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Identifying and discriminating thermal effects for structural health monitoring

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ABSTRACT: For exposed structures such as long span bridges and towers, variation of structural temperatures in time and space pose a challenge for effective structural health monitoring. 'Thermal loads' lead to quasi-static variations in deformation that usually exceed those due to wind, while the changes in structural configuration arising from expansion and contract can result in variations of modal properties. The thermal effects provide a form of structural microscope for studying structure performance 'mechanisms', but may impede use of data-driven mathematical tools for inferring structural change from subtle changes in performance characteristics.

The paper focuses on results of and conclusions from an elaborate experimental and analytical study on the Tamar Bridge.

1 INTRODUCTION

Effects of slowly varying temperature on bridge behaviour have for decades been studied for short- and medium-span concrete bridges and composite steel-concrete bridges. Their thermal behaviour is mostly governed by deck temperature profile, which is in turn determined by geometry, material composition, bridge location and climate. Long-term monitoring projects have helped improve our understanding of temperature distributions and actions on concrete bridges.

Investigations on large steel bridges have also been researched for several decades, but are limited to a few structures. Two recent studies were carried out on the Ting Kau Bridge in Hong Kong (Nua, Wong, et al., 2007) and the Runyang Bridge in China (Ding & Li 2011a), which derived data-driven performance models to relate the bridges' temperature to the expansion at the abutments. Probably the most comprehensive study to date involved the use of finite element heat transfer analysis and field monitoring data to investigate the temperature distribution and thermal response of the Tsing Ma Bridge in Hong Kong (Xu & Xia 2012).

Dynamic response is also temperature dependent (XChen, Weng, et al., 2012), where typically modal frequencies fall and rise in diurnal cycles, while the structure's temperature rises and falls in a similar but inverted profile (Cornwell et al. 1999; Peeters & De Roeck 2001; Zhou et al. 2010; Ding & Li 2011b). In steel structures thermal variation of Young's modulus is quite small, so it is suspected that for cable-supported structures the consequent changes in the tensions and the static configuration of a bridge may affect the dynamics.

Principal Component Analysis (PCA) has also been used to discriminate temperature related effects in data (Yan et al. 2005), while (nonlinear) Kernel Principal Component Analysis

(KPCA) was conducted by Oh et al. (2009) on the hanger tensions of the Yeongjong Grand Bridge. Physics based (finite element) modeling has also be used e.g. by Miao et al. (2011) for Runyang Bridge and compared favorably to observations on the prototype.

2 THE TAMAR SUSPENSION BRIDGE

2.1 Structure

Completed in 1961, the Tamar Bridge is a symmetrical suspension bridge comprising a main span of 335m and two almost identical 114m side spans aligned in approximate East (Plymouth, Devon) –West (Saltash, Cornwall) direction. Reinforced concrete towers rise 73m above their caisson foundations and support two 350m diameter suspension cables as well as 16 stay cables with nominal 100mm diameter. The 5.5m-deep deck trusses made of welded hollow-box steel sections are suspended from the hangers, which are attached to the suspension cables at 9.1m intervals. The truss deck directly supports a lightweight orthotropic steel deck with an asphalt topping, providing three vehicle lanes. Two extra lanes were cantilevered off the truss to accommodate traffic during a strengthening and widening exercise and these remain as a footpath/cycleway and an Eastbound lane for light local traffic. The two lanes wrap around the outside of both towers but accommodate an expansion joint at the Saltash tower.

A detailed description of the Tamar Bridge's and its instrumentation is provided elsewhere (Koo et al. 2012). It comprises an array of sensors sampling stay cable tensions, temperatures and environmental conditions at 0.25Hz, accelerometers monitoring deck vibrations and automatically generating time series of the modal properties, a wire sensor network to track movements at the Saltash expansion joint and a slow-sampling robotic total station to track 3D movements of the deck and Saltash towers.

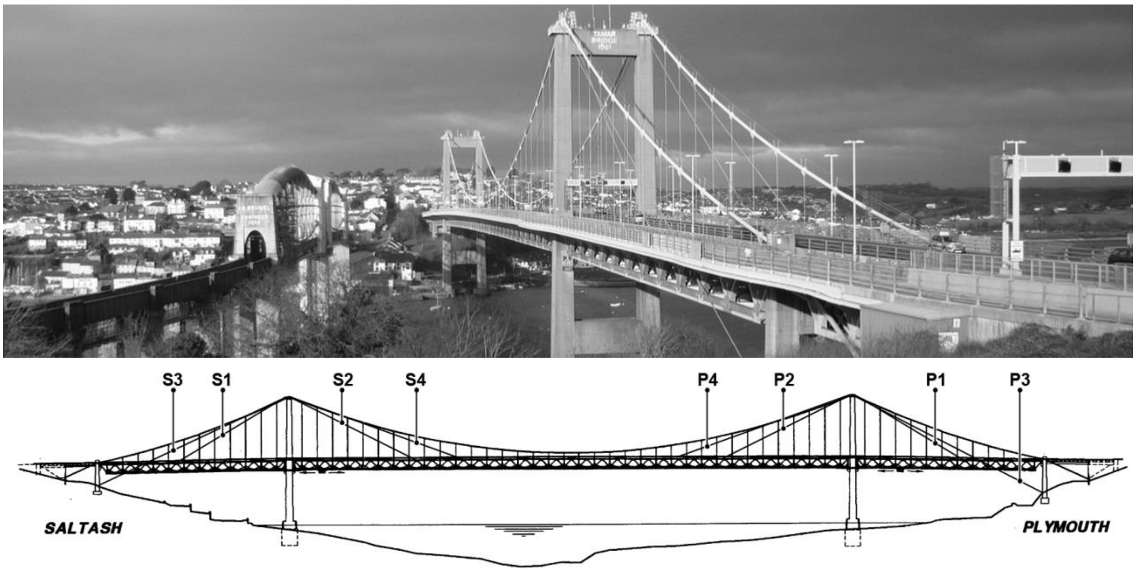

Figure 1: Tamar Bridge (Royal Albert Bridge to left)

2.2 Quasi-static structural response due to temperature: displacements

Time series of quasi-static deformations demonstrate that the response follows diurnal cycles. Approaching noon the deck RTS reflectors move towards the Saltash expansion gap as shown in

Figure 2 (top-left). Figure 2 (top-right) shows that the deck sags during the morning, and rises in the afternoon. Due to the Saltash expansion gap the bridge deforms asymmetrically with greater deflections on the Saltash half. As shown in Figure 2 (bottom-left) this causes the tensions of the stay cables attached to the Saltash side of the main span (S2 and S4) to relax during the day, while having an opposite effect for the stay cables on the Plymouth side (P2 and P4).

There are significant temperatures differences between the orthotropic deck, suspension cable and truss, shown in Figure 2 (bottom-right). Deck and suspension cables are generally the warmest; the deck being slightly warmer due to the dark surface, while the truss however is shaded by the cantilevered deck. Most of the heat transfer and temperature variation is via air circulation or by conduction across the deck and truss connections. Temperature differences are greatest during the summer months.

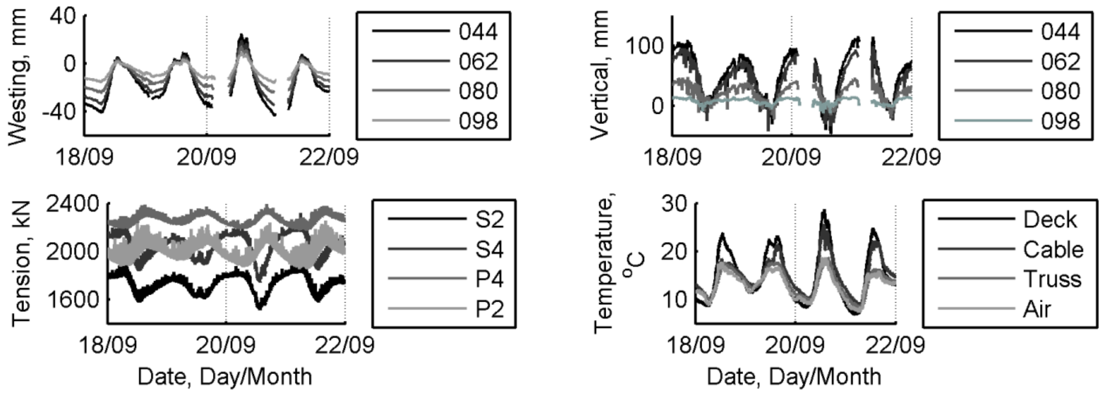

Figure 2: (left) westerly movement/longitudinal expansion and (right) vertical movement.

2.2.1 Longitudinal and vertical displacement variation with temperature

Figure 3 shows how deck expansion (upper plots) and vertical deflection (lower plots) vary with temperature; left plots are different locations, right plots are for different structure temperatures. The expansion correlates well with the expansion coefficient of steel (12×10^{-6}m/m°C), but for higher temperatures the relationship becomes nonlinear.

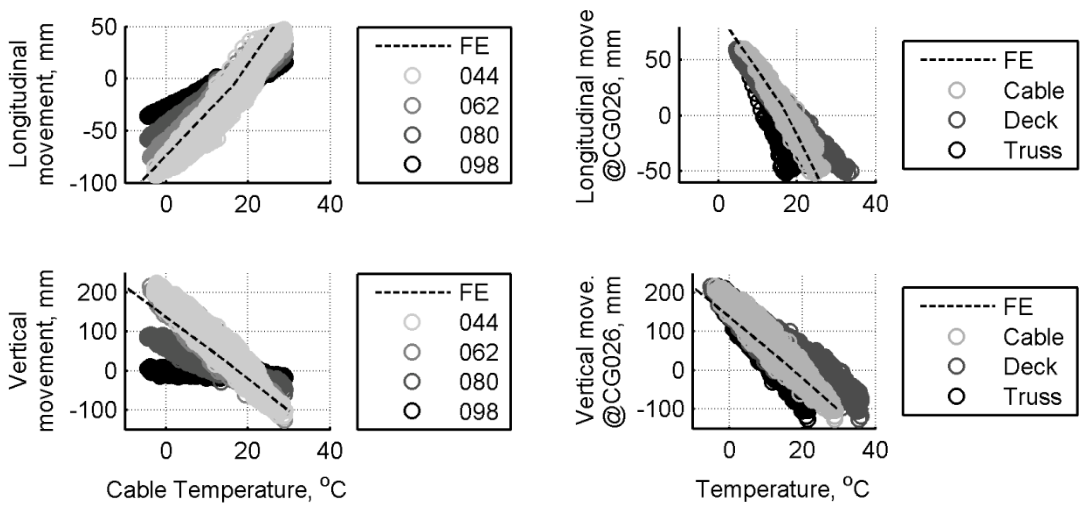

Figure 3: Longitudinal expansion of the deck (left) by location and (right) by measurement location.

2.3 Correlating quasi-static structural response and temperature: stay cable tensions

The strongest correlations are shown with S2/S4/P2/P4, which are shown in Figure 4. The clear correlation is likely to be a consequence of the almost perfectly linear expansion of the bridge deck with temperature. P2 and P4 tensions (connecting to the Plymouth tower) show more scatter due to thermal lag, which cause the winter data to fan out at high temperatures and the summer data to 'arch'. The relationship has been studied and simulated using the FE model, and the result is shown in the rightmost plot.

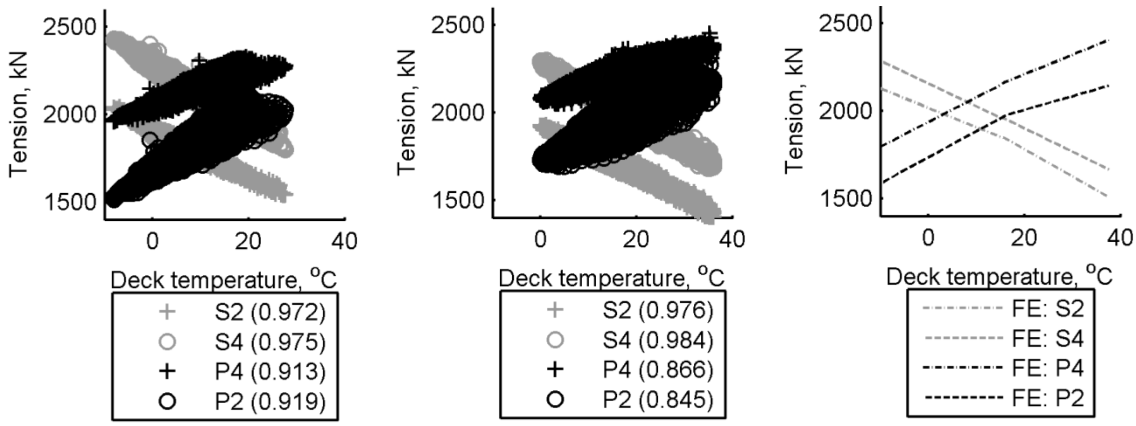

Figure 4: Stay cable tensions vs. deck temperature. Left: Winter period. Middle: Summer period, Right: FE simulation. Correlation coefficients are given in the legend.

PCA was carried out to study the link between temperature and tension data. PCA works in an analogous way to normal mode analysis in dynamics: multi-channel time series are reduced to principal components (PCs), the first carrying most of the information, while in higher components information diminishes. The vectors show the pattern of the channels and the scores scale them. Figure 5 shows the first three vectors in each case and relationships between the two best correlated pairs of PC scores, while Figure 6 shows time series of PC scores.

The largest common variation (PC1) of temperature is a flat distribution, while for tensions it involves Saltash tower stay cables moving broadly in opposite sense to Plymouth side tensions. Temperature PC2 appears to capture the differential heating on sunny days but not to be strongly linked to tension changes. FE modeling shows that this pattern is primarily driven by deck expansion and to a lesser extent by main cable extension. The relationship of the two PC1 scores is clear but the correlation for PC2 is a small mystery.

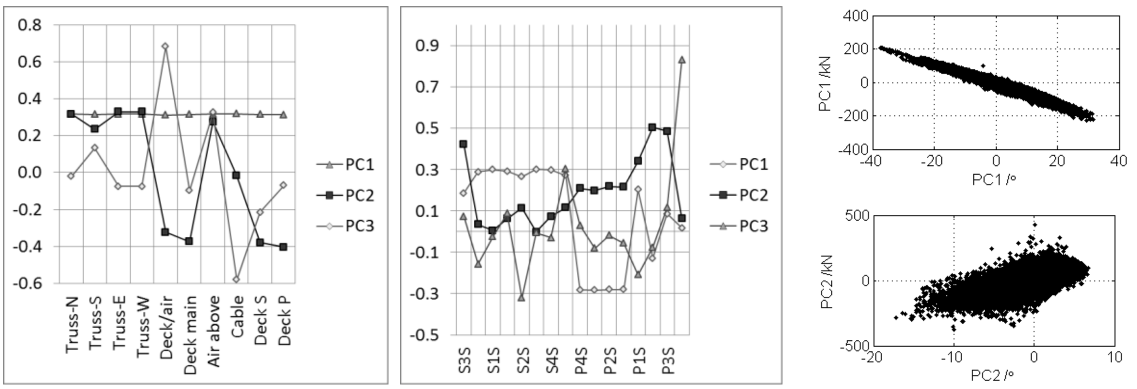

Figure 5: Principal vectors for temperatures and stay cable tensions, also correlations between scores.

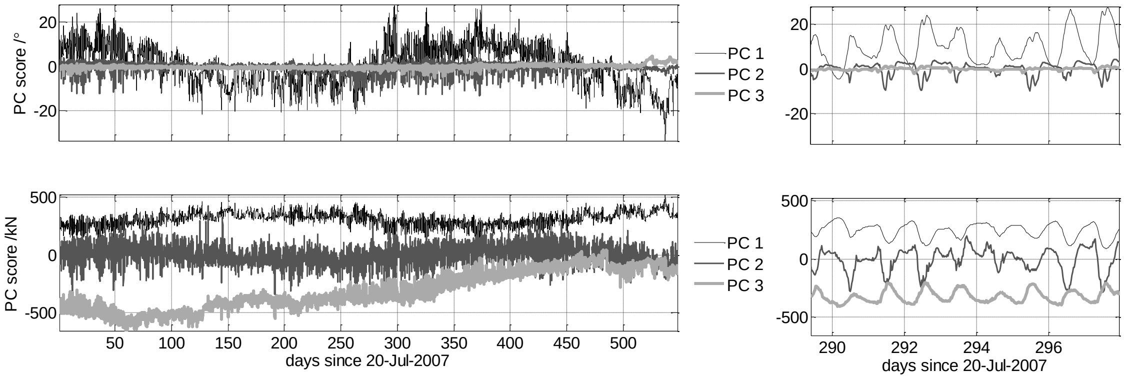

Figure 6: Principal component analysis of structure temperature and stay cable tension time series.

2.4 *Correlating dynamic characteristics with temperature.*

Statistics of modal properties obtained automatically from the cable and deck accelerations automatically using the data-driven stochastic subspace identification (Van Overschee & De Moor 1996) and the first five mode shapes from the FE analysis are presented in Table 1.

Table 1: Tamar Bridge modes, mode shapes and frequency statistics

Mode	Type	Shape	μ(*f*)/Hz	σ(*f*)/ Hz	σ(*f*)/ μ(*f*) %
1	VS1		0.391	0.0025	0.64
2	LS1a		0.472	0.0118	2.49
3	VA1		0.596	0.0057	0.96
4	LS1b		0.688	0.0037	0.54
5	TS1		0.728	0.0053	0.73

Figure 7 shows frequency variations for periods with and without significant structure temperature variations. The small temperature fluctuations are due to overcast weather.

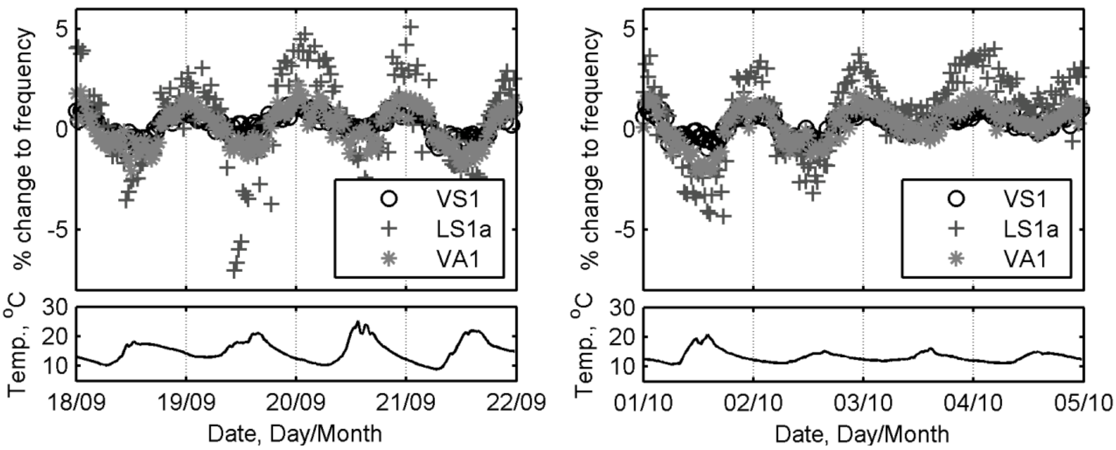

Figure 7: Frequency variations for days with strong (left) and weak (right) structure temperature variations.

Figure 8 groups frequency values into bins for each half hour of the day, done separately for weekdays and weekends, as a rudimentary means to show the effect of traffic loads. There is a clear trend in the 4AM values, but obvious differences between the weekday and weekend characteristics, suggesting that vehicle mass and weight play a significant part in the frequency variations. Mass reduces frequency through the inertia terms of the dynamic equilibrium, whereas weight affects the tensions for the suspension and stay cables, resulting in changes in geometric (tension) stiffness contributions. Separating effects of the environment from the modal properties or 'normalisation' is a major challenge for structural health monitoring (Cross et al. 2013). PCA does not work here, so the response surface method is used.

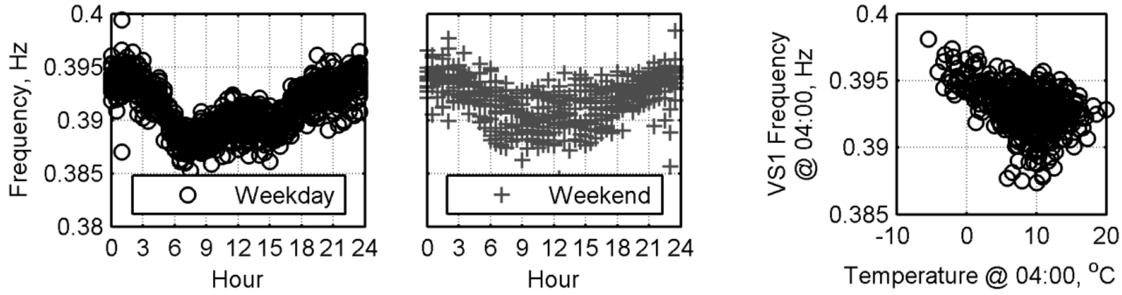

Figure 8: Mode VS1 frequencies by time of day for weekday and weekend and vs. 4AM temperature.

Figure 9 shows results for a short time series of mode VS1 frequencies. The fit using temperature alone is surprisingly poor, whereas traffic mass fits far better. The difference between the two is not great, and there remains a large discrepancy on November 18 which is well covered by including a third variable: the modal acceleration level. Nevertheless there is a clear temperature/frequency correlation, whose causes can be explored using the FE model.

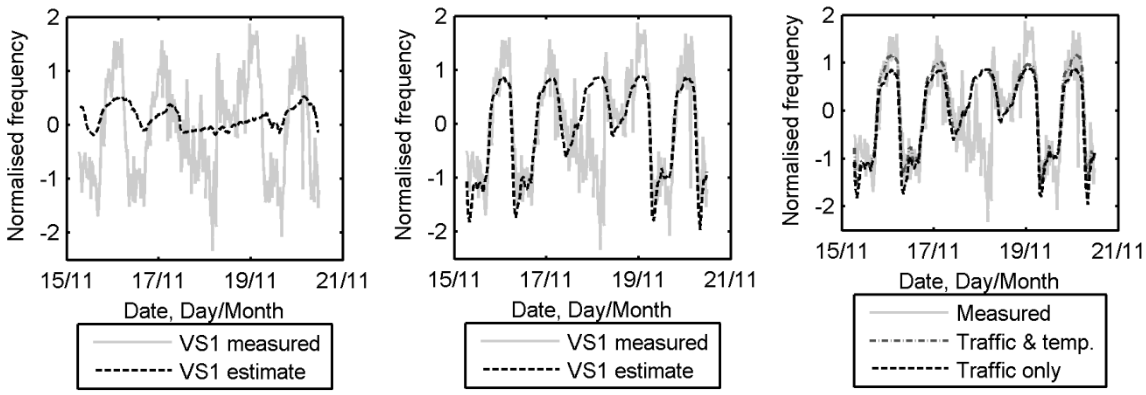

Figure 9: Response surface predictions of VS1 frequencies comparing effects of traffic and temperature. From left to right: temperature only; traffic mass only; traffic mass with and without temperature.

2.4.1 Predicted frequency change by finite element model (FEM)

The FE model developed and validated by the modal test was used in simulations to investigate the cause of the significant temperature ranges. There are two obvious major factors likely to affect modal properties in a suspension bridge. First, the Young's modulus for steel drops by 46.5N/mm²°C for climatic temperatures. Second, thermal expansion and contraction causes change in the bridge configuration with consequent changes in tensions in main and stay cables.

For example, the horizontal tension in the main span suspension cable varies by 6.23kN/°C. There are potentially less obvious and indirect consequences, such as nonlinear modulus variations of surfacing and changes to boundary conditions.

The obvious influences can be explored through the FEM using a two-step approach. The procedure was the same as used for exploring static effects: first a thermal analysis of the model determines the thermal stresses of the structure, which are adopted as loads in the structural analysis. The following modal analysis incorporates the pre-stressed effects from the static analysis to find changes in the dynamic properties.

Figure 10 demonstrates the predicted change in frequency caused by changing material properties and elongation of the cables respectively, their responses separated to compare their influence on the overall change in dynamic response. The plots show the change in frequency with respect to values obtained at the reference temperature, 17.5°C. The results are presented as a percent change. For modes VS1, LS1b and TS1 there is approximately 0.65% variation in the frequencies across the observed 40°C range.

The mostly linear frequency variation caused by the elongation of the elements is very significant for the lateral modes (LS1a and LS1b), which suggests that large variations observed on the prototype may be a result of elongation and tension reduction of the main suspension cables. For the other observed modes the changes due to tension reduction are similar to those due to Young's modulus changes. The kink in the slope is due to the incorporation an increasing temperature differential between the deck, cable and truss, as observed from temperature data and due to solar radiation.

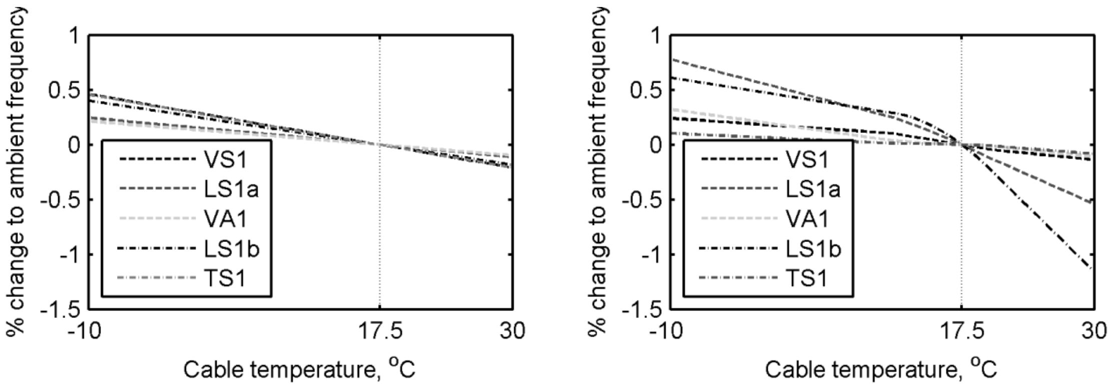

Figure 10: Frequency changes vs. Cable temperature, resulting only from Young's modulus variation (left) and resulting only from thermal expansion (right).

Frequency variations predicted by the FEM are considerably less than those observed from the monitoring. Table 2 and suggests that the model has missed some effects e.g. the effects of various combinations of thermal responses (in the deck, cable and towers).

Table 2: Approximate change in frequency vs. cable temperature for the first 5 modes.

Mode	Type	Δf (Monitored) ×°C /10-3 Hz	Δf (FE) ×°C /10-3 Hz
1	VS1	0.098	0.097
2	LS1a	0.990	0.197
3	VA1	0.497	0.114
4	LS1b	0.348	0.354
5	TS1	0.307	0.191

3 CONCLUSIONS

Monitored and modeled data from the Tamar Bridge show that the longitudinal and vertical deflection of the bridge is dependent on the temperature of the bridge deck and the cables. The stay cable tensions also vary due to temperature, but show responses caused by time-dependent effects. The research has shown that the natural frequencies of the structure also vary, but relate more to traffic-induced effects than temperature. The most substantial changes in modal properties caused by temperature appear to be a result of the changes in the suspension and stay cable tensions.

Space has not permitted presentation of results for other structures, but from our observation of other monitored structures we know that temperature affects configuration with consequent secondary effects on dynamic properties.

Some of the promising methods to filter environmental effects have been tried and there are a number of other tools that can be applied.

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