Measurement of wind-induced response of buildings using RTK-GPS and integrity monitoring

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ABSTRACT: An RTK-GPS (Real Time Kinematic – Global Positioning System) has a nominal accuracy of ±1cm +1ppm for horizontal displacements with a sampling rate of 10Hz. It was found to be suitable for measuring building responses when the vibration frequency is lower than 2Hz and the vibration amplitude is larger than 2cm. The object of this study was to measure the wind-induced response using RTK-GPS and to study the feasibility of hybrid use of FEM analysis and RTK-GPS for confirming the integrity of structures during strong typhoons. It is shown that RTK-GPS can measure not only dynamic components but also static components and quasi-static components. The member stresses obtained by hybrid use of FEM analysis and RTK-GPS were close to the member stresses measured by strain gauges.

KEYWORDS: RTK-GPS, Static displacement, FEM, Integrity monitoring, Steel tower

1 INTRODUCTION

Accelerometers have been used for field measurements of wind-induced responses of buildings. However, wind-induced responses consist of a static component, i.e. a mean value, and a dynamic fluctuating component. The static component is difficult to measure with accelerometers. Çelebi[1] proposed the use of RTK-GPS for measurements of building responses. An RTK-GPS (Leica MC1000) has a nominal accuracy of ±1cm +1ppm for horizontal displacements and ±2cm +2ppm for vertical displacements with a sampling rate of 10Hz[2]. Considering the static component and the first mode predominance for wind-induced responses, GPS is better for wind-induced response measurements. According to the feasibility study of RTK-GPS for measuring wind-induced responses of buildings, responses with amplitudes larger than 2cm and natural frequencies lower than 2Hz can be detected by RTK-GPS[3][4][5].

The object of this paper is to demonstrate the efficiency of RTK-GPS in measuring the displacement of a full-scale tower and to study the feasibility of hybrid use of FEM analysis and RTK-GPS for detecting the integrity of structures during strong typhoons.

2 WIND-INDUCED RESPONSES OF HIGH-RISE STEEL TOWER

2.1 *Outline of field measurements*

The field measurements were performed on a high-rise steel tower belonging to the Urban Development Corporation. As shown in Figure1, an anemometer, an RTK-GPS antenna and accelerometers were set on the top of a 108m-high steel tower, and another RTK-GPS antenna erometers were set on the top of a 108m-high steel tower, and another RTK-GPS antenna was set as the reference point on top of a rigid 16m-high RC building next to the tower. In addition, to measure member stresses, strain gauges were set in the base of the tower. Before measurement, the zero-position was carefully defined as the mean value of almost three months of data. These data satisfied the following condition to minimize the wind and solar heating effects: PDOP less than 1.5, mean wind speed less than 1m/s and the data from 0:00am – 5:00am.

2.2 *Wind-induced responses during Typhoon 0221*

Figure 2 shows the temporal variations of wind and response data every 10min during Typhoon 0221. The wind direction was mostly NNW – NW when the typhoon came closest, and the wind speed reached its maximum, as shown in Figure 2(a). The maximum wind speed was about 22m/s and the peak gust wind speed was about 30m/s, as shown in Figure 2(b). The acceleration data shown in Figure 2(c) varies following the variation of wind speed shown in

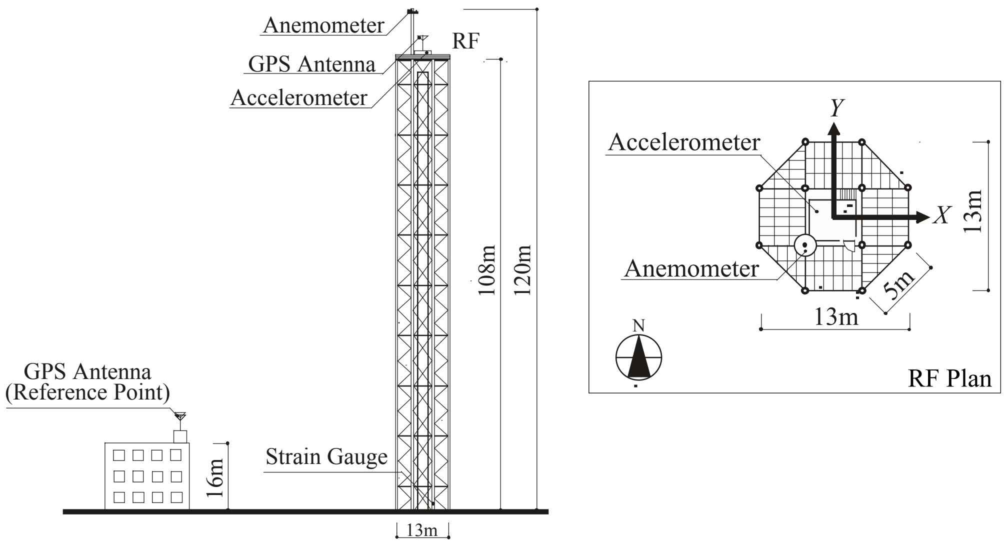
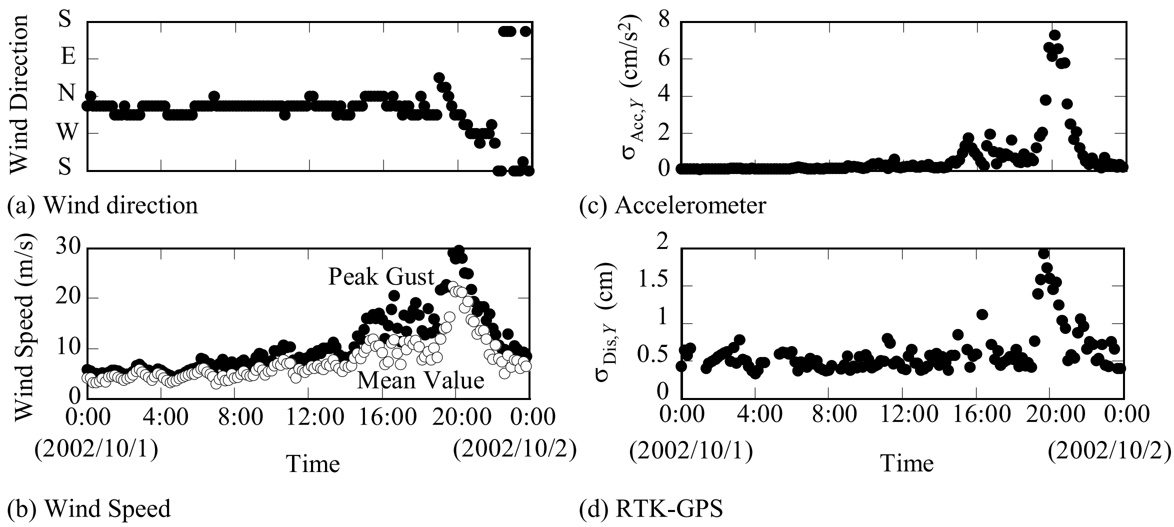


Figure 1. A 108m high steel tower for full-scale measurements



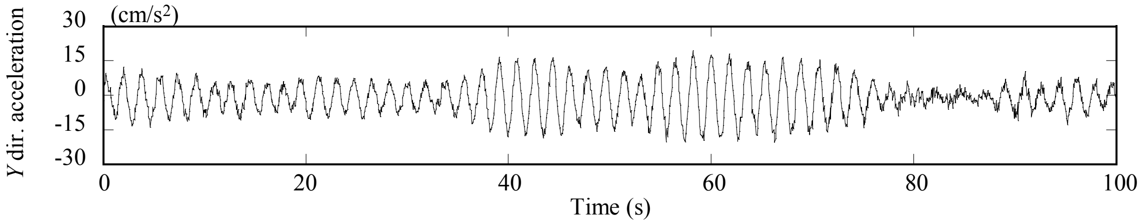
(a) Wind direction
(c) Accelerometer
(b) Wind Speed
(d) RTK-GPS

Figure 2. Temporal variations of 10 min mean values of wind speed and response of the tower.

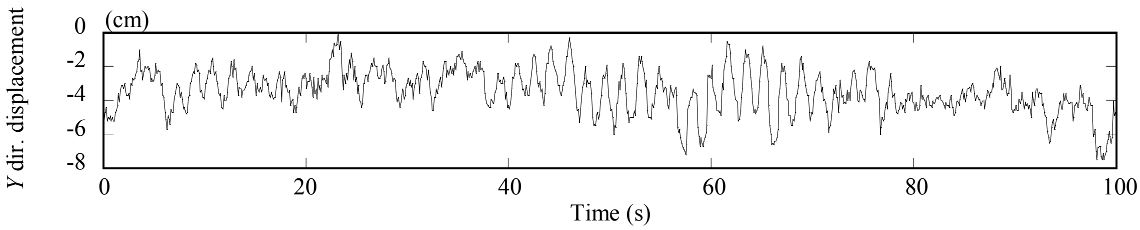
Figure 2(b), and the RTK-GPS displacement shown in Figure 2(d) also follow the variation of acceleration data. Here, only the RTK-GPS data obtained under the conditions of PDOP less than 3 were analyzed. Figure 3 shows an example of the temporal variation of the tower's response in the *Y*-direction, which coincides with wind direction NW when the typhoon was located closet to the site. The RTK-GPS data is the sum of the static displacements of about 4cm, the fluctuating component with a long period, i.e. about 20 seconds, and that with a dominant frequency equal to the lowest natural frequency of 0.57Hz. The acceleration record seems to correspond closely to the predominant frequency component of the displacement by RTK-GPS.

Figure 4 shows an example of the tip displacement and acceleration locus showing static component and fluctuating component. The RTK-GPS could measure not only dynamic components but also static components of about 5cm corresponding to wind direction.

Figure 5 shows the power spectrum densities of the tip responses. The power spectral density of the acceleration was converted to that of displacement multiplied by $(2\pi f)^{-4}$ for comparison with the displacement by the RTK-GPS. For *X* direction response as shown in Figure 5(a), there are two peaks, and the accelerometer and RTK-GPS results show the same tendency. Both spectra in Figure 5(b) have a peak at 0.57 Hz corresponding to the lowest natural frequency of the tower.

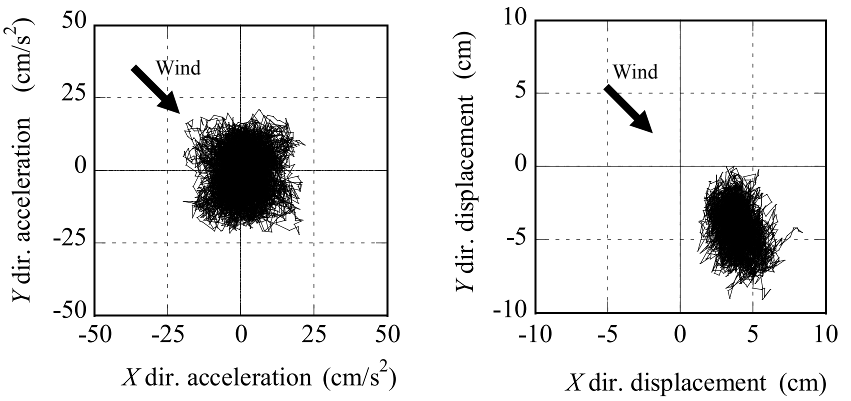


(a) Accelerometer



(b) RTK-GPS

Figure 3. Examples of temporal variations of wind-induced responses of the tower during Typhoon 0221.



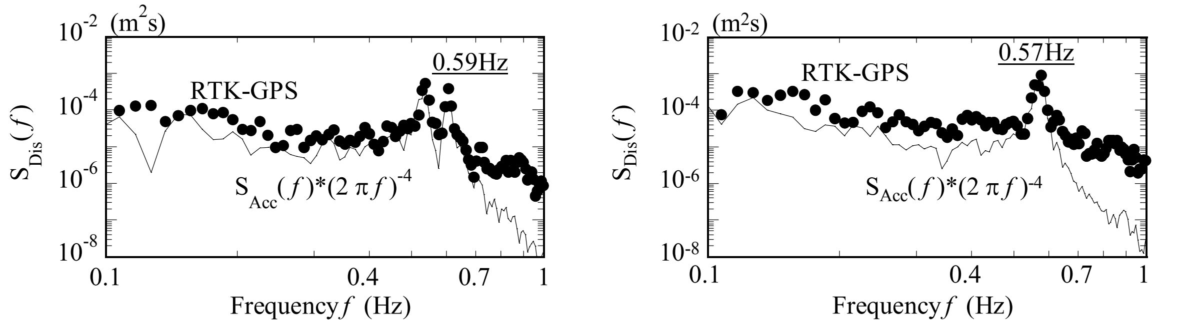
(a) Accelerometer (b) RTK-GPS

Figure 4. Example of tip locus during Typhoon 0221

However, those of the displacement by the RTK-GPS show almost constant energy in the higher frequency range, which is attributed to the background noise of the RTK-GPS in both figures.

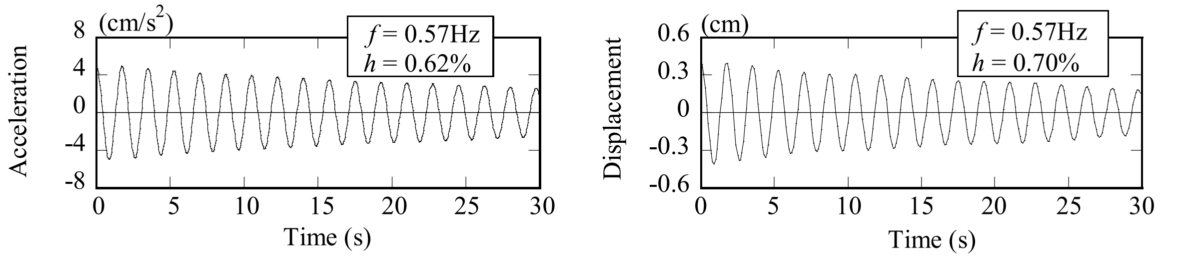
The vibration characteristics are estimated by the RD technique. Figures 6(a) and (b) show the random decrement signature obtained by this technique from the acceleration record and the RTK-GPS displacement record in the *Y* direction, respectively. The damping ratio and the natural frequency were estimated using the least square fitting to a SDOF system. The lowest natural frequency was estimated at 0.57Hz for both cases. The damping ratio was estimated at 0.62% for the acceleration record and 0.70% for the RTK-GPS displacement.

Since the RTK-GPS can measure the static displacement, the deformation of the tower caused by the solar heating effect could also be detected. Figure 7 shows the tower deformation caused by solar heating on a calm and clear day. Each plot indicates the preceding hour's mean displacement with time. Just after sunrise, the tower began to move about 4cm in the NW direction. The top of the tower moved in an almost circular shape in the daytime, and returned to its zero point after sunset.



(a) X direction (EW dir.) (b) Y direction (NS dir.)

Figure 5. Power spectra of tip displacement during Typhoon 0221.



(a) Accelerometer (*Y* direction) (b) RTK-GPS (*Y* direction)

Figure 6. Random decrement signature obtained by RD technique.

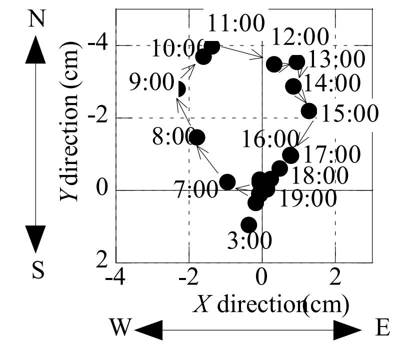


Figure 7. Tower deformation caused by solar heating effect

3 FEM ANALYSIS OF TOWER

An FEM tower model based on the design documents was created in the computer. SAP2000 was used for the FEM analysis. The total mass of the upper structure was 7.3×10^5 kg. The 1st mode natural frequency of the FEM model was calculated to be 0.57Hz: exactly the same as the full-scale result. The lowest three modes of the FEM model for the X direction are shown in Figure 8. In addition, ambient vibration tests were performed to investigate the vibration characteristics of the tower using the FDD (Frequency Domain Decomposition) method [6][7]. The lowest three modes obtained by FDD are also shown in Figure 8. These results show good agreement.

Figure 9 indicates the relation of the mean displacements obtained by GPS and FEM analysis. In the FEM analysis, mean wind force F_z at height z was evaluated from $F_z = \rho U_z^2 CA/2$, where the mean wind speed U_z was estimated assuming a power-law index $\alpha = 0.2$, and the wind force coefficient C was estimated from the following equation [8].

$$C = 4.0\phi^2 - 5.9\phi + 4.0 \tag{1}$$

Here, ρ is air density, A is projected area, and ϕ is solidity ratio (in this case, ϕ =0.65). Figure 9 shows good agreement between the FEM analytical result and the GPS full-scale results, although the full-scale results are somewhat scattered. The GPS displacement used for the analysis satisfied the following conditions: most frequent wind direction is N and the weather is cloudy or rainy day due to a minimized the solar heating effect.

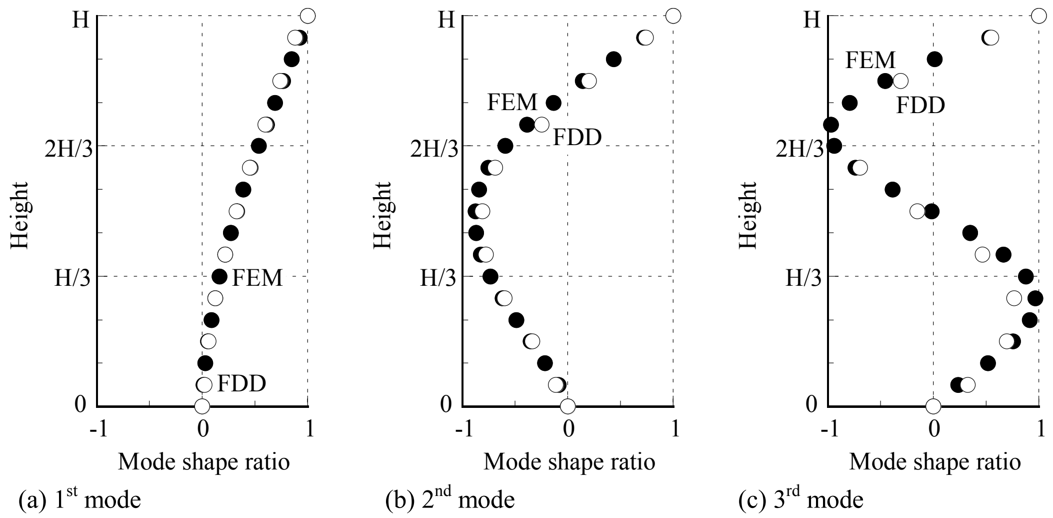


Figure 8. Mode shapes obtained by FEM and FDD

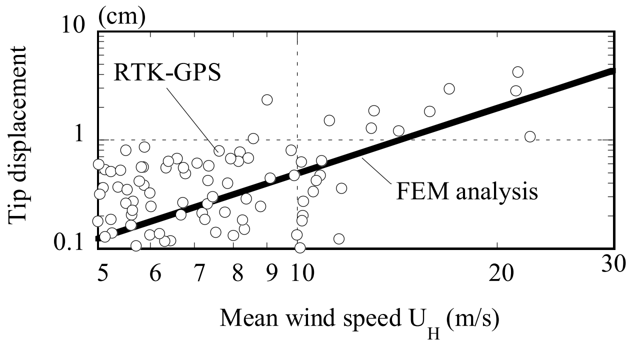


Figure 9. Changes of mean tip displacement by mean wind speed

4 HYBRID USE OF FEM ANALYSIS AND RTK-GPS FOR INTEGRITY MONITORING

The above results encourage us to evaluate the member stresses by hybrid use of FEM analysis and RTK-GPS to create a real time monitoring system to establish the tower's integrity. The tip displacement obtained by GPS can be easily converted into member stresses based on the FEM analysis as shown in Equation 2 and Figure 10.

$$\sigma = \sigma_{x_{DIS}=1} \times x_{GPS} + \sigma_{y_{DIS}=1} \times y_{GPS} \tag{2}$$

Where σ is member stress by hybrid use of FEM analysis and GPS (only for axial forces), $\sigma_{x(y)_{DIS=1}}$ is member stress calculated by FEM analysis when tip displacement is 1 cm for $x(y)$ direction, $x(y)_{\mathrm{GPS}}$ is tip displacement measured by RTK-GPS.

The system can monitor the stresses in all members during typhoons, and can even send out a warning if one of the member stresses exceeds an allowable level. For example, the stresses in members at the tower base shown in Figure 11 were calculated from the temporal variation of the GPS tip displacement. Figure 12 shows the temporal variations of stresses measured by strain gauges and virtually monitored by hybrid use of the FEM and RTK-GPS. The results shown in Figure 12 are member stresses converted from GPS displacement during Typhoon 0221. They don't include the stresses caused by tower dead load. These members, i.e. inner column, outer column and diagonal member shown in Figure 11, were compressive members as shown in Figure 12. Reflecting the fluctuation of wind forces, the outer column stresses (Figure 12(a)) and diagonal member stresses (Figure 12(b)) fluctuated. However, the inner column stresses (Figure 12(c)) fluctuated much less than the outer column and diagonal member, and it bore mainly vertical load. They show good agreement with member stresses obtained from strain gauges and hybrid use of FEM analysis and GPS.

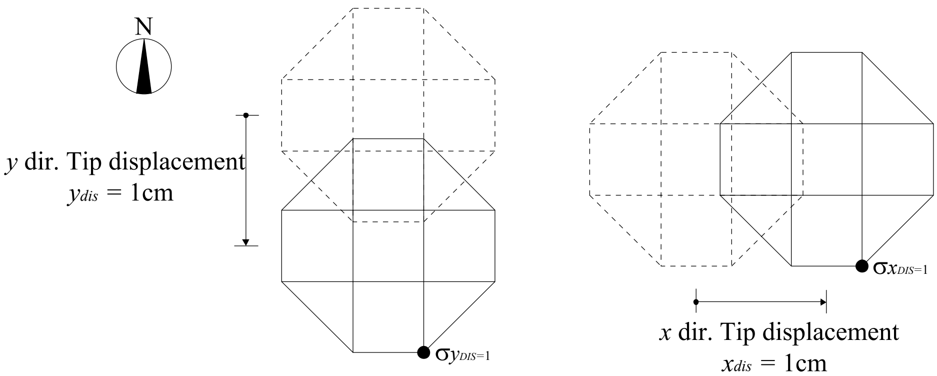


Figure 10. Solution of member stresses by hybrid use of FEM analysis and GPS (for "Outer column")

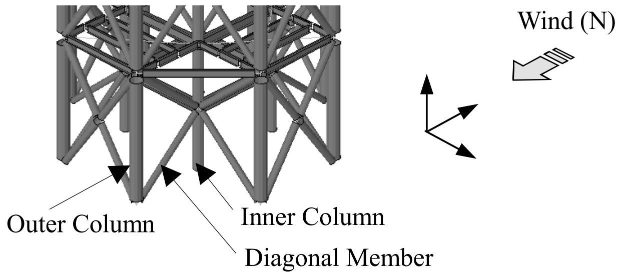
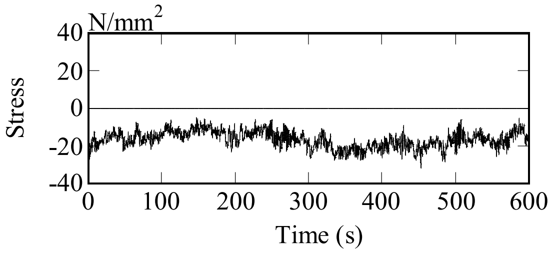
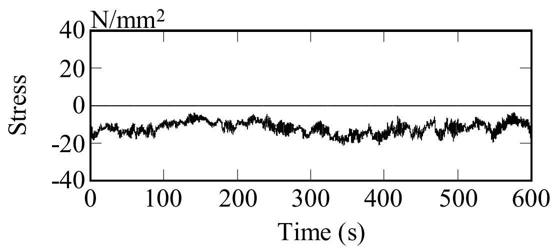


Figure 11. Members detected by hybrid use of FEM analysis and RTK-GPS

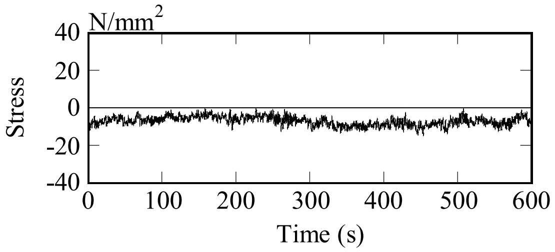


(a1) Strain gauge

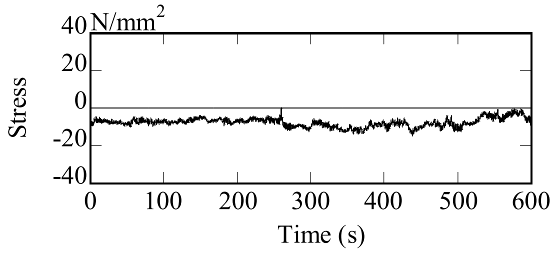


(a2) FEM & GPS

(a) Stresses in outer column

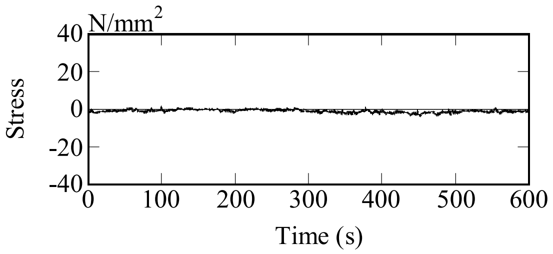


(b1) Strain gauge

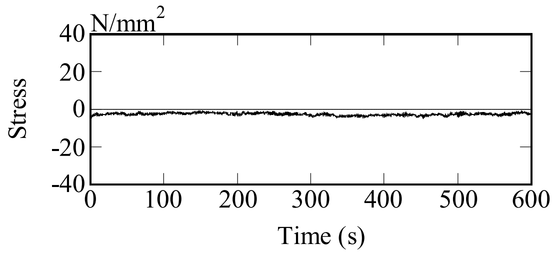


(b2) FEM & GPS

(b) Stresses in diagonal member



(c1) Strain gauge



(c2) FEM & GPS

(c) Stresses in inner column

Figure 12. Temporal variations of stresses by field measurement and hybrid use of FEM analysis and RTK-GPS

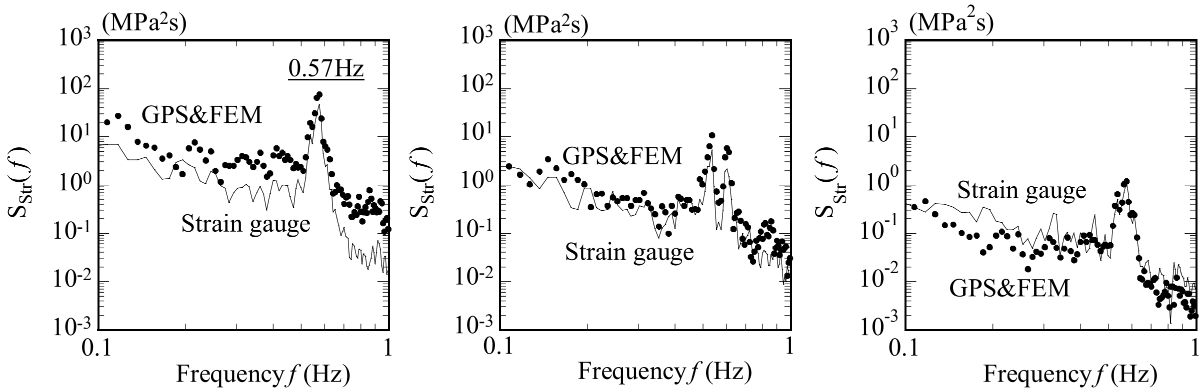
Figure 13 shows the power spectrum of member stresses obtained by strain gauges and hybrid use of FEM analysis and GPS. For the power spectrum of stresses in the outer column as shown in Figure 13(a), that by hybrid use of FEM analysis and GPS showed higher energy in all parts than that by strain gauge. However, for the power spectrums of stresses in the diagonal member (Figure 13(b)) and in the inner column (Figure 13(c)), that by strain gauge and that by hybrid use of FEM analysis and GPS showed good agreement.

Figure 14 shows changes of stresses in the outer column with changes in mean wind speed. As shown, changes in mean stresses become large when mean wind speed becomes large. The results of strain gauge and hybrid use of FEM analysis and GPS show fairly good agreement. When mean wind speed is less than about 10m/s, R.M.S values of stresses in the outer column by hybrid use of FEM analysis and GPS are almost constant and are higher than those by strain gauge. This is considered to be due to the background noise of RTK-GPS[3][4][5].

5 CONCLUSION

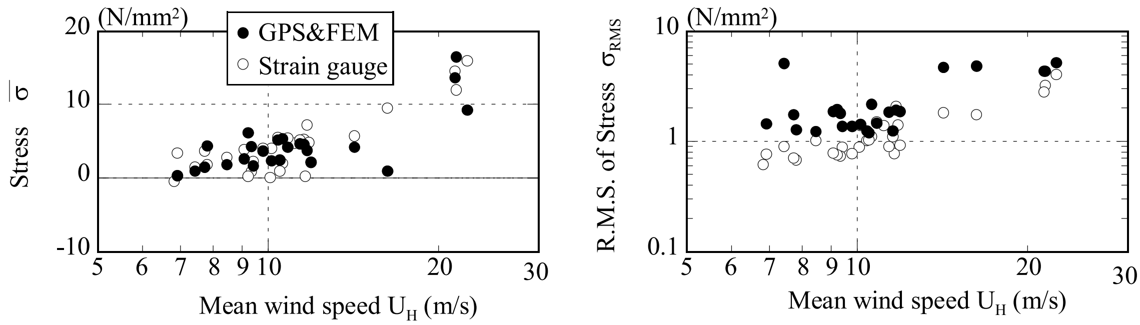
The RTK-GPS system was able to measure not only the dynamic components but also the static component and quasi-static components of the wind-induced responses of a high-rise steel tower.

Using FEM results and displacement by GPS, member stresses could be monitored in real time for integrity monitoring.



(a) Outer column (b) Diagonal member (c) Inner column

Figure 13. Power spectrum of member stresses during Typhoon 0221



(a) Mean value of stresses (b) R.M.S. of stresses

Figure 14. Changes of stresses of outer column by mean wind speed.

REFERENCES

1 M. Çelebi, GPS and/or strong and weak motion structural response measurements - Case studies, Structural Engineering World Congress ‘98, San Francisco, Conference Proceedings on CD-ROM, 1998, T193-1, pp.8

2 Y. Tamura, M. Matsui, M. Uchiyama, K. Hibi and K. Ishihara, Feasibility study on observation of wind induced building responses by real-time-kinematic GPS - to construct comprehensive urban disaster prevention system, Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, 1999, B-1, 203-204 (in Japanese)

3 Y. Tamura, A proposal of simultaneous monitoring of responses of tall buildings in an urban area during strong winds and earthquakes using GPS - Construction of a new disaster prevention system, Research in Architecture, 2000, 1-7 (in Japanese)

4 Y. Tamura, M. Matsui, L.C. Pagnini, R. Ishibashi and A. Yoshida, Measurement of wind-induced response of buildings using RTK-GPS, Journal of Wind Engineering and Industrial Aerodynamics, 90 (2002) 1783-1793

5 Y. Tamura, A. Yoshida, R. Ishibashi, M. Matsui and L.C. Pagnini, Measurement of wind-induced response of building using RTK-GPS and integrity monitoring, Proc. 2nd Int. Symposium on Advances in Wind & Structures, 2002, pp. 599-606.

6 R. Brincker, L.-M. Zhang and P. Anderson, Modal Identification from Ambient Response using Frequency Domain Decomposition, Proc. of the 18th IMAC, San Antonio, TX, USA, 2000, T1-1-1a

7 Y. Tamura, L.-M. Zhang, A. Yoshida, S. Nakata and T. Itoh, Ambient Vibration Tests and Modal Identification of Structures by FDD and 2DOF-RD Technique, Proc. of the 18th IMAC, San Antonio, TX, USA, 2000, T1-1-1b

8 ASCE Standard, Minimum Design Loads for Building and Other Structures, 2000