Temperature Effect on Vibration Properties of Civil Structures: A Literature Review and Case Studies

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ABSTRACT

Changing environmental conditions, especially temperature, have been observed to be a complicated factor affecting vibration properties, such as frequencies, mode shapes, and damping, of civil structures. This paper reviews technical literature concerning variations in vibration properties of civil structures under changing temperature conditions. Most of these studies focus on variations in frequencies of bridge structures, with some studies on variations in mode shapes and damping and other types of structures. Statistical approaches to correlation between temperature and frequencies are also reviewed. A quantitative analysis shows that variations in material modulus under different temperatures are the major cause of the variations in vibration properties. A comparative study on different structures made of different materials is carried out in laboratory. Two real structures, the 1377 m main span Tsing Ma Suspension Bridge and the 610 m tall Guangzhou New Television Tower, are examined. Both laboratory experiments and field testing, regardless of different construction materials used and structural types, verify the quantitative analysis. Variations in frequencies of reinforced concrete (RC) structures are much more significant than those of steel structures.

KEYWORDS

temperature effect, vibration properties, modal testing, structural health monitoring

1. INTRODUCTION

Vibration-based structural condition assessment and health monitoring have been widely investigated across the world during the last decades [1~6]. A successful condition assessment relies heavily on the accuracy of the measured vibration properties, such as natural frequencies and mode shapes, of structures. A practical difficulty lies in that structural vibration properties vary with changing environmental conditions, particularly temperature. Some studies have found that changes in structural vibration properties because of temperature variations could be more significant than those caused by a medium degree of structural damage [7] or under normal operational loads [8].

For example, researchers from the Los Alamos National Laboratory [9] found that the first three natural frequencies of the Alamosa Canyon Bridge varied to about 4.7%, 6.6%, and 5.0%, respectively, over a 24-hour period as temperature of the bridge deck changed by approximately 22 °C. They [10] also did a well-known field testing on the I-40 Bridge over the Rio Grande, in which a girder was cut through the web center to the bottom flange, causing the first three natural frequencies to decrease by 7.7%, 4.1%, and 0.3%, respectively. The frequency changes caused by this significant damage are in the same level as those caused by environmental temperature variations.

If temperature effects are not fully understood, then false structural condition identification may occur [11] [12]. Although many experimental and field studies have observed the importance of varying temperatures in structural vibration properties and the associated damage detection and condition assessment, some different conclusions have been drawn for different structures. A quantitative explanation on temperature effects lacks. It is widely believed that an increase in structural temperature leads to a decrease in material modulus and thus a decrease in vibration frequencies. In practice, temperature affects structures in a rather complicated manner. For example, it may also lead to support movements or changes in boundary conditions [13] and, consequently, affect modal parameters. Boundary condition changes are structurally dependent and difficult to quantify. For cable-supported bridges, varying temperatures may affect the tension forces of the cables and, consequently, the vibration properties of the bridges. Another complexity of this issue is the non-uniform temperature distribution of a structure. Different surfaces of a large-scale structure receive different solar irradiations at different times. Thermal inertia makes variations of the surface temperature larger than those inside the structure, and the latter lags behind the former by a few hours, depending on structural configuration. Consequently, using different temperatures may lead to different conclusions qualitatively and quantitatively. Wind conditions also affect the thermal absorptivity of structural surfaces. For a large-scale structure, finding two time instants having identical temperature distributions is difficult. Consequently, comparing vibration properties directly under different environmental conditions is not easy.

This paper reviews laboratory and field findings of the temperature effects on structural dynamic properties. A simplified quantification of the temperature effects is proposed. Three physical models made of steel, aluminum, and reinforced concrete (RC) are tested in laboratory for comparison and verification. Two large-scale structures, the Tsing Ma Suspension Bridge and the Guangzhou New Television Tower, are studied through their long-term structural health monitoring systems. These two structures are especially selected because one is made of steel and the other is RC. Laboratory and field testing results show that the change in the material modulus under different temperatures is the main contribution to the change in structural vibration properties.

2. VARIATIONS IN NATURAL FREQUENCIES

Thermal effects on structural dynamic properties have been investigated since the 1970s. In their pioneer study, Adams et al. [14] investigated the relation between temperature and axial resonant frequency of a bar. Since then, many researchers have studied temperature-induced variations in natural frequency of structures because natural frequencies can be measured in practice more easily and more accurately. In field measurements, bridges have been paid more attention than other types of structures, possibly because bridges are exposed to the ambient environment directly.

2.1 Bridges

Askegaard and Mossing [15] studied a three-span RC footbridge and observed a 10% seasonal change in frequency over a three-year period. Cornwell et al. [9] investigated the thermal variations in the dynamic properties of the Alamosa Canyon Bridge and found about 5% daily changes in the first three natural frequencies.

Peeters and De Roeck [16] monitored the Z24 Bridge continuously for nearly a year and they reported a bilinear relation between the first two frequencies and the structural temperature. They found that the two frequencies increased by about 10% when temperature decreased from 0 to −7 ^{o}C. For temperatures above 0 ^{o}C, the first frequency decreased slightly when the wearing surface temperature went up, whereas the second frequency increased slightly when the deck soffit temperature went up.

Fu and DeWolf [17] studied a two-span, slightly skewed composite bridge and found that the expansion bearings were approximately partially constrained below 60 ^{o}F. The first three frequencies decreased by 12.3%, 16.8%, and 9.0%, respectively, as the temperature increased from 0 ^{o}F (−17.8 ^{o}C) to approximately 60 ^{o}F (15.6 ^{o}C), whereas they changed little as the temperature was above 60 ^{o}F. The authors then simulated a thermal axial load and applied it to the girder eccentrically for calculating the frequencies under different temperatures. The change in frequencies agreed well with the measurement.

Ni et al. [18] [19] [20] extracted one-year modal properties of the Ting Kau cable-stayed bridge in Hong Kong. The relative variations in the measured modal frequencies (i.e., the ratio of frequency change to average frequency for each mode) under weak wind conditions ranged between 1.7% (the 8th mode) and 6.7% (the 1st mode) when bridge temperatures ranged between 3 and 53 ^{o}C. They concluded that the effective temperature (i.e., temperature averaged over the cross section weighted by areas) was insufficient in formulating a good correlation between the modal frequencies and temperatures because of the existence of temperature gradient over the cross section.

Macdonald and Daniell [21] investigated variations in natural frequencies of the Second Severn Crossing cable-stayed bridge because of wind, temperature, and traffic loading. They reported that there was no apparent trend between the natural frequencies and the mean bridge deck temperature because the temperature change was small.

Desjardines et al. [22] studied the variations in frequencies of the Confederation Bridge (made of pre-stressed concrete) over a six-month period. They reported a clear trend of reduction in the modal frequencies by about 4%, when the average temperature of the concrete of the bridge varied from −20 to +25 ^{o}C.

Liu and DeWolf [23] reported that, during a one-year measurement, the first three frequencies of a curved concrete box bridge decreased when concrete temperature increased. A linear regression analysis showed that frequencies decreased by 0.007, 0.008, and 0.007 Hz as temperature increased by one Fahrenheit degree, which is equivalent to 0.8%, 0.7%, and 0.3% per degree Celsius.

The Yunyang Suspension Bridge [24] with a 1490 m main span experienced about 2% variation in the first six modal frequencies during a period of ten months, as the ambient temperature of the steel bridge varied from −5 to +50 ^{o}C. During 16 days of continuous monitoring of a cable-stayed bridge, Li et al. [25] found that the first six frequencies varied by about 1.5%~3.2% as ambient temperature changed from −11.5 to +3.7 ^{o}C.

2.2 Buildings

Variations in frequencies of high-rise structures have not been studied as extensively as bridge structures. Nayeri et al. [26] monitored a 17-story steel frame building, which showed a strong correlation between frequencies and air temperature, whereas frequency variations lagged behind temperature variations by a few hours. Yuen and Kuok [27] extracted the modal frequencies of a 22-story RC building for one year using the Bayesian spectral density approach. They found that the first three frequencies increased with an increase in ambient temperature, which was opposite their analytical results. Faravelli et al. [28] observed variations in frequencies of the 600 m Guangzhou New TV Tower during a 24-hour period. As variations in ambient temperature were about 3 °C only, variations in frequencies were as small as 0.5%.

2.3 Other types of structures

Li et al. [29] measured frequency variations of the Chinese National Aquatics Center (also called “Water Cube”), a steel spatial structure 177 m long and 177 m wide. The first frequency decreased with an increase in temperature, whereas the second and the third frequencies went up as temperature increased. The variations in frequencies were about 1% at a temperature range of 40 °C. They explained that variations in the modulus of elasticity, temperature-induced internal force, and non-uniform temperature might contribute to frequency changes.

2.4 Laboratory and numerical studies

An experiment in a climatic chamber [30] demonstrated that the axial prestress of an aluminum beam because of thermal change varied significantly and led to changes in the first four frequencies by 16%, 8%, 5%, and 3%, respectively. Xia et al. [12] conducted experiments on a continuous concrete slab for nearly two years and found that the frequencies had a strong negative correlation with temperature and humidity.

Breccolotti et al. [31] reported that variations in frequencies of a bridge because of simulated damage were comparable with those attributed to simulated temperature changes. In their study, thermal analysis was conducted to obtain the steady temperature of the bridge, and then the modulus of elasticity was adjusted to derive the frequencies. Xia et al. [32] conducted a transient heat transfer analysis on an RC slab to obtain the non-uniform temperature field of the structure. Young's modulus of each component was estimated according to the relation between Young's modulus and temperature. Subsequently, variations in frequencies were calculated with respect to time and were in good agreement with the experimental results.

Kim et al. [33] carried out laboratory tests on a steel plate-girder bridge model. The first four frequencies decreased by about 0.64%, 0.33%, 0.44%, and 0.22%, respectively, when temperature increased per unit degree.

Xu and Wu [34] investigated numerically the temperature effect on the frequencies of a cable-stayed bridge and compared the sensitivity of the variations in the frequencies to various factors, including changes in geometric size, in modulus of elasticity, and in cable sag. Both seasonal temperature change (uniform change) and radiation-induced temperature change (non-uniform change) were considered. The numerical analysis showed that frequency changes could be 2% as uniform temperature increased from −20 to +40 °C.

3. VARIATIONS IN MODE SHAPE AND DAMPING

Previous studies demonstrated that natural frequencies of structures decrease with an increase in structural or ambient temperature, whereas thermal effect on mode shapes is negligible. For example, the first two modal frequencies identified from the Bill Emerson Memorial Bridge [35] decreased monotonically as temperature went up in a linear way, whereas the mode shapes did not show any significant change.

In Ni et al.'s study [18] on the Ting Kau cable-stayed bridge, some mode shapes were stationary at different times, some mode shapes at some points were stationary, but other points were not, and some mode shapes had considerable variations. Quantitative analysis found that the mode shapes were out of proportion to temperature.

Xia et al. [12] investigated the effects of temperature on a continuous concrete slab for nearly two years and observed that damping ratios had a positive correlation with temperature, whereas mode shapes had no correlation with temperature as ambient temperature affects the entire structure in a uniform manner.

Xu and Wu's numerical analysis [34] showed that the mode shape curvature at some local points of a cable-stayed bridge changed slightly by about 1% ~ 8% as seasonal temperature increased from −20 to +40 ^{o}C because changes in cable tensions and sags caused the change in the mode shapes.

In Balmes et al.'s chamber experiment [30], variations in mode shapes were invisible when temperature decreased by about 17 ^{o}C.

Li et al. [29] observed that there was no clear correlation between mode shape MAC values and air temperature, and that the absolute correlation coefficients were less than 0.2.

As the effect of temperature on damping is concerned, no consistent conclusion has been drawn. One reason is that the damping of structures is more difficult to measure accurately compared with the frequencies and the mode shapes. A large uncertainty in modal damping might mask the temperature effects [30].

In two months of monitoring the Chinese National Aquatics Center, Li et al. [29] found that mode shape MAC values and air temperature had no clear correlation because their absolute correlation coefficients were lower than 0.2. The first and the third damping ratios had a negative correlation with temperature and the second had a positive correlation. They [25] also found that some modal damping ratios of a cable-stayed bridge had a negative correlation with temperature, whereas others had a positive correlation. At the same time, the variation range of damping ratios could be quite large and could reach 280%.

Although studies on the effects of temperature on damping of civil structures are rare, some studies have focused on small structures and composites [36-38]. Review on these is excluded in the present paper.

4. STATISTICAL MODELS OF TEMPERATURE EFFECTS ON MODAL FREQUENCIES

Although a change in frequency is usually at the level of a few percentages under normal temperature range, it could be more significant than that caused by a medium degree of structural damage because frequency is a global characteristic of a structure. To avoid false condition assessments, the relation between temperature and dynamic properties of a structure should be established so that temperature effects can be accommodated in the condition assessment.

In the pioneering study, Adams et al. [14] aimed to eliminate temperature effects on damage detection according to the sensitivity of the material modulus to the temperature. For a large-scale civil structure, this simplification may not be feasible as temperature is not uniformly distributed throughout the structure; thus, the use of one or two temperature data is insufficient to describe the whole temperature distribution. Statistical techniques have been developed to describe the relation between temperature and dynamic properties, and eliminate the temperature factor from the measurements.

4.1 Regression models

Regression models, in particular linear regression models, have been commonly used to describe the relation between temperature and frequencies because of convenience and simplicity, for example, Xia et al. [12]. When temperature data at multiple spatial points are available, a multiple linear regression model is used. Sohn et al. [30] applied the trained multiple linear regression model to new measurement data and checked if the new frequencies matched the model at the specified confidence level, which was used to determine whether frequency changes were caused by temperature changes or by stiffness deterioration. Selection of input variables was also discussed when temperature at some points had a high correlation with others.

Kim et al. [33] employed a control chart analysis on the first four frequencies of the bridge model for damage detection. They obtained the mean values and the standard deviations of the frequencies at each temperature, and then built the upper and the lower control limits. The frequencies of the damaged structure were smaller than the lower control limits, indicating the exsitence of damage.

Ni et al. [19] applied the support vector machine technique to quantify the relation between temperature and modal frequencies of the cable-stayed Ting Kau Bridge. The basic idea of this technique is to establish a hyperplane that has the largest distance to the nearest data points of any class. Partial data were used to train the nonlinear regression models and the remaining data for model validation. They concluded that this technique could predict results better than the linear regression model.

4.2 Autoregressive (AR) models

On account of the thermal inertia of materials, structural temperature distribution at one time is associated not only with the present ambient temperature and sunshine condition, but also with the conditions at earlier periods. As a consequence, the relation between frequencies and temperature can be represented by an autoregressive (AR) model or an autoregressive model with an exogeneous input (ARX).

Peeters and De Roeck [16] trained an ARX model using measurement data of the Z24 Bridge. They successfully detected a damage when the prediction error was over the confidence intervals of the model.

4.3 Principal component analysis (PCA)

Yan et al. [40] employed the principal component analysis (PCA) to remove the temperature effect on modal frequencies. The residual was used as the novelty index, and control limits were calculated for novelty (or damage) detection. The basic idea of the technique is that temperature and damage are different principal components that contribute to frequency changes. The advantage of the method is that the measurement of the temperature is not required. They further extended the method to the nonlinear case [41], wherein data space was divided into several subgroups and PCA was applied to each subgroup.

Sohn et al. [42] and Li et al. [25] applied artificial neural networks to perform nonlinear PCA.

Giraldo et al. [11] employed PCA for damage detection under varying temperatures, in which element stiffness was identified from frequencies and used as the features. Consequently, not only the presence of damage but also the location of the damage can be detected. Hsu and Loh [43] extended this to the nonlinear case by training neural networks.

5. QUANTITATIVE ANALYSIS

In the above literature, most studies show that an increase in temperature leads to a decrease in structural frequencies, while magnitude varies, depending on structures, materials, and temperature range. Variations in natural frequencies of structures with temperature are caused by change in material properties, in particular, the modulus of elasticity. To quantify the effect of temperature on natural frequencies, a single-span or multi-span prismatic beam made of an isotropic material is used as an example. Its undamped flexural vibration frequency of order n is [44]:

$$f_n = \frac{\lambda_n^2}{2\pi l^2}\sqrt{\frac{EI}{\mu}} \tag{1}$$

where λ_n is a dimensionless parameter and is a function of the boundary conditions, l is the length of the beam, μ is the mass per unit length, E is the modulus of elasticity, and I is the moment of inertia of the cross-sectional area. It is assumed that variations in temperature will not affect mass and boundary conditions, but only the geometry of the structure and the mechanical properties of the material.

It can be shown that

$$\frac{\delta f_n}{f_n} = -2\frac{\delta l}{l} + \frac{1}{2}\frac{\delta E}{E} + \frac{1}{2}\frac{\delta I}{I} - \frac{1}{2}\frac{\delta \mu}{\mu} \qquad (2)$$

where δ represents an increment in the corresponding parameters. Assuming that the thermal coefficient of linear expansion of the material is θ_T and the thermal coefficient of modulus is θ_E, one obtains

$$\frac{\delta l}{l} = \theta_T \delta T, \quad \frac{\delta E}{E} = \theta_E \delta T, \quad \frac{\delta I}{I} = 4\theta_T \delta T, \quad \frac{\delta \mu}{\mu} = -\theta_T \delta T \qquad (3)$$

Here, we assume that variations in Young's modulus with temperature are linear for small changes in temperature, variations in moment of area are four times the variations in linear expansion, and the mass per unit length is inversely proportional to the length as the total mass is a constant. Consequently, Equation (2) yields

$$\frac{\delta f_n}{f_n} = \frac{1}{2}(\theta_T + \theta_E)\delta T \qquad (4)$$

Equation (4) estimates the dimensionless rate of the frequency change with the temperature change. The linear thermal expansion coefficients (θ_T) of steel [45], aluminum [46], and concrete [47] are 1.1×10^{-5}, 2.30×10^{-5}, and $1.0\times10^{-5}/^{\circ}\mathrm{C}$, respectively. The modulus thermal coefficients (θ_E) of the three materials are -3.6×10^{-4}, -5.6×10^{-4}, and $-3.0\times10^{-3}/^{\circ}\mathrm{C}$, respectively. θ_E is obviously much larger than θ_t for the three materials, which indicates that variations in natural frequency subjected to temperature change are controlled by θ_E. It also shows that the variation percentage of natural frequency is a function of the modulus thermal coefficients only, regardless of modes, spans, and beam types (simply-supported or cantilever beam). Consequently, theoretical variation percentages of the natural frequency of steel beams, aluminum beams, and RC beams are 0.018%, 0.028%, and 0.15% per degree Celsius, respectively. These are verified through laboratory experiments and field investigations in the paper. The big difference in the modulus thermal coefficient contributes to significantly different observations in literature. For example, variations in natural frequencies of a steel beam and an RC beam are about 0.36% and 3.0%, respectively, under a temperature change of 20 $^{\circ}$C. The former is difficult to observe in practice and may be masked by measurement noise or other factors, especially for lower modes with small absolute frequencies.

In addition, structural temperature rather than air temperature is employed in the above analysis. As the temperature distribution of a large-scale structure is generally non-uniform and time dependent, using ambient air temperature, structure surface temperature, structure interior temperature, or averaged temperature causes different quantitative results [32]. Moreover, temperature variations inside a structure lag behind those on the surface because of temperature inertia, especially for concrete structures. Consequently, frequency changes and air temperature changes may not occur simultaneously. Xia et al. [32] measured the non-uniform temperature field of an RC slab and calculated Young’s modulus of each component, according to the relation between Young’s modulus and temperature. Natural frequencies of the structure were then calculated, which showed good agreement with the measurements. They concluded that consideration of the temperature distribution of a whole structure leads to more accurate results of the temperature effect on the vibration properties of a structure. When measurement of all components is difficult, a heat transfer analysis can be carried out.

In the above quantitative analysis, the effect of the internal force on frequency is not considered. The internal force has a stronger effect on lower modal frequencies [12] [29]. When the thermal stress is negligible, its effect on frequency can be neglected. Variations in temperature may affect boundary conditions, which are difficult to quantify. For bridges, if expansion joints are not prevented from moving, the boundary conditions can be regarded as unchanged.

6. LABORATORY COMPARATIVE STUDY

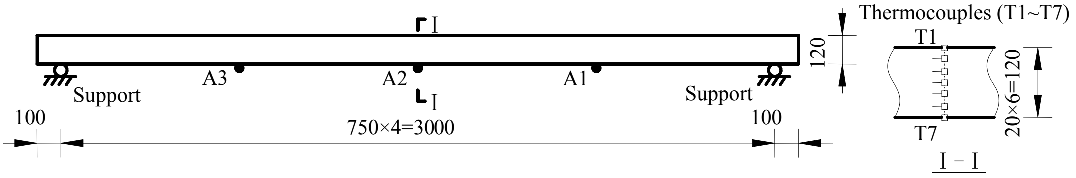
Although temperature effects on structures have been extensively studied, they have been rarely compared for different construction materials. In this section, we investigate the effect of temperature on vibration frequencies of different structures made of different materials, in particular, steel, aluminum, and RC, through laboratory studies.

6.1 Description of the models and the experiments

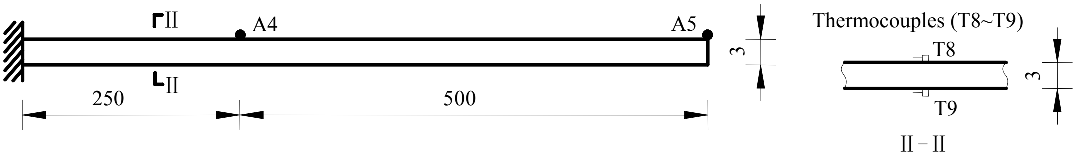
An RC slab, a steel beam, and an aluminum beam were constructed outside the laboratory and exposed to solar irradiation. Configuration of the models is illustrated in Fig. 1. The RC slab is simply supported while the support conditions of the two metallic beams are cantilever. Therefore, the slab and beams can move freely. It assumes that temperature variation doesn’t affect the support conditions but only the geometric dimensions and Young’s moduli of the structures. Temperature variations along the horizontal direction of the slab are assumed to be insignificant. Consequently, temperature gradient may occur in the thickness direction only.

Seven thermocouples (T1 to T7), with an even interval of 20 mm in the vertical direction, were embedded in the RC slab to collect the time-dependent temperature data.

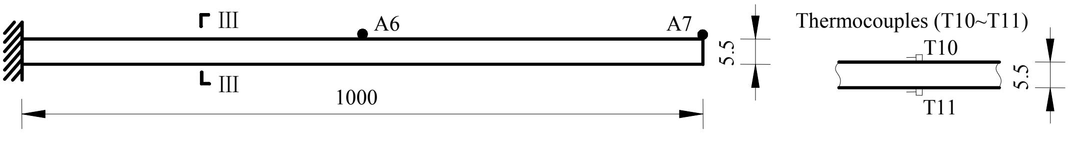
As the thermal conductivity coefficients of steel and aluminum are rather large and the thickness of the beams is small, the temperature difference between the top and the bottom surfaces is expected to be small. Therefore, only the top and the bottom surfaces of the two metallic beams were mounted with thermocouples (T8 and T9, and T10 and T11) to measure the temperature. A total of seven accelerometers (A1 to A7) were firmly mounted on the models to measure their vibration and extract the modal properties, as shown in Fig. 1.



(a) RC slab



(b) Steel beam



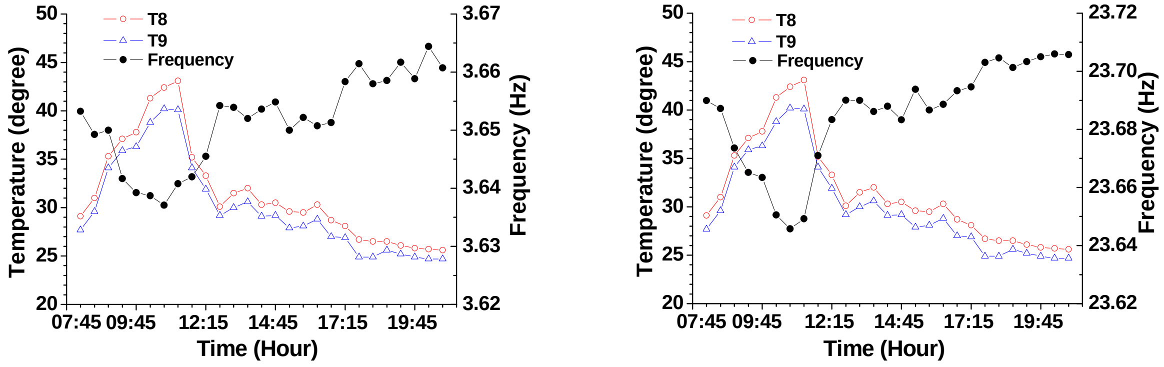
(c) Aluminum beam

Fig. 1. Configuration of the slab and the beams (unit: mm)
(A1~A7: accelerometers; T1~T11: thermocouples)

Temperature variations were recorded from the embedded thermocouples. Modal testing was carried out using an instrumented hammer. Six impacts were exerted at each time to average the signal. Frequency response functions (FRFs) of the three models were derived in a frequency range of 0 to 500 Hz. Natural frequencies were then extracted from the FRFs using the global rational fraction polynomial method [48].

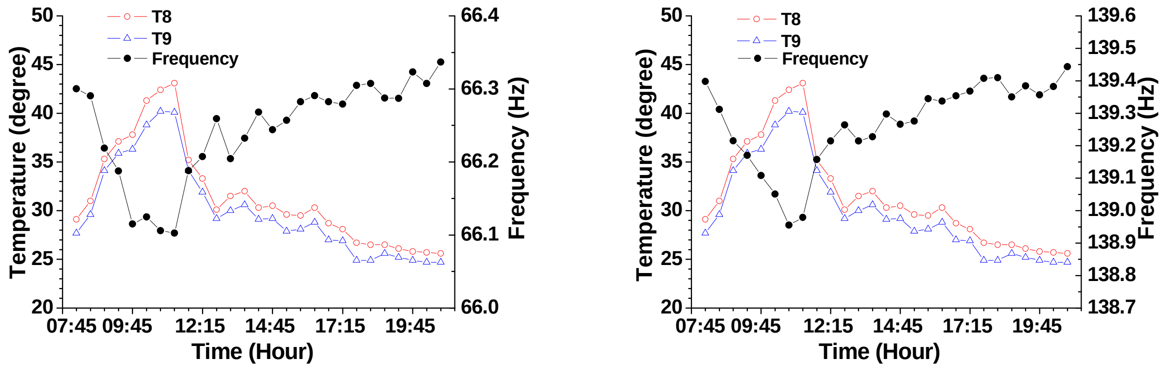
6.2 Variations in frequency with respect to temperature

The first four frequencies of the two metallic beams and the first two frequencies of the RC slab were extracted from the collected data at different times. Fig. 2 shows the first four natural frequencies of the steel beam with respect to the surface average temperature. All natural frequencies decreased with an increase in surface temperature before 11:30 and increased slowly after that time, with a decrease in surface temperature. The variation trend matched the surface temperature very well although the frequency variations were very small. For comparison of different modes, the variation percentage of the natural frequencies with respect to the surface temperatures, is shown in Fig. 3, in which the natural frequencies are divided by the first measurement of the modes. Different modes have a similar relative frequency change (−0.45% to 0.3%).



(a) 1st mode

(b) 2nd mode



(c) 3rd mode

(d) 4th mode

Fig. 2. Variations in natural frequencies of the steel beam with respect to temperature

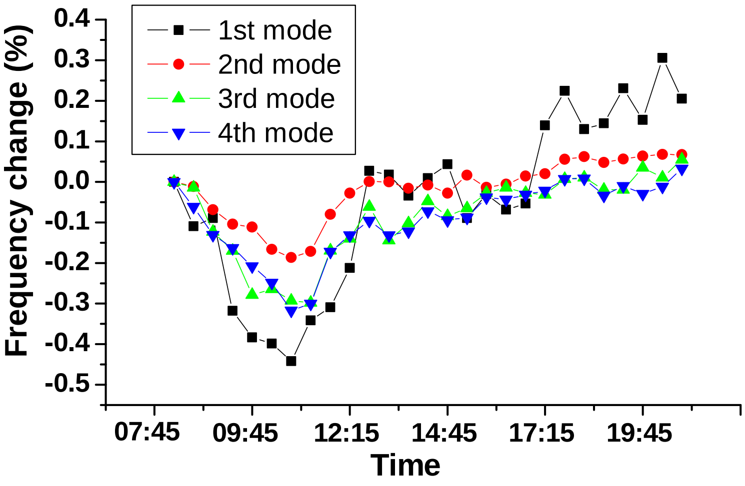
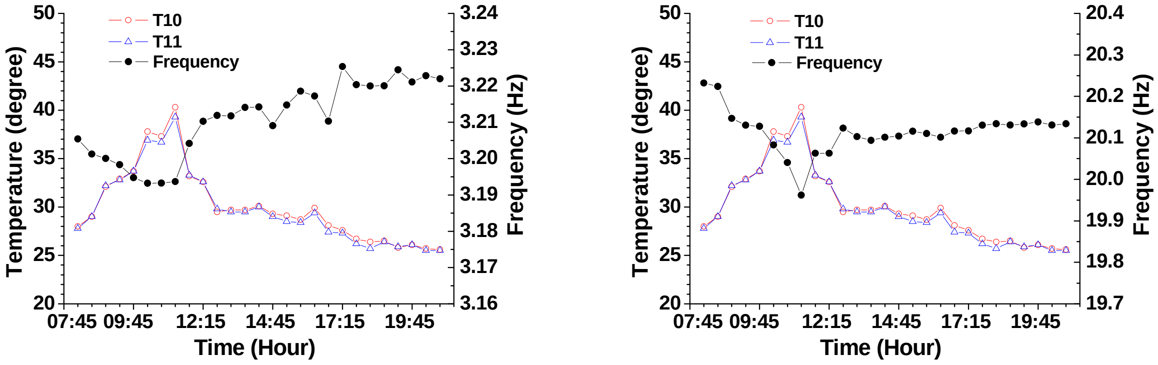
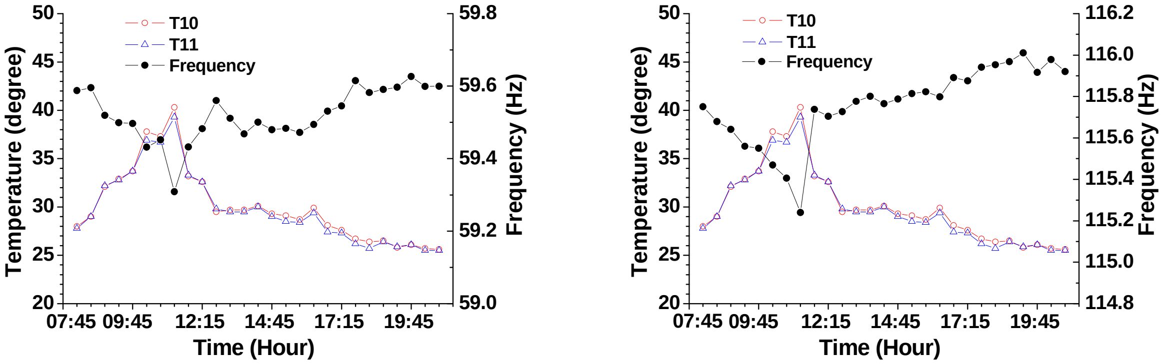


Fig. 3. Variation percentage of the natural frequencies of the steel beam

Variations in the first four natural frequencies of the aluminum beam with respect to the temperature are plotted in Fig. 4. Again, variation trend of all four natural frequencies agrees well with the surface temperature. The higher modes match better with the temperature than the lower modes do. One reason is that the variation magnitude of the lower frequency is smaller than that of the higher frequency under the identical percentage change. For example, the absolute variation in the first frequency is 0.03 Hz only, whereas the counterparts for the second, the third, and the fourth frequencies are 0.25, 0.30, and 0.51 Hz, respectively. Consequently, the measurement noise has a larger effect on the lower modes than on the higher modes. Nevertheless, the experimental results still show a strong correlation between the frequencies and the temperature.



(a) 1st mode　　　　　　　　(b) 2nd mode

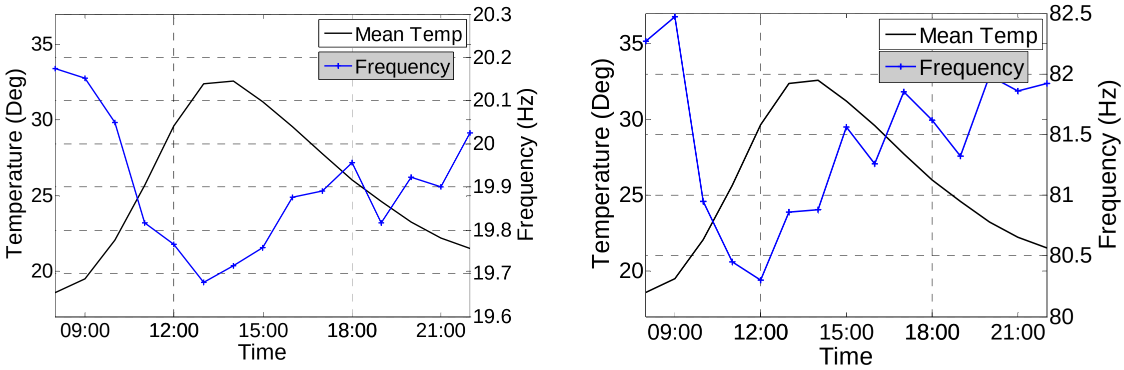


(c) 3rd mode

(d) 4th mode

Fig. 4. Variations in natural frequencies of the aluminum beam with respect to temperature

For the RC slab, variations in the first two natural frequencies and the averaged structural temperature are illustrated in Fig. 5. Again, the natural frequencies generally decrease with an increase in temperature in the morning. They increase slowly in the afternoon with a decrease in temperature. In addition, frequency variations of the RC slab (2.5%) are much larger than those of the metallic beams.



(a) 1st frequency

(b) 2nd frequency

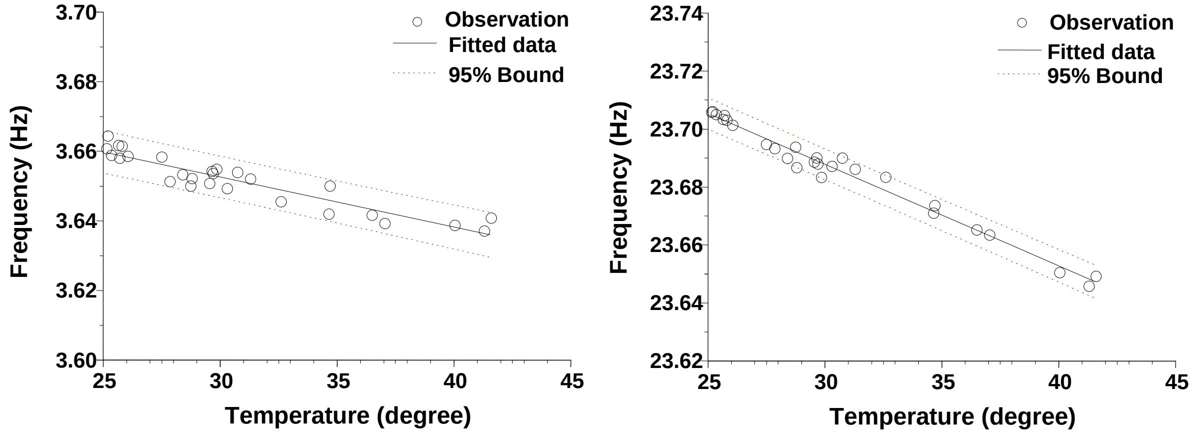
Fig. 5. Variations in natural frequencies of the RC slab with respect to temperature

6.3 Quantitative relation between frequency and temperature

The linear regression technique is utilized to examine the relation between the frequencies and the structural temperature of the models. A linear regression model has the form of [49]

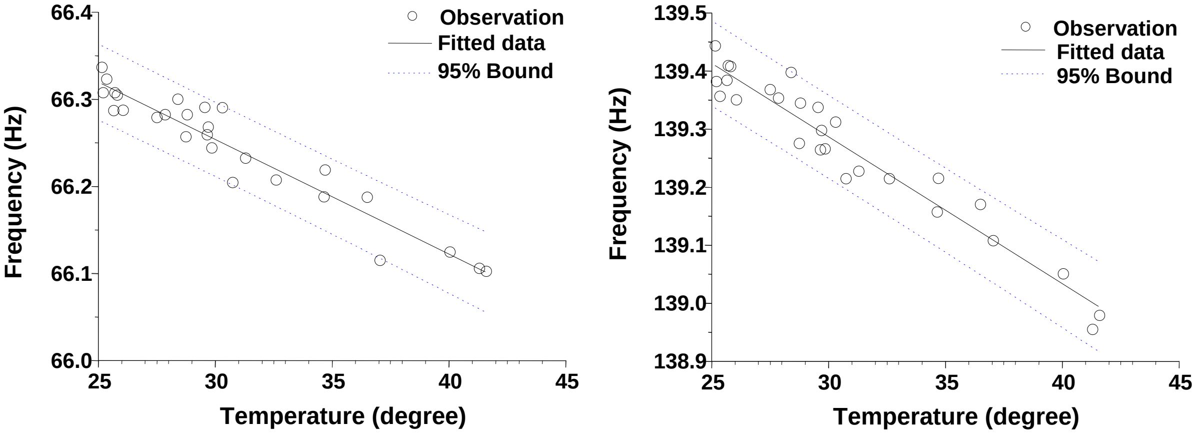
$$f = \beta_0 + \beta_T T + \varepsilon_f \tag{5}$$

where f is the frequency, T is the temperature explanatory variable, β_0 (intercept) and β_T (slope) are the regression coefficients, and ε_f is the regression error. In the regression analysis, the averaged temperature measured across the structural cross section is adopted. The correlation coefficients of the first four natural frequencies of the steel beam are −0.93, −0.99, −0.96, and −0.97, respectively, implying a very good linear correlation between the averaged temperature and the natural frequencies. The fitted regression lines of the steel beam with 95% confidence bounds are plotted in Fig. 6.



(a) 1st mode

(b) 2nd mode



(c) 3rd mode

(d) 4th mode

Fig. 6. Relation of natural frequencies to temperature of the steel beam

The regression coefficients of the three structures are also obtained and listed in Table 1 for each mode. The slope β_T represents frequency change with respect to temperature and the intercept β_0 represents the frequency at 0 °C. For comparison of different modes, β_T is normalized to β_0 and listed in Table 1 as well. β_T/β_0 indicates the percentage of the frequency change when the structural temperature increases by unit degree Celsius. The changes of the first frequency of the two metallic beams are larger than those of the higher modes. This is because the measurement noise has a larger effect on the lower modes, as the lowest modal frequency has the smallest amplitude. Except for the first mode of the metallic beams, the modal frequencies of the steel beam, the aluminum beam, and the RC slab decrease by about 0.015% to 0.020%, 0.027% to 0.042%, and 0.11% to 0.14%, respectively, when the structural temperature increases by unit degree Celsius. The averaged values are 0.018%, 0.03%, and 0.12%, respectively. These are very close to half of the modulus thermal coefficients of the material (θ_E = 0.036%, 0.056%, 0.30% for steel, aluminum, and concrete, respectively) according to Eq. (4). This verifies Eq. (4) and indicates that the variations in the bending frequencies of the structures are mainly caused by the change in the modulus of the materials.

Table 1. Regression coefficients of the models

Mode	Steel beam			Aluminum beam			Concrete slab		
	β_0	β_T	β_T/β_0	β_0	β_T	β_T/β_0	β_0	β_T	β_T/β_0
1	3.69	−0.0014	-3.78×10^{-4}	3.28	−0.0024	-7.31×10^{-4}	20.65	−0.029	-1.4×10^{-3}
2	23.79	−0.0035	-1.47×10^{-4}	20.37	−0.0086	-4.22×10^{-4}	83.74	−0.089	-1.1×10^{-3}
3	66.64	−0.0132	-1.98×10^{-4}	60.01	−0.0163	-2.72×10^{-4}			
4	140.06	−0.0253	-1.81×10^{-4}	117.63	−0.0470	-4.00×10^{-4}			

6.4 Variations in damping with respect to temperature

Variations in the four damping ratios of the steel beam are shown in Fig. 7. No clear correlation between damping ratios and temperature can be found, indicating that temperature has little effect on damping ratios. Similar conclusions can be drawn from the aluminum beam and the RC slab. The results are not shown here for brevity. Nevertheless, variations in damping ratios are quite significant because damping ratios are difficult to measure accurately in practice.

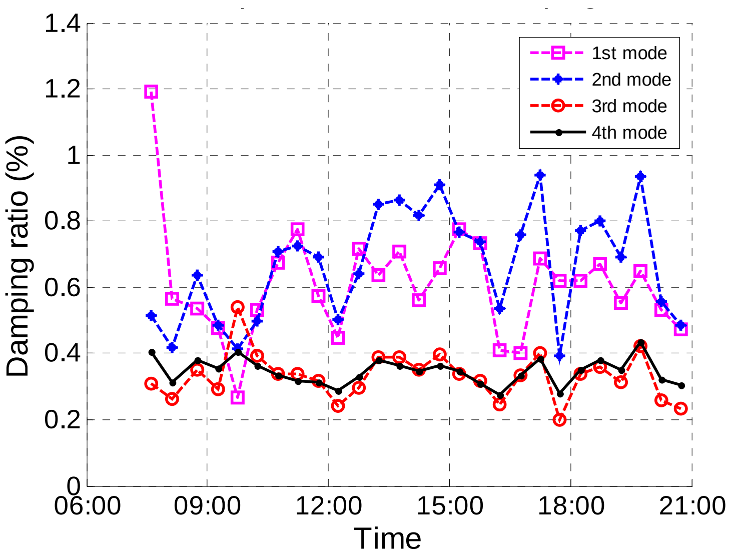


Fig. 7. Relation of damping ratios to temperature of the steel beam

7. CASE STUDIES

7.1 The Tsing Ma Suspension Bridge

A long-span bridge, the Tsing Ma Suspension Bridge is investigated in this section regarding its variations in vibration properties. The Tsing Ma Suspension Bridge has a total span of 2,132 m and carries a highway on the upper level of the bridge deck and railway tracks on the lower level within the bridge deck. Its main span is 1,377 m long, the longest of the type. The configuration of the bridge is shown in Fig. 8.

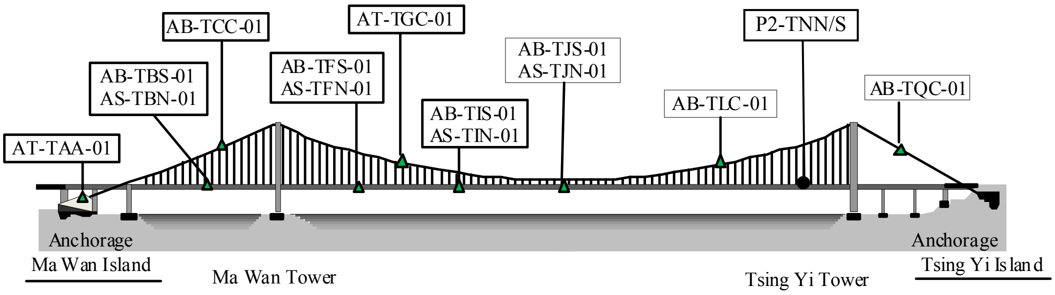


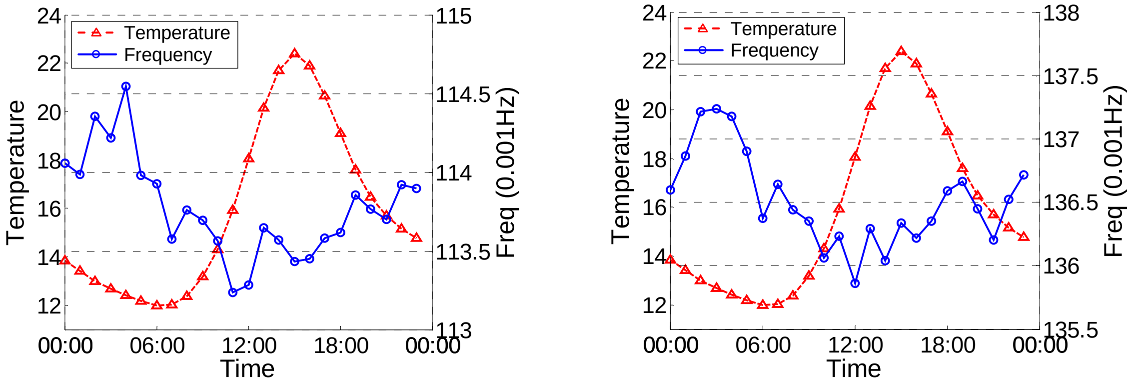
Fig. 8. The Tsing Ma Bridge and its accelerometers and temperature sensors

A structural health monitoring (SHM) system for the Tsing Ma Bridge has been operated since 1997. It is composed of about 280 sensors, including 13 accelerometers and 110 temperature sensors [50]. Here, only three uni-axial accelerometers installed on the deck (AS-TFN-01, AS-TIN-01, and AS-TJN-01) for measuring vertical acceleration are employed. Hourly acceleration time histories are recorded on tapes, with a sampling frequency of 51.2 Hz. P2-TNN/S includes 28 Platinum resistance temperature sensors installed in one deck section, which are used to calculate the effective temperature of the section. The effective temperature is the averaged temperature of the cross section weighted by the areas around the sensors.

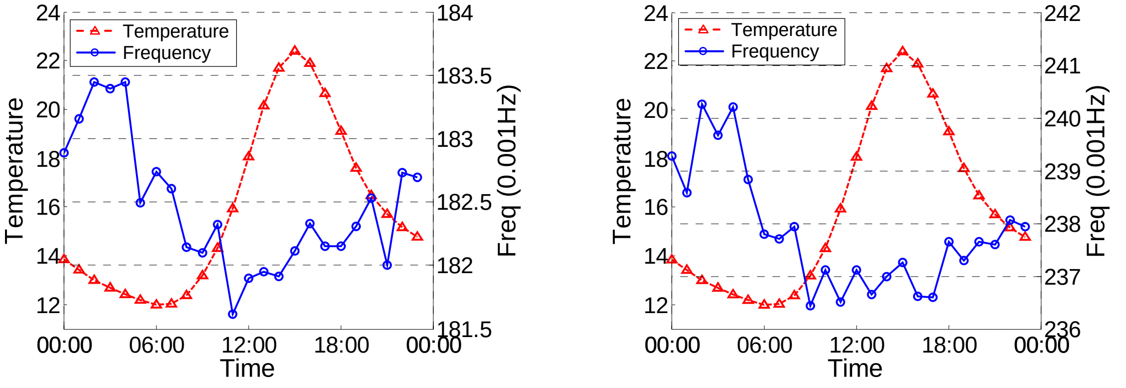
The first four bending frequencies of the global structure in the vertical direction in different seasons are studied here. The frequencies are identified from the ambient excited acceleration data at the vertical direction measured by sensors AS-TIN-01 and AS-TJN-01 using the stochastic subspace identification method [51]. The vertical acceleration data at AS-TFN-01 are employed as the reference.

Fig. 9 shows the variations in the first four vertical frequencies and temperature on 17th January 2005. In the figure, the frequency data at each hour are obtained from the acceleration data recorded during that hour, and the temperature is the averaged effective temperature of the deck section over the hour. Based on the figure, one can find that all frequencies generally decrease when the temperature goes up before noon, whereas they increase as the temperature drops in the afternoon although the variations are quite small. The minimum frequencies and the maximum temperatures do not occur at the same time, and the time difference is about three hours. One reason for this is because the temperature is non-uniformly distributed across the bridge and the frequencies are global properties and are associated with the temperature distribution of the entire structure. Different components have different contributions to the global frequencies, and using one temperature may not represent the variations of the whole structure [32]. Another reason is because the variations in temperature also cause internal stresses of the components, for example, the cables. These increase the complexity of the problem and are not studied here.

The variation percentage of the frequencies, with respect to effective temperature, is shown in Fig. 10, where the frequencies are divided by the maximum values of the mode. The variation trends of the vertical modal frequencies are very similar and the maximum variations are about 1% to 1.5%.



(a) 1st vertical (b) 2nd vertical



(c) 3rd vertical (d) 4th vertical

Fig. 9. Variations in frequencies with respect to the temperature of the Tsing Ma Bridge on 17 January 2005

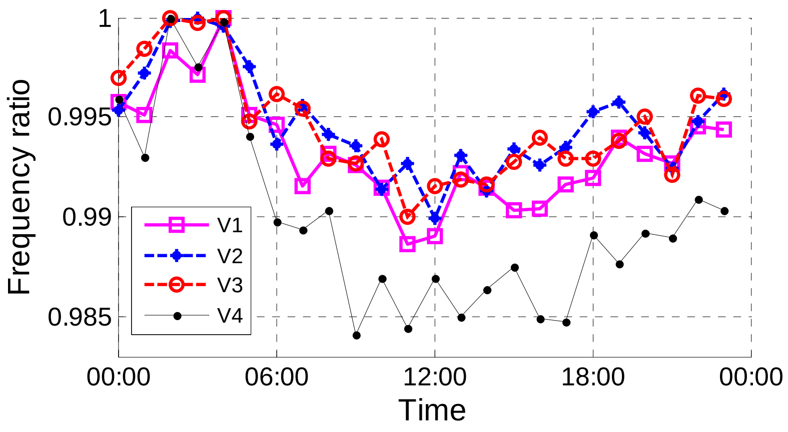
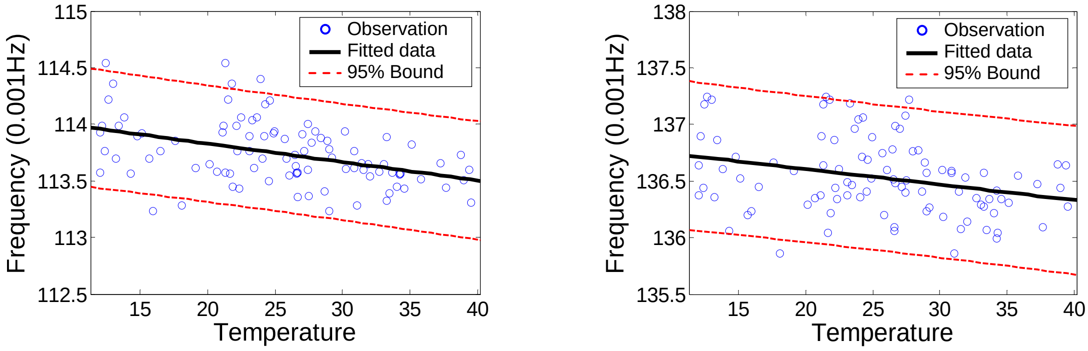
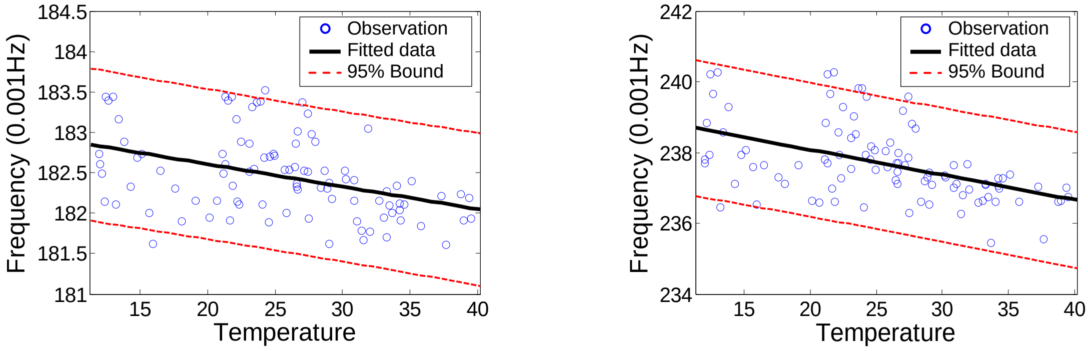


Fig. 10. Variation percentage of frequencies on 17 January 2005

The frequencies in three other seasons (18 April, 17 July, and 26 October in 2005) are also studied. Similar results have been observed but are not shown here for brevity. A linear regression model, as in Eq. (5), is applied to the first four vertical modal frequencies in four days, as shown in Fig. 11. Good linear correlation can be observed from the figure. The quantity β_T/β_0 for the four modes is calculated as -1.42×10^{-4}, -1.00×10^{-4}, -1.52×10^{-4}, and -2.94×10^{-4}, respectively. The averaged value (β_T/β_0) is -1.72×10^{-4}, very close to that of the laboratory-tested steel beam (0.018%) and also to half of $\theta_E = -3.6\times10^{-4}/^{o}\mathrm{C}$, as described in Eq. (4). This implies that variations in the bending frequencies of the structures are mainly caused by the change in the modulus of the material used, although the two structures are quite different in terms of size, type, and boundary conditions.



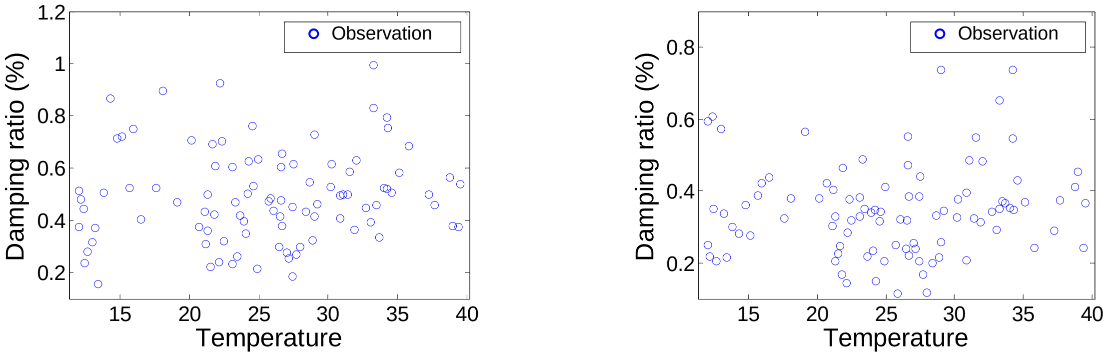
(a) 1st vertical mode (b) 2nd vertical mode



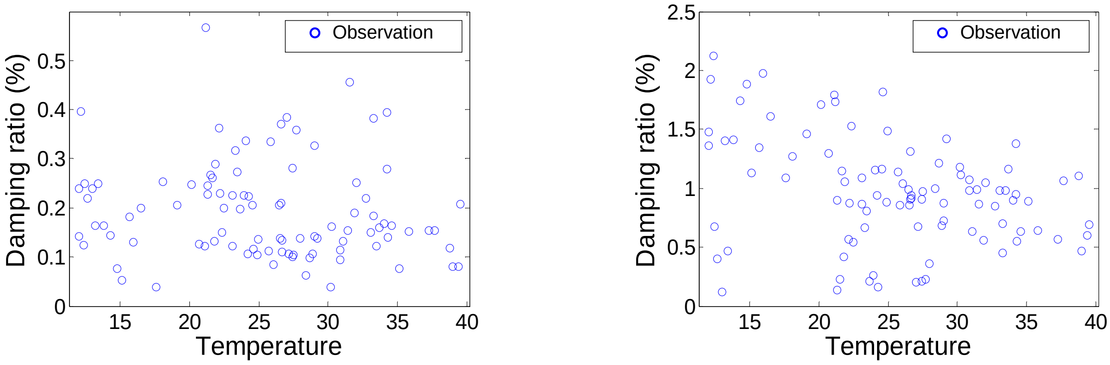
(c) 3rd vertical mode (d) 4th vertical mode

Fig. 11. Relation of natural frequencies to temperature of the Tsing Ma Bridge

Damping ratios of the first four modes versus effective temperatures are shown in Fig. 12. No clear correlation between damping ratios and temperature can be observed. Applying the linear regression model (Eq. (5)) to the damping data shows that their correlation coefficients are 0.10, 0.07, −0.11, and −0.33, respectively.



(a) 1st vertical mode (b) 2nd vertical mode



(c) 3rd vertical mode (d) 4th vertical mode

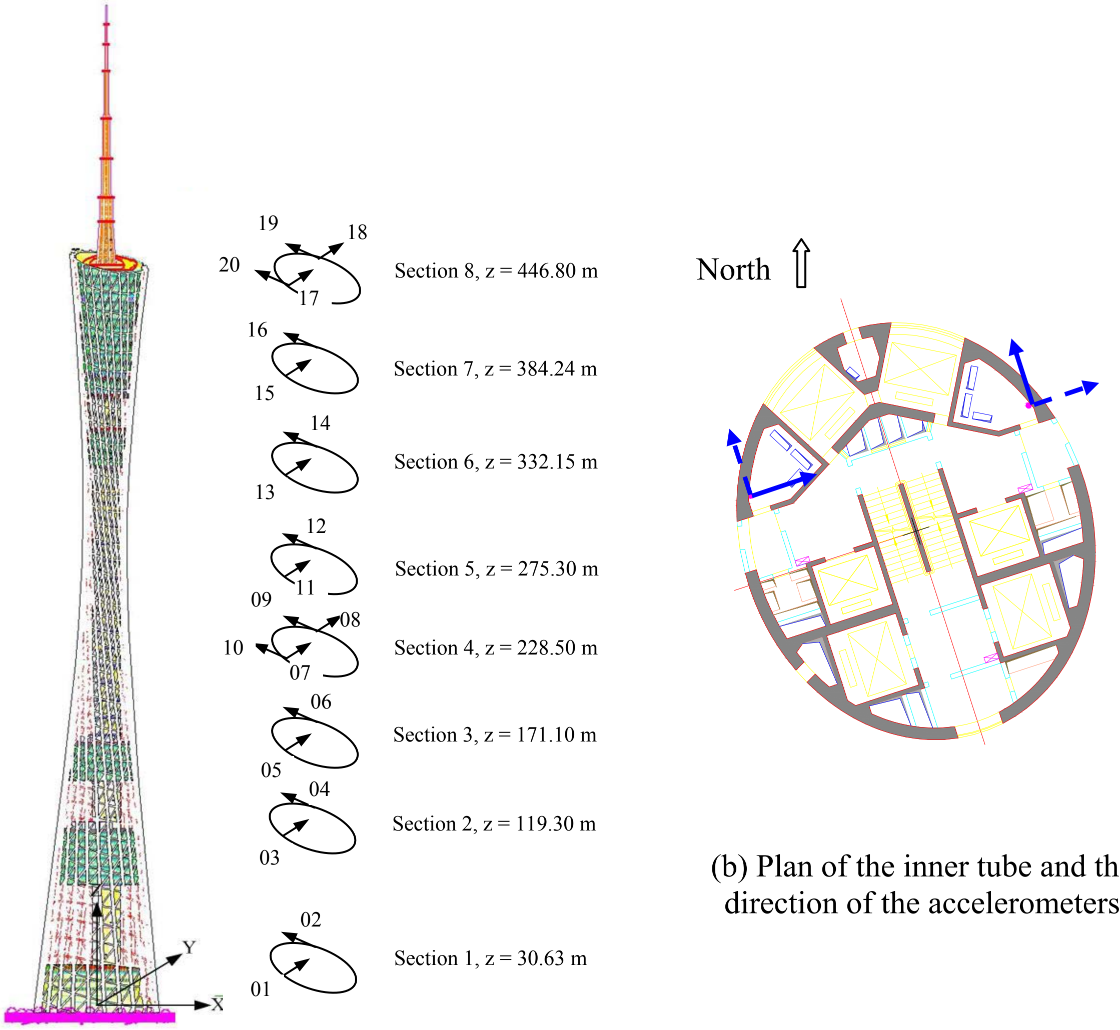
Fig. 12. Relation of damping ratios to temperature of the Tsing Ma Bridge

7.2 The Guangzhou New TV Tower

The Guangzhou New TV Tower is a supertall structure, with a total height of 610 m, consisting of a main tower (454 m) and an antennary mast (156 m). To ensure the safety of the structure during the construction stage and the long-term service stage, a sophisticated SHM system, consisting of more than 700 sensors, has been established by the consortium of the Hong Kong Polytechnic University and the Sun Yat-Sen University [52]. This tube-in-tube structure comprises an inner oval tube made of RC shear wall and an outer tube, consisting of 24 concrete-filled steel tubular columns and 46 rings and braces. Details of the structure can be found in Reference [52].

Twenty uni-axial accelerometers were installed at eight different cross sections of the inner tube, as shown in Fig. 13. The 4th and the 8th sections were equipped with four accelerometers, two for measuring horizontal vibrations along the long axis and the other two for the short axis of the inner tube. At six other sections, each is equipped with two accelerometers, one for the long axis and the other for the short axis of the inner tube.

Here, we studied the variations in the modal properties extracted from the acceleration data versus the ambient temperature from 9:00 of 15 January 2009 to 11:00 of 16 January 2009, lasting 26 hours. The wind speed was stable (about 3.0 m/s) during the period and the wind direction was from north-east-east. Both the anemometer and the temperature sensor were placed on top of the main tower, about 461 m high.



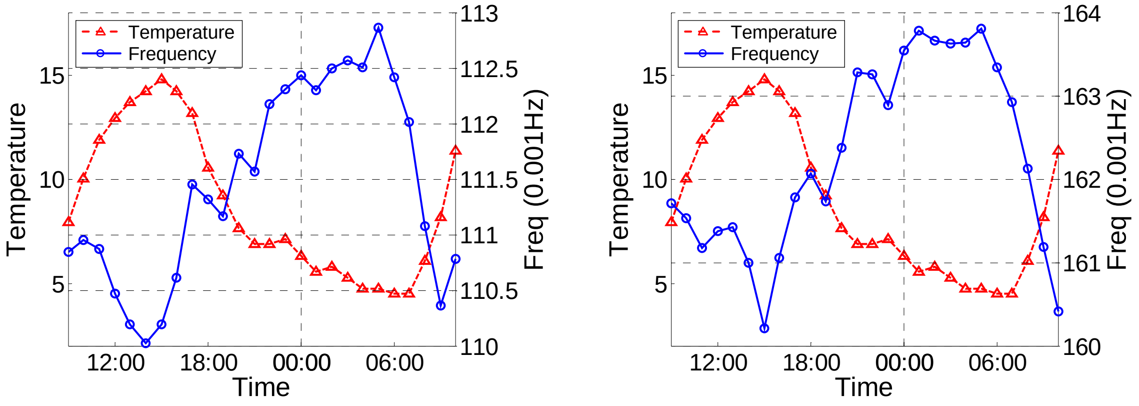
(a) Isometric view of the structure and the accelerometers

(b) Plan of the inner tube and the direction of the accelerometers

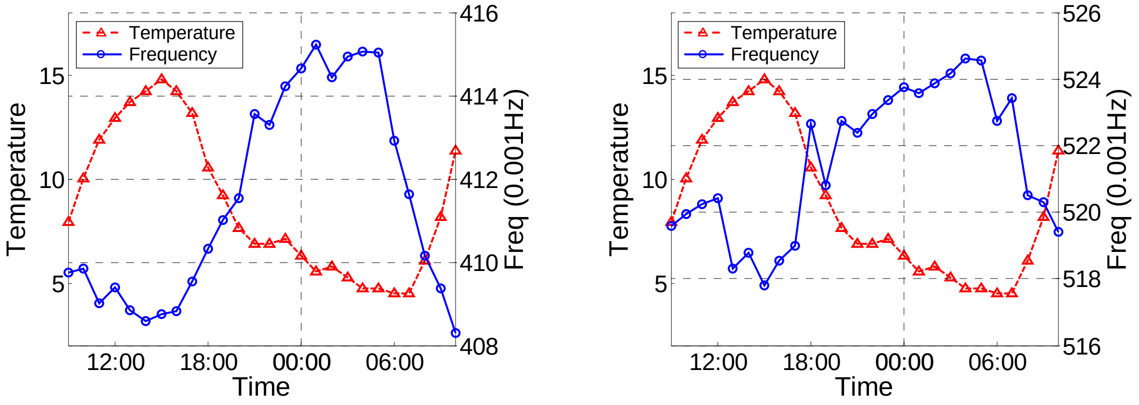
Fig. 13. The Guangzhou New TV Tower and the layout of accelerometers

Hourly acceleration time history data are used to extract the modal properties using the stochastic subspace identification method [51]. The sampling frequency is 50 Hz. Variations in the first four frequencies and temperature at different hours are shown in Fig. 14. The frequencies include two bending modes along the short axis and two bending modes along the long axis of the inner tube.

Based on the figure, the frequencies generally decrease when temperature goes up and increase when temperature goes down, although variations in the frequencies are very small. Similar to the Tsing Ma Bridge, minimum frequencies and maximum temperatures do not occur at the same time.



(a) 1st short axis (b) 1st long axis



(c) 2nd short axis (d) 2nd long axis

Fig. 14. Variations in frequencies versus temperature of the Guangzhou New TV Tower

The linear regression model, as shown in Eq. (5), is applied to the four modal frequencies and temperature. A good linear correlation can be obtained, and the correlation coefficients for the four modes are 0.84, 0.86, 0.82, and 0.87, respectively. The quantity β_T/β_0 for the four modes is calculated as -1.87×10^{-3}, -1.70×10^{-3}, -1.41×10^{-3}, and -1.03×10^{-3}, respectively. Frequencies versus the temperature are illustrated in Fig. 15, in which the frequencies are normalized with β_0 of the mode (intercept at temperature 0 °C). A good linear correlation can be observed for all modes, and the slope of the linearly fitted curve is -1.50×10^{-3}, very close to half of the modulus thermal coefficients of concrete ($\theta_E = -3.0\times10^{-3}/^{o}C$), as described in Eq. (4). This implies that even this large-scale structure is quite complicated, variations in the bending frequencies are mainly caused by modulus change of the material under different temperatures. Other researchers [28, 53] have also studied on this structure. They obtained similar qualitative results but did not present the regression coefficients.

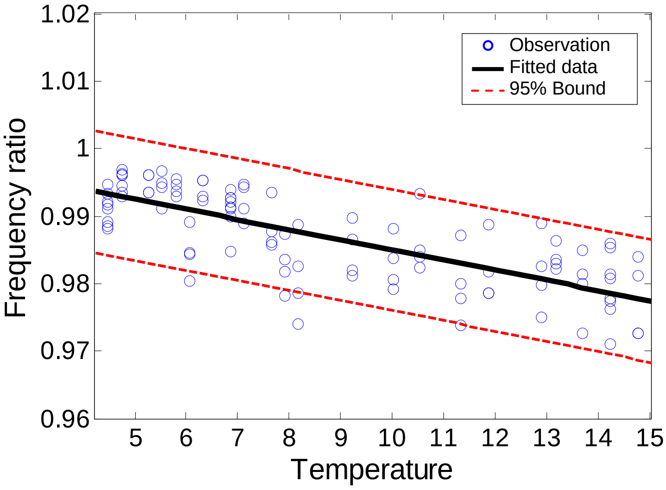
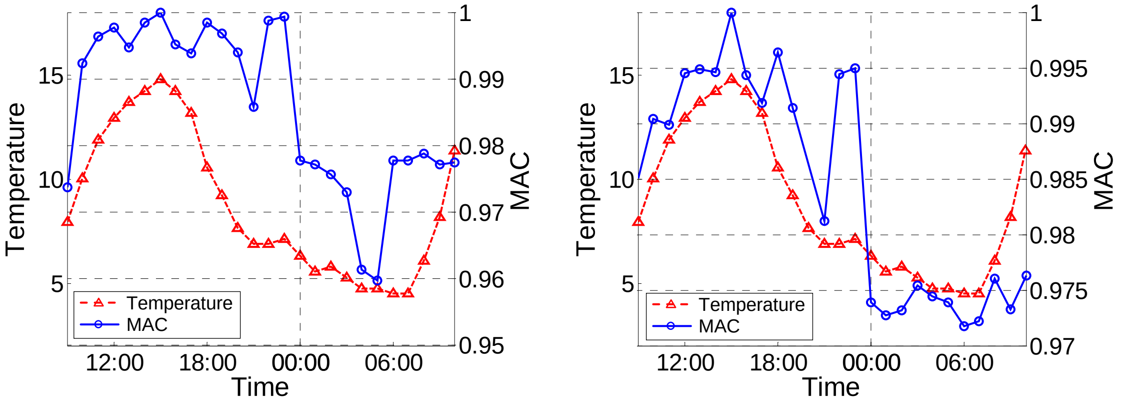
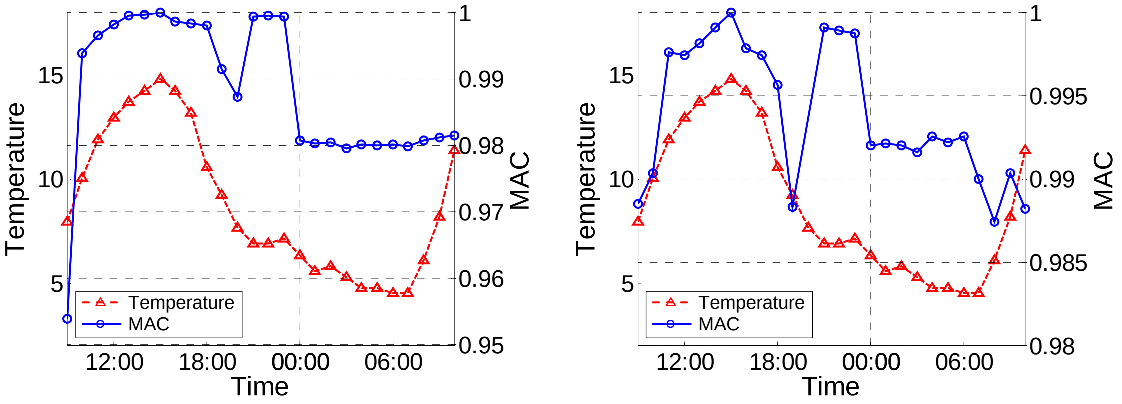


Fig. 15. Relation of natural frequencies to temperature of the Guangzhou New TV Tower

To investigate variations in mode shapes, the modal assurance criterion (MAC) [48] is used. Here, the MAC is calculated between the mode shapes measured at different hours and those at 16:00, with the highest temperature. Variations in MAC versus the temperature are shown in Fig. 16. A lower temperature leads to a smaller MAC, indicating a worse correlation between the mode shapes. This differs from a previous experiment on an RC slab in 2006 [12], in which no clear correlation between MAC and temperature was observed. In that experiment, an entire RC slab was exposed to the environment and experienced identical temperature changes. The present structure, however, is over 600 m tall. The temperature distribution along the height and the cross section is not uniform and varies with respect to time. For example, the east facade has higher temperature than the west facade in the morning, and is lower in the afternoon. This leads to variations in mode shapes. Moreover, the air temperature decreases with the height of the structure.



(a) 1st short axis (b) 1st long axis



(c) 2nd short axis (d) 2nd long axis

Fig. 16. Variations in mode shapes versus temperature of the Guangzhou New TV Tower

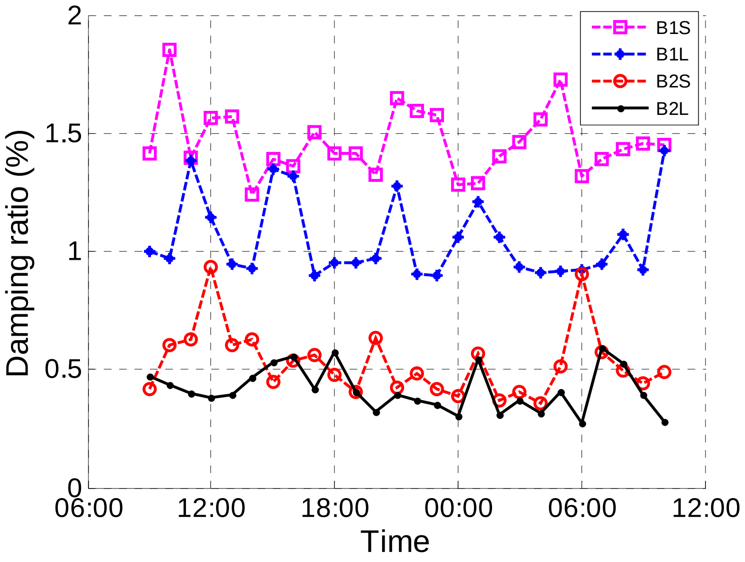


Fig. 17. Variations in damping ratios of the Guangzhou New TV Tower

Finally, variations in the four damping ratios are shown in Fig. 17. Again, no clear trend can be observed from the figure, indicating that temperature has little effect on damping ratios. In addition, variations in damping ratios are quite significant because damping ratios are difficult to measure accurately.

8. CONCLUSIONS AND DISCUSSIONS

This paper reviews temperature effect on variations in modal properties of civil structures. Most studies show that an increase in temperature leads to a decrease in structural frequencies, whereas temperature has little effect on mode shapes, and its effect on damping has not been well understood because of large uncertainty of damping. Three laboratory-tested models and two field-monitored large-scale structures have been investigated. Besides similar conclusions as other researchers have found, the following conclusions can be drawn from the present study:

1. Variations in frequencies are caused mainly by the change in the modulus of a material under different temperatures. That is, modal frequencies of the steel structures, the aluminum beam, and the RC structures decrease by about 0.02%, 0.03%, and 0.15%, respectively, when temperature increases by one degree Celsius, regardless of modes and structural types. Frequencies of concrete structures are more sensitive to temperature change than metallic structures.
2. Mode shapes of high-rise structures may vary at different time instants as temperatures of different components vary as well. This is different from the situation of some bridges, in which temperatures along the longitudinal direction are regarded as identical.

The temperature distribution of large-scale structures is usually non-uniform. Different components have different contributions to the global frequencies. Using air temperature or averaged temperature of a few measurement points may lead to incorrect quantitative relations between temperature and frequencies. Heat-transfer analysis can provide more comprehensive temperature distribution. Then a global eigenvalue analysis combining the relation of modulus to temperature can predict a more accurate relation between temperature and frequencies.

Young's modulus of concrete is usually measured from ultrasonic methods or stress-strain diagram, which exhibits significant uncertainties. In the natural condition, temperature variation is not significant and thus the modulus thermal coefficient is very difficult to be measured accurately. On the other hand, vibration frequency of simple structures can be measured with high accuracy, thanks to the rapid development of hardware and analytical techniques in modal testing. In addition, modal testing is a non-destructive technique and can be carried out repeatedly under different temperature conditions. This is another advantage of the vibration-based method as the traditional uni-axial compression test may cause damage to the specimen and thus cannot be carried out repeatedly under different temperature conditions. Consequently, the vibration-based method can be a promising alternative approach to measure the material thermal coefficient of modulus. Larger temperature variation, larger frequency changes, and thus results in more accurate thermal coefficient of modulus.

For practical structures, factors such as varying boundary conditions, load conditions, and damages may also affect the structural vibration properties. Measurement noise may also mask this variation. In addition, it is very difficult to separate the effects from different sources. Therefore, controlled laboratory experiments are necessary and imperative to provide accurate and reliable results regarding the temperature effect on the structural vibration properties. In laboratory experiments in this paper, varying temperature can be the main reason of the frequency changes and frequencies can be measured very accurately. For example, the first author [54] has conducted a modal testing on a RC slab repeatedly under a stable temperature condition. It shown that the coefficient of variation (ratio of standard deviation to mean value) of the first four modal frequencies were 0.04%, 0.09%, 0.31% and 0.35%, respectively, which is equivalent to about 0.3-2.3 degrees temperature variation of concrete. Doebling et al. [55] also estimated that the frequency uncertainties of Alamosa Canyon Bridge were about 0.06-0.73%. For metallic structures, the measurement noise can be smaller.

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