Model Updating for Loading Capacity Estimation of Concrete Structures using Ambient Vibration

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Abstract

This paper presents a model updating approach for determining the loading capacity of a concrete structure utilising measured ambient vibration responses. The proposed method uses Operational Modal Analysis (OMA) with the Enhanced Frequency Domain Decomposition (EFDD) technique to identify the natural frequencies and mode shapes of an experimental replica specimen of a Sydney Harbour Bridge concrete jack arch component. For vibration testing, the structure is excited with ambient vibration recordings from the actual Sydney Harbour Bridge using a vibro tactile transducer. The vibration responses of the structure are measured using an array of strategically placed accelerometers. A numerical model is developed and updated using the vibrational characteristics with the aim of estimating the load capacity of the structure. The results show that the proposed updating method using partitioning has great potential to be used for determining the loading capacity of a structure as part of a Structural Health Monitoring (SHM) system.

Keywords: Structural health monitoring (SHM), operational modal analysis (OMA), ambient vibration, finite element analysis (FEA), model updating

1. Introduction

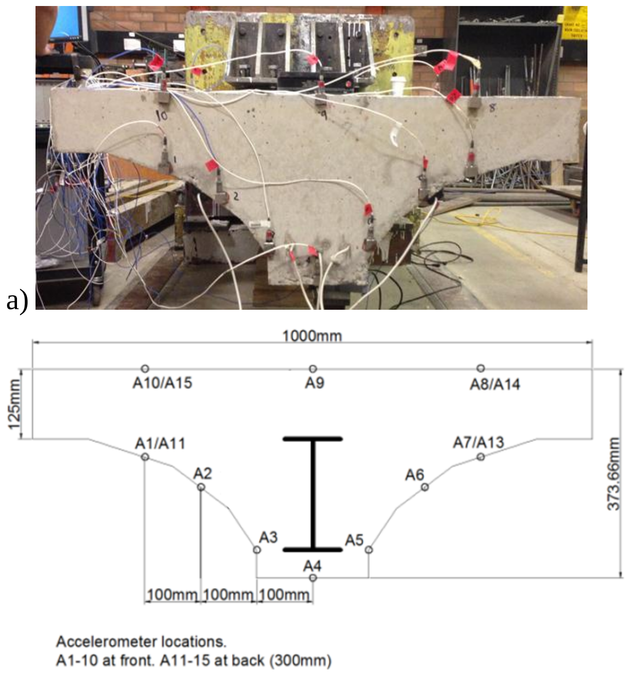
Asset managers of large bridges require reliable information about the health condition of a structure and its resulting load capacity to ensure the reliability and safety of the bridge. The load carrying capacity of a bridge affects the serviceability, the traffic safety and the transportation costs [1]. Load carrying capacity tends to decrease over time due to deterioration. It is therefore essential to gain a thorough understanding of the health condition of the structure and correlate this information to its load capacity. Much research has been conducted on the implementation of structural health monitoring (SHM) systems of bridges as a means of solving the inverse problem of assessing the condition of a bridge using various forms of measurements and correlating this information to the performance of the structure [2]. In comparison to traditional condition assessment methods, such as visual inspection and load deflection proof tests, SHM has the advantage of continuously assessing the bridge condition without obstructing the operational use of the structure.

A more common used form of measurements in a SHM system is vibration due its ability to capture the global behaviour of a bridge [3]. In-situ bridges are subjected to various forms of dynamic loads including traffic and pedestrian activity as well as environmental loads such as wind. These dynamic ambient loads can excite various vibrational modes of a structure, which are sensitive to changes in material properties, boundary conditions and damage, and can therefore be used for assessing the health condition and determining the loading capacity of a structure. A strategic arrangement of sensors is typically used to capture the dynamic responses of the in-situ structure and Operational Modal Analysis (OMA) can be conducted to determine the vibrational properties including the natural frequencies and mode shapes. In order to study the load capacity of the bridge, it is generally necessary to create a finite element model (FEM) that can simulate the dynamic features of the structure. Researchers have found that the natural frequencies and mode shapes of a structure are sensitive to changes of material properties, boundary conditions and damage. Thus, model updating using the dynamic characteristics identified through OMA is capable of identifying the material properties, boundary conditions and possible damage of an in-situ structure for the determination of its loading capacity.

In this study, an experimental replica structure of a jack arch of the Sydney Harbour Bridge bus lane is used to test the concept of using model updating techniques to calibrate a FEM to an in-situ structure with imperfect boundary conditions with the aim of assessing the load capacity of the structure. Vibration measurements from the actual Sydney Harbour Bridge are used to excite the experimental specimen. OMA is conducted to determine the vibrational characteristics and model updating techniques are applied to a FE model to determine the loading capacity of specimen.

2. Experimental Set-Up and Testing

The specimen used in this study was a replicated jack arch of a structural component under the bus lane of the Sydney Harbour Bridge. It consists of a 200UB18 steel I-Beam embedded into a concrete cantilever structure with 50 mm concrete cover on both sides. A photo of the specimen and the cross sectional dimensions with sensor locations are shown in Figure 1a and Figure 1b. The cantilever specimen is 1.6 m long with a rectangular concrete block of an additional 0.4 m length at one end of the structure to allow for a rigid restraint. A vibro tactile transducer (IBEAM® IB-200) was attached to the specimen to induce ambient vibration. Therefore, actual recordings of common buses driving over the Sydney Harbour Bridge were processed and used as input to the tactile transducer to simulate real ambient excitation under operating conditions. The total duration of the excitation was 8 minutes with a sampling frequency of 1 kHz. An array of 15 accelerometers (PCB 352C34) was used to measure the vibrational response of the structure under ambient excitation. The data was recorded using the National Instruments data acquisition system PXIe-4492.



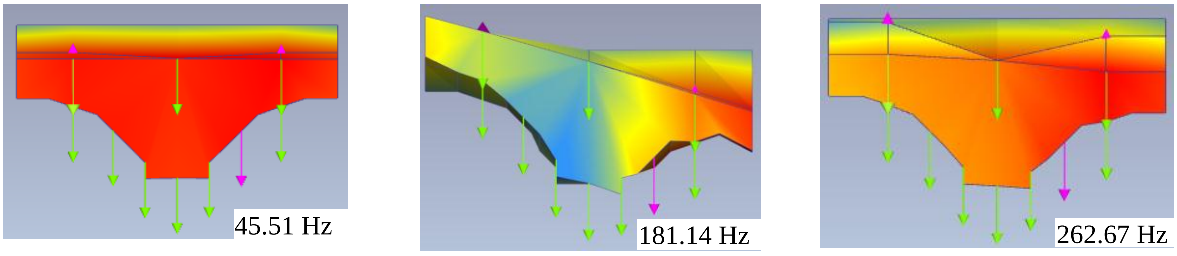
b)

Figure 1. (a) Photograph of test specimen, and (b) cross-sectional geometry of the structure with accelerometer locations.

3. Modal Parameter Identification using Operational Modal Analysis

As described above, a tactile transducer was used to generate ambient vibration recordings from the operating conditions of the bus lane of the Sydney Harbour Bridge to excite the structure while the strategically placed accelerometers were used to capture the dynamic characteristics of the specimen. The first three natural frequencies and mode shapes of the experimental specimen were determined from the acceleration response measurements using the OMA software package ARTeMIS® and applying the Enhanced Frequency Domain Decomposition method (EFDD) method. The determined mode shapes and corresponding frequencies are shown in Table 1.

Table 1. First three natural frequencies and mode shapes.



f_1 – Vertical Bending f_2 – Torsion f_3 –Vertical Bending

4. Numerical Modelling and Model Updating

A numerical FE model with the geometrical and nominal mechanical properties of the experimental structural component was created to evaluate its load capacity using the software package ANSYS®. The generated model is illustrated in Figure 2. The SOLID185 elements were used to model the concrete and steel to allow for model updating techniques to calibrate the numerical model to the experimental specimen within the linear elastic range. Modal analysis was used to identify the natural frequencies and mode shapes of the structure. The determined natural frequencies of the structure in the initial numerical model were found to be significantly higher than the experimental values, as the boundary conditions were modelled as being perfectly fixed. However, this idealised condition is not the case for real structure, as their connections are often not perfectly rigid and the supports of these components are not perfectly stiff. Hence, thin layer element strips with reduced stiffness, shown in Figure 2b, were modelled at the boundary conditions to obtain a closer representation to the actual boundary conditions of the physical specimen.

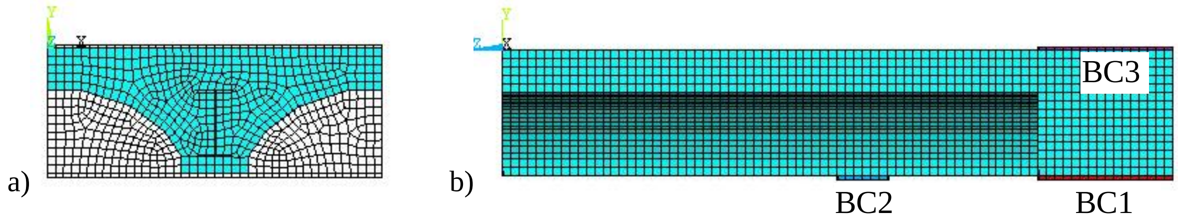


Figure 2. (a) Front view of FEM, (b) Side view of FEM with thin layer element strips at the boundary conditions.

An optimisation procedure was run to calibrate the numerical model to the experimental specimen by adjusting the model input parameters to optimise the objective function that aimed to minimise the normalised sum of squares error of the natural frequencies of the structural component. From this study, it was found that the contacts of the boundary conditions were not uniform. To address this issue, the thin layer contact element strips used to model BC1 and BC3 were first divided into 4 partitions and then 16 partitions, shown in Figure 3, to allow for the variation of stiffness in these areas. BC2 was not partitioned due to the limitations of the number of allowable design variables in the optimisation tool in ANSYS® and because it is significantly smaller than BC1 and BC3.

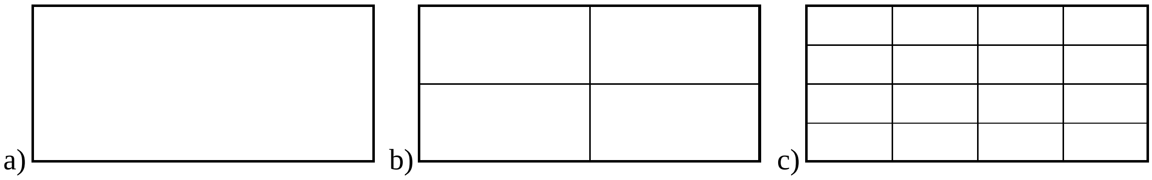


Figure 3. BC1 and BC3 division into (a) 1 partition, (b) 4 partitions, and (c) 16 partitions.

Table 2. Summary of optimisation results for model updating.

	Exp. Spec.	Fully Fixed BC		1 Partition		4 Partitions		16 Partitions	
		Value	Error	Value	Error	Value	Error	Value	Error
E_C (GPa)		30.10		30.09		30.07		30.07	
E_S (GPa)		200.00		200.00		199.99		199.98	
f_1 (Hz)	45.51	132.62	191.4%	48.99	7.6%	47.8	5.0%	46.36	1.9%
f_2 (Hz)	181.14	239.94	32.5%	172.6	-4.7%	171	-5.6%	178.2	-1.6%
f_3 (Hz)	262.67	528.048	101.0%	252.9	-3.7%	260.3	-0.9%	258.2	-1.7%

The results in Table 2 demonstrate that partitioning the contact surface between the supports and the specimen significantly reduced the error of the natural frequencies. With 16 partitions, the error of the first natural frequency was found to be 1.9% as opposed to having an error of 7.6% using just 1 partition. In this optimisation procedure, the Elastic modulus for concrete and steel was found to be 30.07 GPa and 199.98 GPa, respectively. Data of these material properties can then subsequently be used to evaluate the load capacity of the structure.

5. Conclusion

This paper described the model updating procedure used to determine the material properties of a replica structural component of the Sydney Harbour Bridge bus lane jack arch used for experimental testing. The specimen was excited with ambient vibration recordings from the bus lane of the Sydney Harbour Bridge during its operating conditions using a vibro tactile transducer (IBEAM®). The first three natural frequencies and mode shapes were identified using the EFDD technique in the OMA software ARTeMIS®. A numerical model was created to simulate the experimental structure, which involved the use of model updating techniques to calibrate the numerical model to the experimental specimen, and to allow for determining its loading capacity. Since the natural frequencies of the structure are sensitive to its material properties and the boundary conditions, they were used to update the numerical model using optimisation procedures. It was found that partitioning the boundary conditions can account for the non-uniform contact between the specimen and the supports and reduce the error of the model. The updated numerical model can subsequently be used to determine the load capacity of the structure.

6. References

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