Real-time long-term monitoring of static and dynamic displacements of an office tower, combining RTK GPS and accelerometer data

James BROWNJOHN, UK
Chris RIZOS, Australia
Guan-Hong TAN, Singapore
Tso-Chien PAN, Singapore

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SUMMARY

Since 1993 a 280m building in Singapore has been instrumented using an evolving monitoring system that began with manual static readings of stress and strain and progressed through a full-scale vibration survey to a permanent remote control system using basement and roof accelerometers together with anemometers to capture the effect of wind and seismic loads. Recently a dual-rover RTK GPS system has been operating in synchronisation with the wind and acceleration system in order to test the feasibility of GPS for building performance monitoring and to understand the way the building responds quasi-statically to wind, temperature and seismic loads. The paper describes the system integration for the present monitoring system and presents some results on performance of the building and the GPS system.

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1. INTRODUCTION

The city state of Singapore, at Latitude 1.3°, Longitude 103.8° with land area of approximately 620km^2, has no local seismic activity and no strong cyclonic or anti-cyclonic weather systems. The only real limitations on tall buildings are aviation regulations restricting maximum height of permanent structures to 280m. So far, only office towers have been built to heights exceeding 150m, but high rise apartment blocks are now being constructed up to 168m stories, for which a better understanding of lateral static and dynamic loading is required.

In Singapore, building design has to consider lateral loading (still) usually according to CP3[1] and design using either BS5950[2] or BS8110[3]. There is currently no specific code provision for dynamic lateral loading due to seismic activity and equivalent static approaches are used for wind. According to BS8110 a 'notional horizontal load' (NHL) equivalent to 1.5% of dead load has to be applied to cater for accidental eccentricity and is believed to cater for seismic actions, while using the CP3 3-second gust as a static wind load is believed to cover dynamic wind effects. While on the surface specific provisions for dynamic effects seem to be unnecessary, close examination shows the need to assess how far existing code provisions are adequate to provide for occasional unusual dynamic loads.

Despite having no local seismic activity and no seismic code, Singapore is 700km from the source of the largest recurring earthquakes on the planet. The wind speeds used for design are widely regarded as over-conservative yet attempts to determine a more appropriate design value and procedure face the difficulty that the localised, short-lived and highly turbulent storms provide the strongest loads and such loading is only recently being addressed in the wind engineering community. As the best gauge of seismic and wind loads is the building performance, it is natural to observe load together with response, an approach used for example by Rainer & Dalgleish[4].

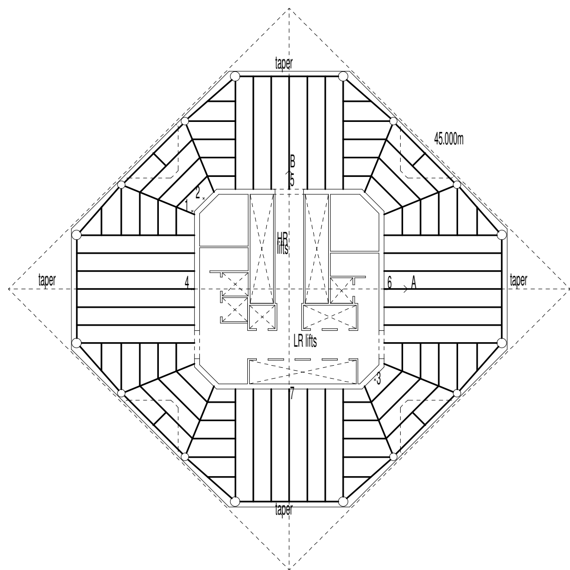
This paper describes the lateral response monitoring program that has been running on Republic Plaza Singapore since 1996. Originally using accelerometers and anemometers it now incorporates a dual-rover GPS system to provide ultra-low frequency response data. The original aim was to capture local wind characteristics but the system has found great use in capturing the attenuated local ground motions due to the numerous large earthquakes occurring in the region.

2. DESCRIPTION OF INSTRUMENTED STRUCTURE

The 280m, sixty-six storey Republic Plaza (Fig. 1) has been studied through static and dynamic response measurements since 1998[5] in parallel with analytical exercises[6]. Hence the structural behaviour of the building is very well understood and it has been possible to use inverse methods to estimate applied loads via measurements of response.

Figure 1 (left) Republic Plaza

Figure 2 (below) Plan at level 18 showing orientation of core wall.



The tower has a frame-tube structural system with an internal lateral load-bearing core wall connected to a ring of eight external columns by horizontal steel framing system at every floor (Fig. 2). The external columns are designed to carry the bulk of the vertical load, and for enhanced stability are filled with concrete up to 49th storey.

3. MODAL CHARACTERISTICS

Fundamental lateral vibration modes do not align with any obvious axes of symmetry and it has been convient to use axes A and B which repesent 'weak' and 'strong' directions to label vibration modes.

The lowest three pairs of lateral modes have been tracked during and after construction and presently the first and second natural frequencies which dominate the structural response occur at frequencies close to 0.2Hz and 0.7Hz respectively, with damping ratios less than 1%.

Fig. 3 shows a typical pair of unscaled acceleration autospectra measured in B and A directions and coherence function from which it can be seen that some modes appear to involve movement in both directions. An ambient vibration survey was conducted in 1995 after completion of the building structure, the main purpose of which was to characterise these modes and identify the deflected (mode) shapes in vertical planes in A and B directions as well as in horizontal planes through four levels.

By piecing together the measurements from a period of five days, a set of 12 modes was characterised; Fig 4 shows three lowest A direction modes and one torsional mode.

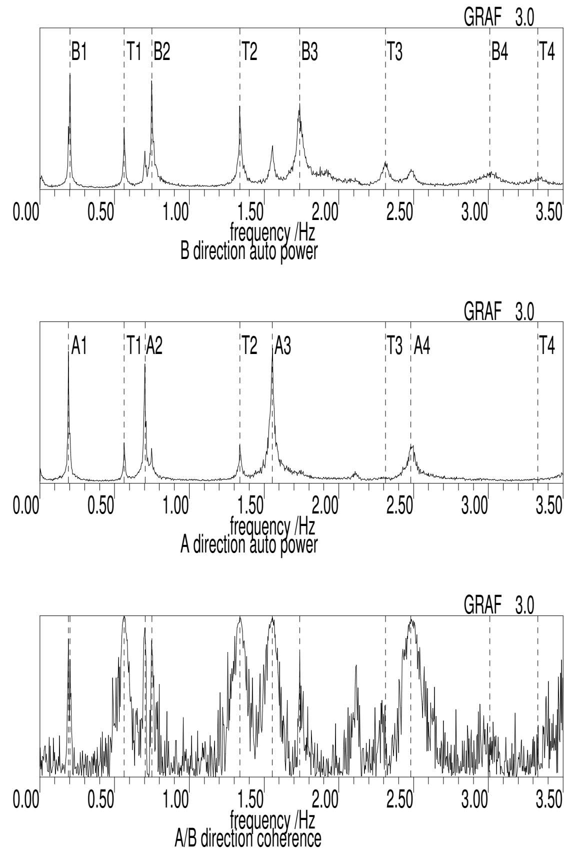


Figure 3 Auto spectra and coherence of A and B direction signals

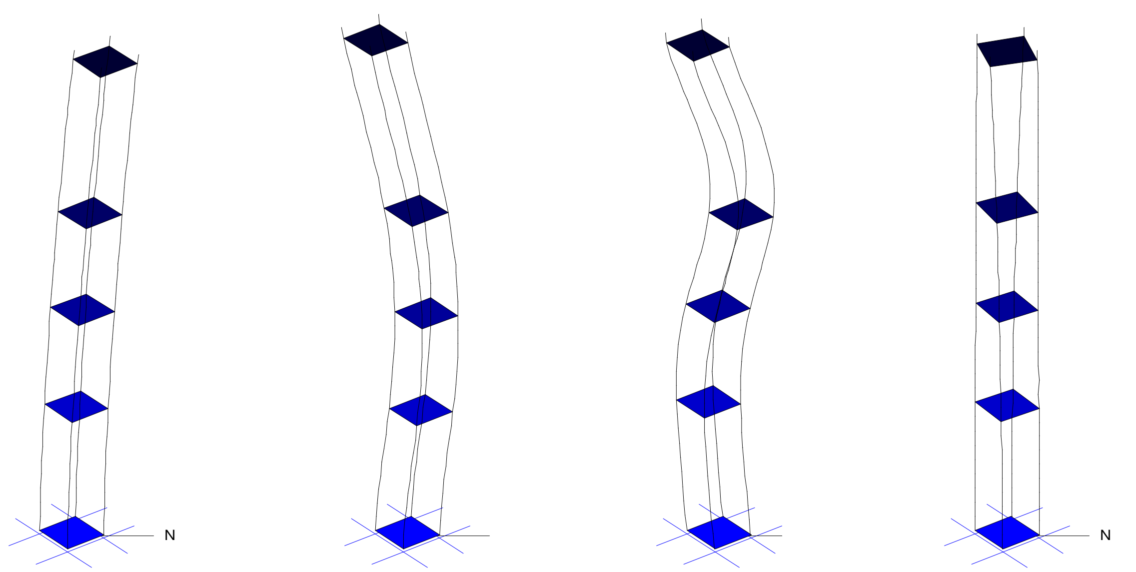


Figure 4 Modes A1, A2, A3 and T1 shapes

4. ANALOG DATA ACQUISITION SYSTEM

From October 1996 to the present, acceleration and wind signals have been recorded and analysed, with a few breaks due to equipment maintenance and system halt for data download or due to hardware faults. Except for the last two months of 1996, this part of the monitoring system comprised two pairs of accelerometers, one attached to the corner of the core wall at location 1 in Fig.2 at basement level (B1) and one vertically above on the top mechanical end electrical floor (65), and a pair of UVW anemometers, one at each corner of the roof parapet.. The accelerometers are connected by signal cable to a four channel signal conditioner comprising power supply, low pass filter, accelerometer offset adjust and amplification. The four conditioned acceleration signals and six anemometer signals feed directly into a sixteen channel acquisition system.

The accelerometers are Honeywell QA-700 servo accelerometers that have noise threshold of around 1 micro-g, can be run on very long cables without loss or noise corruption and generate current proportional to total (static+dynamic) acceleration that is dropped across a user supplied load resistor to provide adjustable gain. In 2001 the two level 65 accelerometers were replaced with units having temperature modeling to correct thermal drift using recorded internal temperature.

Wind and acceleration signals have been sampled in frames of 4096 samples acquired either at 7.5Hz (before 11/2001) or 8Hz (after 11/2001). In fact the data are over-sampled in short frames and decimated in order to benefit from the sharper cut off characteristic of digital filters in the acquisition software that was written in FORTRAN to drive a 12-bit AT-bus analog to digital converter card and process the data. The system uses double-buffering where one buffer is being written to while data from the other is being processed, involving calculation of FFTs and various statistical properties of the signals. Hence for every frame of approximately 9 minutes duration a set of parameters describing mean, total variance and narrow band RMS corresponding to known vibration modes are stored. In addition, when trigger conditions are met such that the signal contains interesting features, the frame of time series is saved to a compact binary file. Necessary trigger conditions relate only to the level 65 accelerometers and include strong broadband response as well as response in specific lower vibration modes. Modal RMS trigger levels are relative to a moving average of response so that weak signals can be captured against a weak background at night when building response due to both wind and internal machinery is very low.

Figs. 5, 6 and 7 show how the system detects and signals 'interesting' events: Total A and B direction 543-second RMS values are plotted in the top row of Fig. 5, the second row plots RMS contribution from modes A2 and B2 and the last row is mean wind total wind speed from two anemometers and the dots indicated triggered events. The strong total dynamic is due to wind; Fig. 6 zooms into one data point showing a triggered time series recording of strong wind and response. Fig. 7 corresponds to strong response in the second modes A2 and B2 (second row in Fig. 5), and the captured signal clearly demonstrates the cause as an earthquake (in Indonesia). Basement signals are shown in the top rows of Figs. 6 and 7; The basement hardly moves due to wind (Fig. 6) but indicates the local ground motion due to earthquakes (Fig. 7).

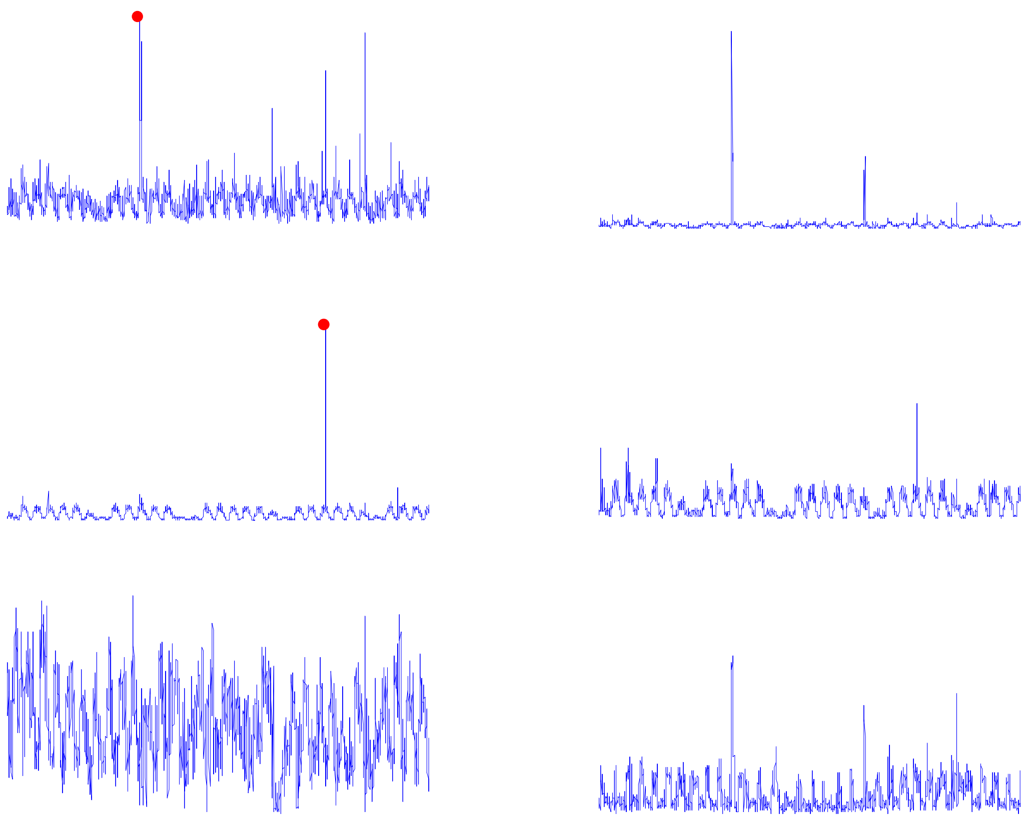


Figure 5 Acceleration and wind statistics for record during 1997

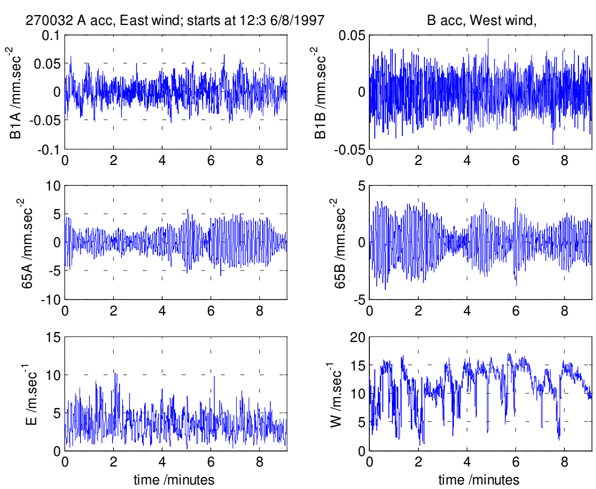


Figure 6 Strong wind during 1997

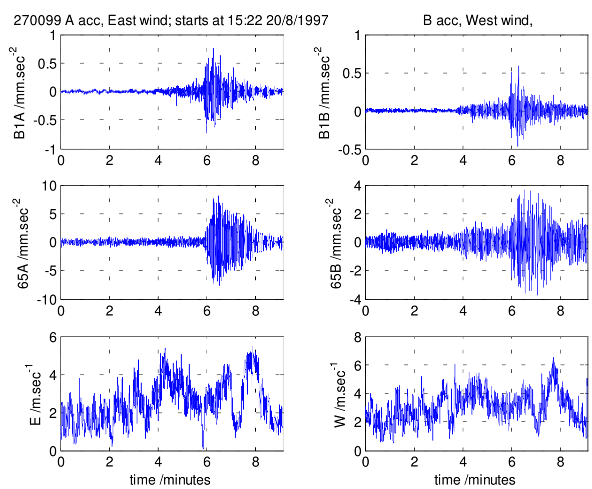


Figure 7 Remote earthquake

5. RECOVERY OF DYNAMIC DISPLACEMENTS BY INTEGRATION

Fig. 8 shows acceleration signals (units are gal, equivalent to 1cm/sec^2) recorded due to an earthquake in a distant part of Indonesia and the corresponding displacements obtained using a baseline correction and double integration procedure (x) incorporating a high pass filter with full and zero attenuation at 0.005Hz and 0.04Hz. From this and other events it is clear that ultra-long period oscillations of complete building and possible the whole of Singapore occur subsequent to the main shock, which itself survives as relatively low frequency components typically concentrated in the 0.5Hz-1.0Hz band, a feature that makes the mode 2 trigger mechanism very effective. The filter will not work at lower frequencies so the response at periods more than one or two minutes cannot be captured, if it exists. Such low frequency may be expected in response to wind, whose frequencies range down to DC. Even fierce tropical storms with sharply rising wind speeds are unlikely to generate quasi-static respone at such (relatively) high frequencies.

6. RECOVERY OF STATIC DISPLACEMENTS FROM MEAN ACCELERATION

Wind acts as a distributed lateral load with a height dependent profile that depends on the direction of the wind due to the surface roughness in the fetch before the building. Without direct measurements this profile can not be known, but wind codes offer such profiles backed up by wind tunnels studies. The ambient vibration survey served a very useful purpose of calibrating finite element studies of the building and the resulting validated model has been used to estimate the deflection of the building due to the assumed wind velocity profile normalised to a specific wind speed at the roof. The model demonstrates that the building behaviour lies between that of a cantilever and a shear building, such that a given loading profile, the lateral displacement is accompanied by a specific rotation. If this rotation is known the corresponding dislacement can be estimated. For example if building behaves as a perfect cantilever with a point load at the tip, the rotation α is related to deflection δ by $\delta = 2h\alpha/3$ where h is height. Since the accelerometers operate down to 0Hz (DC) a rotation of the accelerometer by a small angle α is sensed as a (mean) static acceleration $\ddot{x} = g \cdot \alpha$ so that deflection can be estimated from acceleration via $\delta = 2h\ddot{x}/3g$. Hence a 10mm.sec^{-2} mean acceleration can be interpreted as a static deflection of 188mm. For vibration in mode A1 (again assuming cantilever behaviour) a 10 mm.sec^{-2} acceleration amplitude corresponds to a 6.3mm deflection which, via the corresponding tilt equates to a negative acceleration of 0.33mm.sec^{-2} i.e. the translational accelerations are 3% higher than those recorded.

7. STATIC AND QUASI-STATIC RESPONSE TO TEMPERATURE AND WIND

A secondary cause of a shift in mean acceleration is thermal effects in the structure, and drifting of bias in accelerometers and signal conditioning. The accelerometers themselves have a temperature-dependent bias and gain, the latter having minimal effect due to the low mean value, while the thermal bias is generally less than 0.5mill-g per 10°C temperature variation.

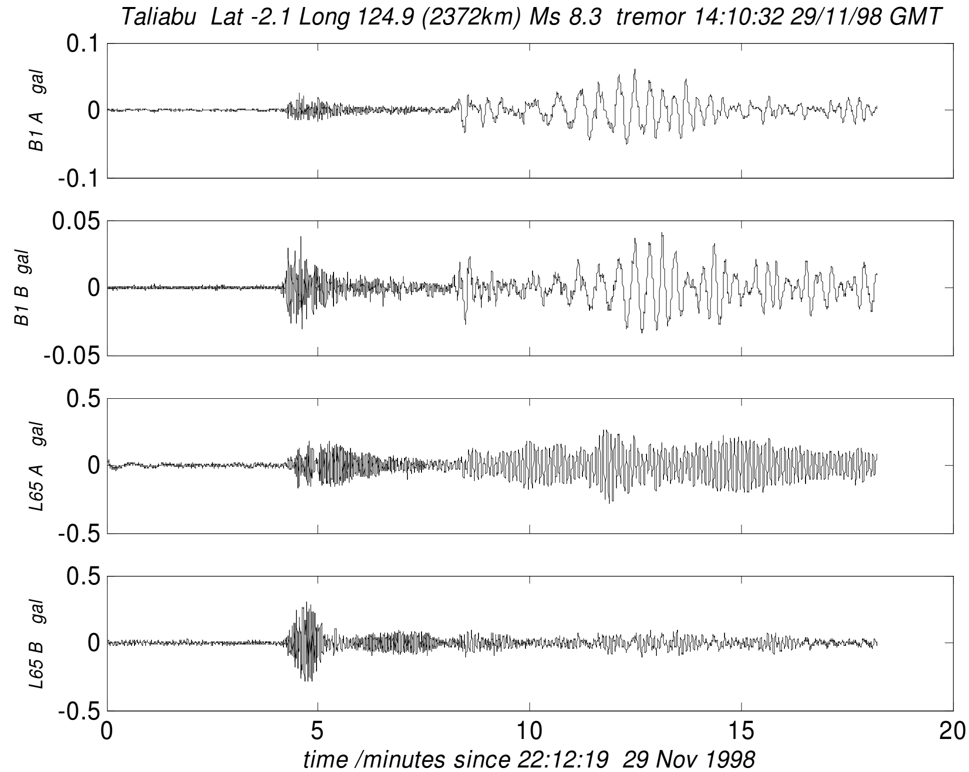


Figure 8 above: accelerations, below: displacements due to remote tremor

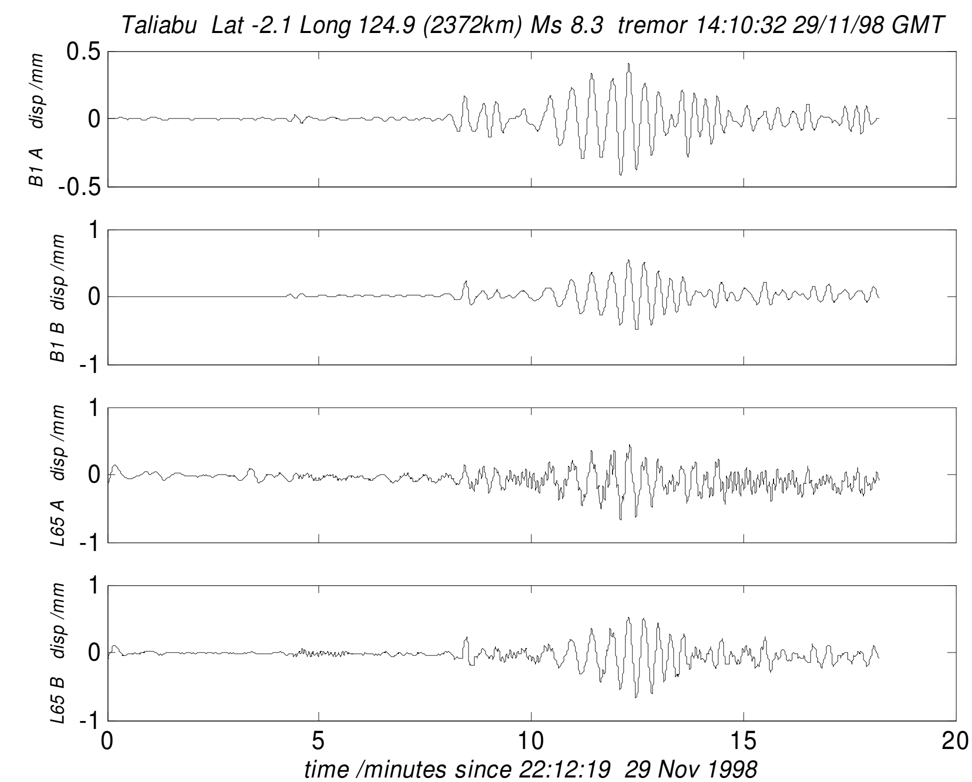


Fig. 9 shows the value of mean acceleration at level 65, converted directly to 'pseudo-displacement' on the assumption that the variations are all due to building tilt. The effect of a sudden strong wind appears to be seen as a discernible shift in mean value. The correlation with temperature in A direction is clear, for B direction it is relatively weak. Correction of thermal bias with manufacturer-supplied thermal modelling coefficients has little impact; the accelerometers are relatively exposed to the open area of level 65 which itself has vents to outside. There is a suspicion that temperature drop due to a strong wind may cause the variation in pseudo-displacement, yet any thermal effects on the acquisition system, which is well insulated, should generate a common effect on both channels. Hence it is still not clear if pseudo-displacement corresponds to real displacement and the answer is 'probably not'.

Figure 9 Pseudo-displacements and temperatures during March 2004

8. PEAK DYNAMIC RESPONSE IN EXTREME EVENTS

Building acceleration and displacement response at level 65 due to the Magnitude 8.0 Bengkulu (Indonesia) tremor and a storm having a 9-minute mean wind speed of 10m/sec gusting to over 21m/sec at the roof, are given in Fig. 10. These events both occurred in 2000, the values are in gals, equivalent to cm/sec^2.

Even for such a tall building the dynamic response to the tremor, ±48mm/sec^2, is far greater than for the wind which produced ±15mm/sec^2. The tremor response may have been even greater as the acquisition system (having range of +/-50mm.sec^{-2}) almost certainly clipped the high frequency components. Corresponding dynamic displacements, by integration, were respectively ±14mm and ±18mm. What is remarkable is that while, as expected, wind-induced response is dominated by first mode, the building response during the tremor was strongest in the second mode of vibration in each direction, although the aftershock generated strong first mode response (hence larger displacements). As with other tremors, basement input (not shown) concentrates within the 0.5Hz-1Hz band and there is a very low frequency (sub-modal) response where the whole building moves as a rigid body.

For tremors all the loading is dynamic, but for wind the loading comprises components due to the mean wind speed, non-resonant response to buffeting (turbulence) and resonant component. The ratio of total loading to the mean wind (static) component is expressed in modern codes by the factor $C_{dyn} = 1 + 2g_w I_u B\sqrt{1 + R^2/B^2}$ where g_w is a peak factor relating maximum velocity v_{peak} to standard deviation $\sigma(v)$, having a value in the range 3.0 to 3.7 for random gusts and I_u is turbulent intensity in along-wind direction. B is a background factor, less than or equal to 1, that accounts for lack of correlation of gusts over tall structures and R is a factor accounting for resonant amplification. Surprisingly, for typical high-rise buildings in Singapore, the reduction due to B approximately balances the additional response due to resonance and C_{dyn} may be little more than 2. Using the same logic, an approximate relationship between peak dynamic acceleration a_p and mean deflections $\bar{\delta}$ for a building with natural frequency f_o is $a_p = 2g_w \cdot I_u B(R/B) \cdot (2\pi f_o)^2 \bar{\delta}$ leading to a value $a_p/\bar{\delta}$ =0.64 for Republic Plaza, or for dynamic displacement, $\delta_p/\bar{\delta}$ =0.45, i.e. total displacement due to wind could be over three times the peak displacement obtained from integration of dynamic first mode response.

The total displacement response of the building is the sum of static response due to mean wind speed, dynamic response in first mode due to resonant amplification of the buffeting spectral load around first mode frequency, together with a non-resonant dynamic response. Resonant response can be measured, while the other components have so far eluded measurement except in a few incompletely reported studies (7). In addition there is possible sway due to themal expansion that may or not be mitigated by the mechanical and thermal insulation of the curtain wall, and the rigid body movement of the complete structure, foundation and all, due to distant tremors.

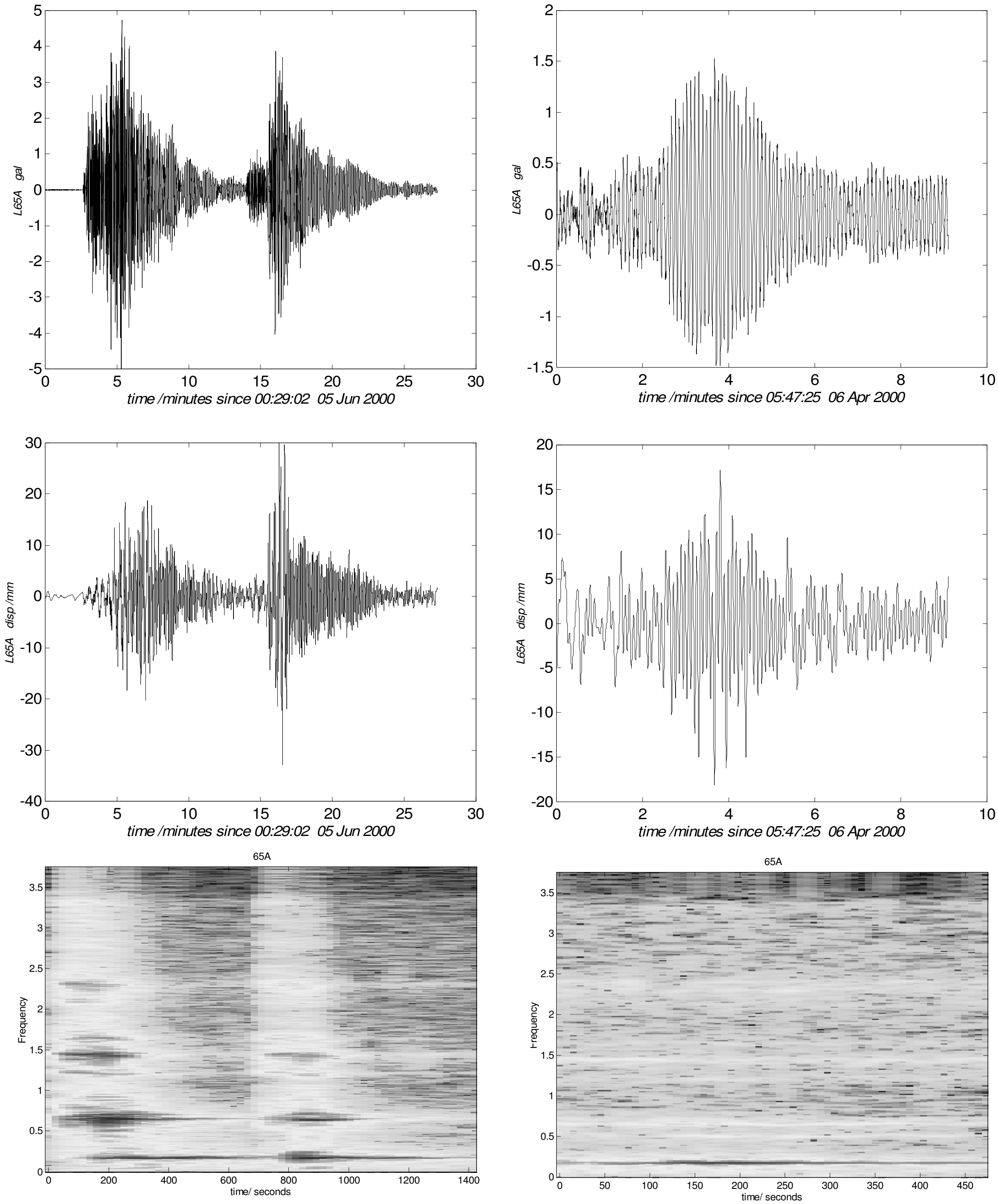


Figure 10 Acceleration (gal), displacement and time-frequency content for strong regional earthquake (left) and wind/rain storm (right).

9. PREDICTIONS OF WIND INDUCED RESPONSE

The ambient vibration survey of the building provided a means to validate finite element modelling of the structure, and this hase been used, together with estimates of pressure coefficints validated by wind-tunnel testing, to estimate the wind-induced response. For example, CP3[1] uses a 3-second gust, and taking (for Singapore) a relatively low value of 30m/sec provides an equivalent static response of 130mm in A (weak) direction. applying the more modern approach with the dynamic response factor C_{dyn} leads to responses of 39mm (mean) + 37mm (dynamic amplitude). For a more typical mean wind of 10 m/sec, the total peak response would be 13mm+13mm=26mm. The dynamic component is in line with the full-scale measurement (Fig. 10) during wind having a 10-minute mean speed of 10m/sec.

10. APPLICATION OF GPS TO TOTAL DISPLACEMENT MEASUREMENT

Clearly it is possible to recover displacements down to periods of around 1 minute, but at lower frequencies, it is uncertain if the changes in acceleration are due to static tilt and sway of the structure and how much is due to instrument effects. The only way to obtain absolute meaaurements of total displacement in the frequency range starting from absolute 0Hz and including the lower modes of dynamic response is GPS, which has previously[7] proved a capability of identifying performance in a low frequency, flexible, exposed structure by comparison with results available from other sources[8].

As the monitoring system for acceleration and wind load is already in operation, addition and synchronization of a GPS system provides a unique opportunity to operate the building ass a giant load cell. Fig. 11 shows one GPS antenna located on the building parapet adjacent to an ultrasonic anemometer. This is one of a pair of antennae located close to positions 2 and 3 as marked on Fig. 2. The units are set flush with the parapet in an attempt to reduce the chances of lightning strike (one antenna has already been replaced due to this). The base station that is a stable reference is located 10km distant and is used to provide correction signals to compensate for effects on signal transmission from satellites to the antennae.

Figure 11 GPS rover and anemometer

Given the known position of the base station and the location estimated by GPS signal transmission times, the differences (errors) are transmitted in real time to the units at Republic Plaza where a ‘real time kinematic’ (RTK) differential GPS solution is provided.

One problem is systems integration, synchronising the GPS receivers and RTK output with the existing system. The solution used is to convert RTK data, output as ASCII (NMEA) values to analog for input to extra channels on the existing analog system. At the same time the raw data (transmission times) are stored on all three Leica SR530 receivers and combined out of real time using the Ski-Pro software. These data are stored only on event trigger commanded by the analog system and it has been found that while quality indicators (variance values and satellite data) are lost in the RTK, the post-processed and real-time data appear sufficiently close to adopt the simpler RTK solution for practical use.

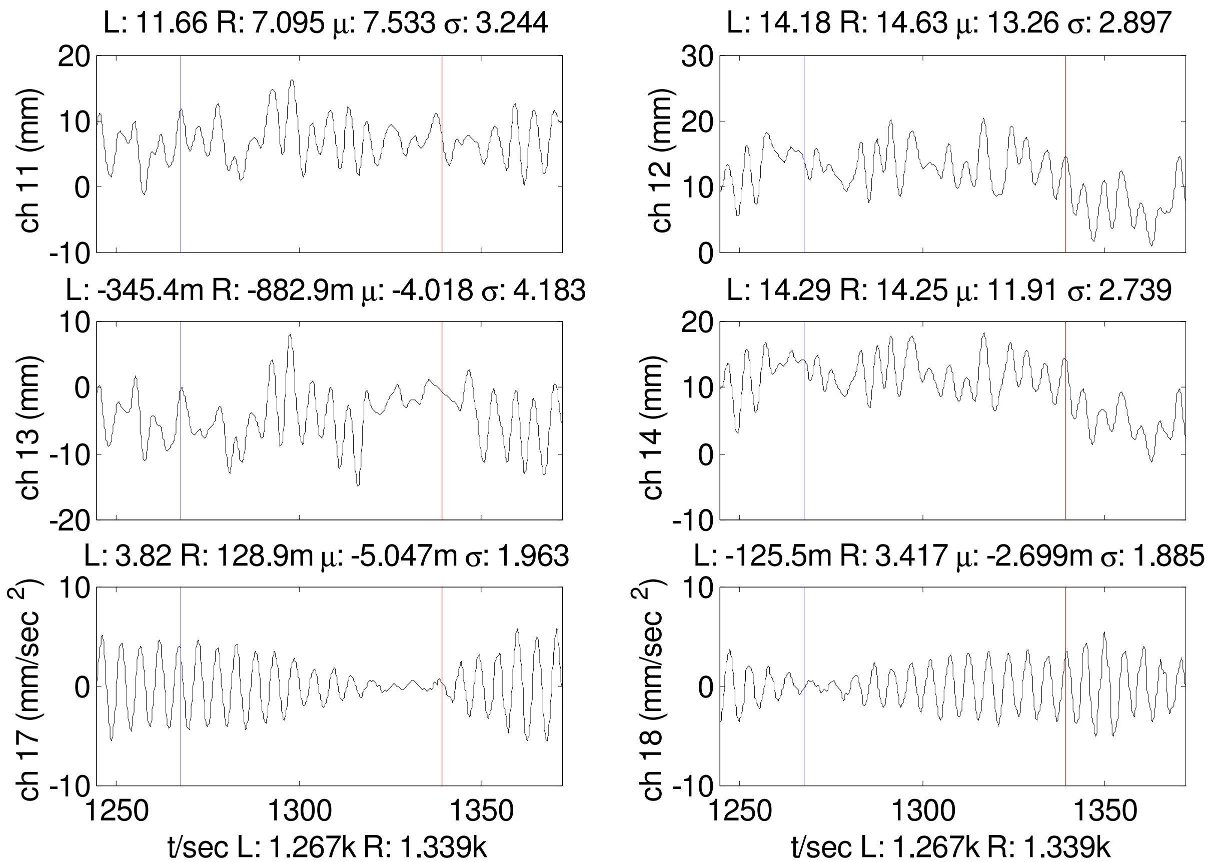
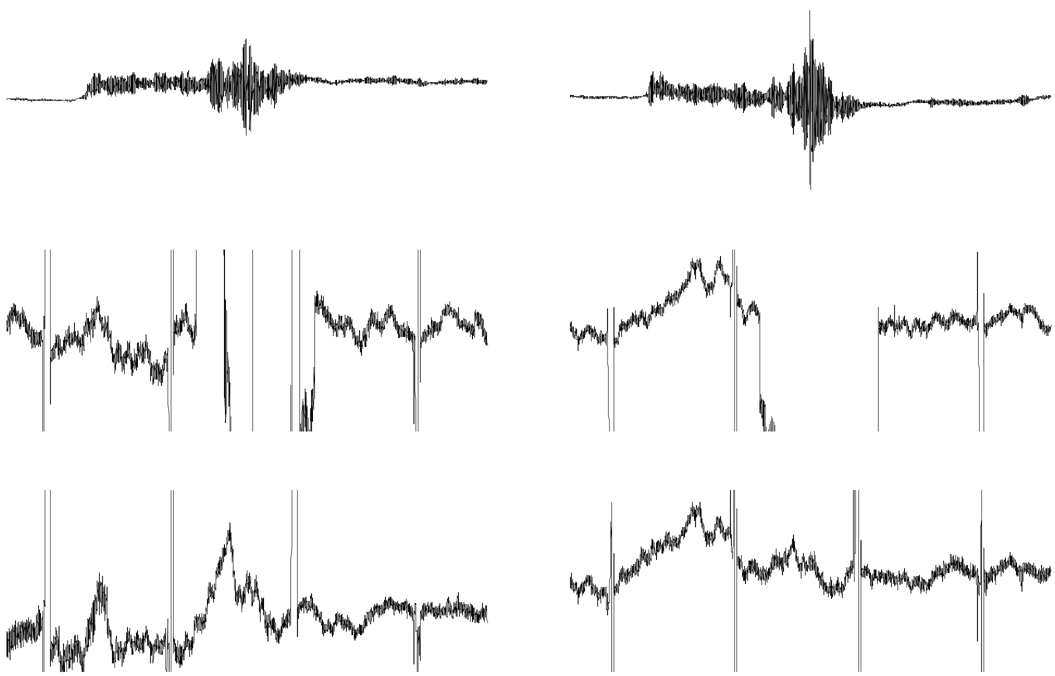


Figure 12 Response during strong wind. Easting (left) and Northings (right), GPS rover 1 and 2 top and second row respectively, acceleration third row.

Various problems such as overheating, power failures and landline reliability have prevented continuous long term operation but data collected in early 2003 and in the first half of 2004 have shown that the system is capable of identifying dynamic response of the building. Figure 12 shows time series obtained from accelerometers and GPS. The top two traces are from receiver 1, below is from receiver 2 and bottom is for accelerometers rotated into the same axes as the GPS.

Differences between receivers 1 and 2 show the level of noise yet the correspondence shows that the oscillations detected by the GPS, at around 3mm RMS, are real and indicate that the system can measure such small displacements. Note the lull in East and North directions at different times reflected in the GPS. The aim is not to identify vibration frequency (from the foregoing it is clear that accelerometers do a cheaper and far better job) but to identify absolute displacements that even careful integration of acceleration data cannot reveal.

Finally, Fig. 13 zooms into the response of Fig. 9 around day 14 during a wind storm. Acceleration signals show enhanced dynamic response plus sudden changes in mean value. GPS rover signals show movements of up to 150mm in an apparently linear manner not predicted by calculations or matched in the mean aceleration, and there is a suggestion of drifting and ratcheting in the response. The noise in the GPS is due to correction transmission loss, and as the uncorrupted record could be recovered from the saved raw data.



11. CONCLUSIONS

From study of dynamic response of one tall building in Singapore, surprising results have been obtained about the relative importance of seismic and wind loading. Attempts to identify the magnitude of the static component of these response have involved integration of acceleration, interpretation of mean acceleration as tilt and finally, use of a dual-rover GPS system Despite all these procedures more questions have been raised than have been answered about the nature and causes of the quasi-static movements of the building. Only long-term study and correlation between various recorded loads and effects will provide the understanding of the mechanisms at work.

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BIOGRAPHICAL NOTES

Professor Brownjohn begun his acadmic career at Bristol University in 1984, working on systems for operating and managing data from the EPSRC earthquake simulator and managing full-scale vibrtion survey and health monitoring exercise on several dams and suspension bridges around the world. Moving to Singapore in 1992 he developed monitoring systems for three large structures and conducted full-scale static and dynamic performance assessment studies on a large range of civil structures. He returned to a chair in structural engineering at Plymouth in February 2004. He is member of insitutions of mechanical and structural engineers and has published widely on a range of topics related to full-scale structural performance.

CONTACT

Professor James MW Brownjohn
University of Plymouth
007 Reynolds, School of Engineering, Drake Circus,
Plymouth PL4 8AA UNITED KINGDOM
Tel. +44 1752 233673
Fax + 44 1752 232638
Email: james.brownjohn@plymouth.ac.uk
Web site: http://plymouth.ac.uk/staff/jbrownjohn