \text{ x } 10^{13}$ Nmm^2

Total weight of the beam = 1800 kg

These values are obtained from the previous static testing regimes of the bridge girder. Table 1 shows the calculated and experimental fundamental frequencies.

Table 1. Calculated and experimental natural frequencies

Mode	Natural Frequency (Hz)			
	Euiler - Bernoli	Time-shenko	Experi-mental	FEA
1	8.81	8.80	7.4	8.5
2	35.23	35.17	---	31.7
3	79.27	78.93	65.9	62.7
4	140.93	139.83	153	147
5	220.21	217.53	244	225
6	317.10	311.58	---	337.2
7	431.61	421.46	452	488.8
8	563.73	546.58	----	586.5
9	713.47	686.31	---	788.9
10	880.83	839.95	----	907

4.4 *Discussion*

Experimental data obtained from the beam dynamic testing captured reasonable number of lateral vibration modes of the girder. The calculated fundamental frequencies has a good agreement with the fundamental frequencies captured by the accelerometer. Referring to Table 1, it can be seen that there are some discrepancies between theoretical and experimental fundamental frequencies mostly due to the mismatch of material properties assumed for the calculations. However, these deviations seems to be negligible and anticipated for this type of complex hybrid construction.

Despite the fact that; the girder's properties are varying along its longitudinal axis due to its hybrid construction, experimental vibration results haven't shown a considerable error in using an equivalent flexural rigidity in theoretical calculations

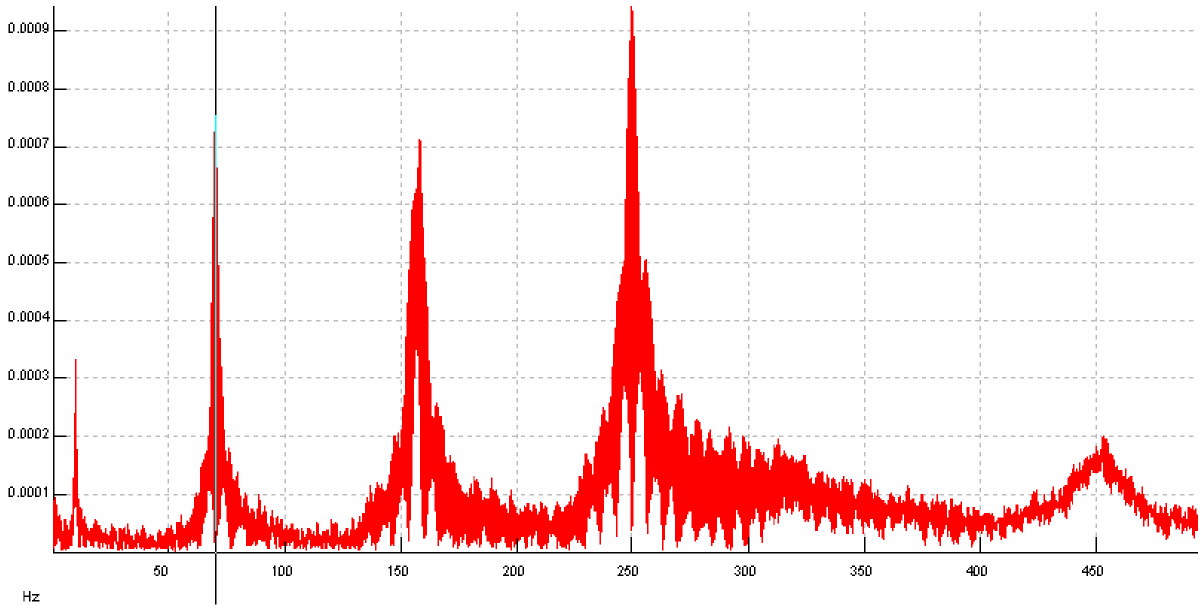

Figure 7 A frequency spectrum of the bridge girder

5 CONCLUSIONS

An investigation was carried out on a hybrid composite girder to establish its dynamic behaviour. It has been found that the girder's fundamental frequency is in the vicinity of 7.4 Hz.. The calculated values are at par with the experimental results. As the experimentations performed with a single axis accelerometer at mid-span is not sufficient to capture complete dynamic response of the beam. A comprehensive modal analysis needs to be performed to fully understand the dynamic behaviour of this hybrid beam. Finally it can be highlighted that the use of beam theories with average material properties and FEA techniques would be a reasonably accurate analytical method in the analysis of hybrid girders.,

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