MEASUREMENT OF WIND-INDUCED RESPONSE OF BUILDINGS USING RTK-GPS AND INTEGRITY MONITORING

*Yukio Tamura[1], Akihito Yoshida[2], Ryukichi Ishibashi[3],
Masahiro Matsui[4] and Luisa Carlotta Pagnini[5]

1) 2) 4) Tokyo Institute of Polytechnics, Atsugi 243-0297, Japan
3) Urban Development Company, Hachiouji 192-0032, Japan
5) University of Genoa, Genoa, Italy

ABSTRACT

An RTK-GPS (Leica MC1000) has a nominal accuracy of ±1cm +1ppm for horizontal displacements with a sampling rate of 10Hz. The object of this paper is to demonstrate the feasibility of RTK-GPS for wind-induced response measurements and its efficiency 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. The efficiency of RTK-GPS is demonstrated in the full-scale measurement of an actual steel tower. According to the feasibility study of RTK-GPS for measuring wind-induced responses of buildings, the responses with amplitudes larger than 2cm and natural frequencies lower than 2Hz can be detected by RTK-GPS. Hybrid use of RTK-GPS and FEM analysis for real time monitoring of the integrity of structures is proposed and its efficiency is demonstrated.

INTRODUCTION

Wind-induced response consists of a static component, i.e. a mean value, and a dynamic fluctuating component. The static component is difficult to measure with accelerometers, which have been generally used so far. Çelebi (1998) proposed the use of RTK-GPS (Real-Time Kinematic Global Positioning System) for measurements of dynamic responses of buildings. 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 (Tamura et al., 1999,

1) Professor 2) Research Associate 3) Senior Researcher
4) Associate Professor 5) Associate Professor

2000, 2001). Considering the static component and the first mode predominance for wind-induced responses, GPS is better for wind-induced response measurements. The objects of this paper are to study the feasibility of RTK-GPS for wind-induced response measurements and to demonstrate its efficiency in measuring the displacement of a full-scale tower. Then, hybrid use of RTK-GPS and FEM analysis for real time integrity monitoring of structures is proposed.

PRINCIPLE OF RTK-GPS

GPS surveys the distance from a certain point on the earth to a GPS satellite by measuring the exact traveling time of an electric wave transmitted from the satellite to an antenna at the measuring position. GPS generally requires 4 satellites to obtain the information of 3 components at a position (X,Y,Z) and the time. However, RTK-GPS requires one more satellite for real-time high-frequency (10Hz) measurements. There are many causes for errors, e.g. PDOP (position dilution of precision), clock and orbit errors of satellites, ionosphere and troposphere delays, multi-path and so on. However, if two antennas relatively close to each other in the global scale receive the same electric waves from the same satellites simultaneously, the error sources should be the same. Therefore, if the position of one of the two points, i.e. the reference point, is fixed and exactly known, the error of the GPS survey can be accurately detected at any moment. If the error information obtained at the reference point is immediately transmitted as a correction signal to the other point, i.e. moving measuring point, the error of the position survey of the measuring point can be minimized. This is the outline of the position survey by RTK-GPS.

ACCURACY OF RTK-GPS

Before full-scale measurement of an actual tower's response, the basic characteristics of RTK-GPS were examined.

The background noise of the RTK-GPS survey was first examined. The GPS antennae not only at the reference point but also at the measuring point were fixed on the roof of a rigid 3-story RC building. Figure 1 shows an example of the10-min mean of the stationary point. The 10-min mean value fluctuated ±5mm, which can be thought to be the background noise of the RTK-GPS monitoring. It should be noted that the background noise was influenced by PDOP, which depends on the geometrical arrangement of the satellites.

The accuracy of RTK-GPS in measuring sinusoidal displacements was next examined, using an electronic exciter. Figure 2 shows the set-up of the sinusoidal vibration tests. A GPS antenna was mounted on the exciter, and a wire displacement transducer was set to accurately measure the displacement. Figure 3 compares the temporal variations of the displacements measured by RTK-GPS and the wire displacement transducer. When the vibration frequency was lower than 2Hz and the vibration amplitude was larger than 2cm, RTK-GPS results seemed to closely follow the actual displacement.

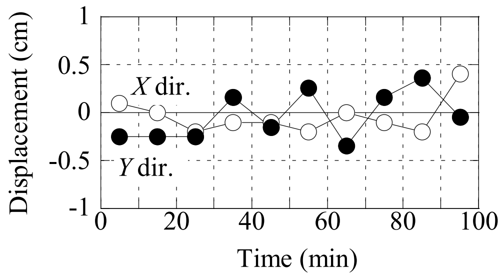


Fig.1 10-min average of GPS signal at the stationary point

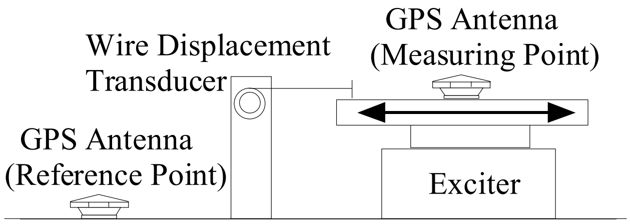
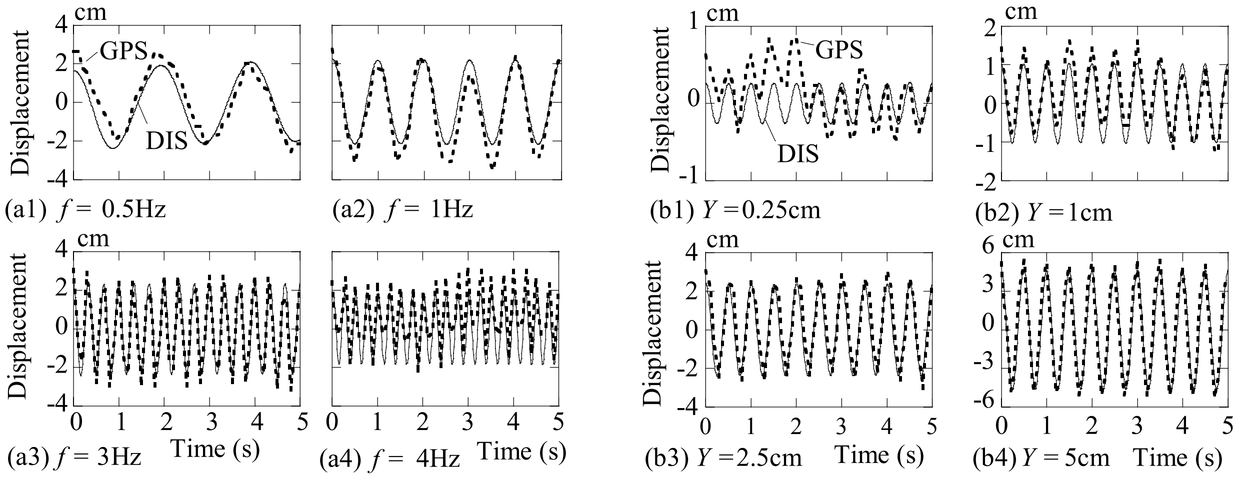


Fig.2 Sinusoidal vibration tests using an exciter



(a) Amplitude $Y = 2$cm (b) Frequency $f = 2$Hz

Fig.3 Comparison of RTK-GPS output and actual displacement by displacement transducer

MEASUREMENTS OF WIND-INDUCED RESPONSES OF AN ACTUAL TOWER.

As shown in Fig.4, an anemometer, an RTK-GPS antenna and accelerometers 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. 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 2, mean wind speed less than 1.5m/s, and the data from 2:00am – 5:00am. Figure 5 shows the temporal variations of the wind and the response data every 10min during Typhoon 0115. The wind direction was almost N, which corresponds to the *Y*-direction, when the typhoon came closest and the wind speed was reaching its maximum. The acceleration data shown in Fig.5(c) varies following the variation of wind speed shown in Fig.5(b), and the RTK-GPS displacement shown in Fig.5(d) also follows the variation of acceleration data. Here, only the RTK-GPS data obtained under the conditions of PDOP less than 2.5 were analyzed. Figure 6 shows an example of the temporal variation of the response of the tower in the Y-direction, which coincides with wind direction N 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 7 shows an example of the tip displacement locus, showing static component and fluctuating component.

Figure 8 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

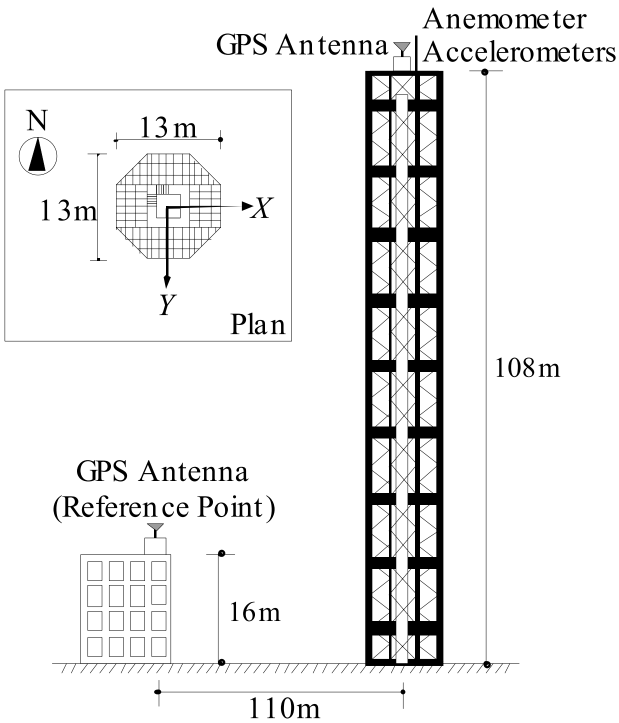


Fig.4 A 108m high steel tower for full-scale tests

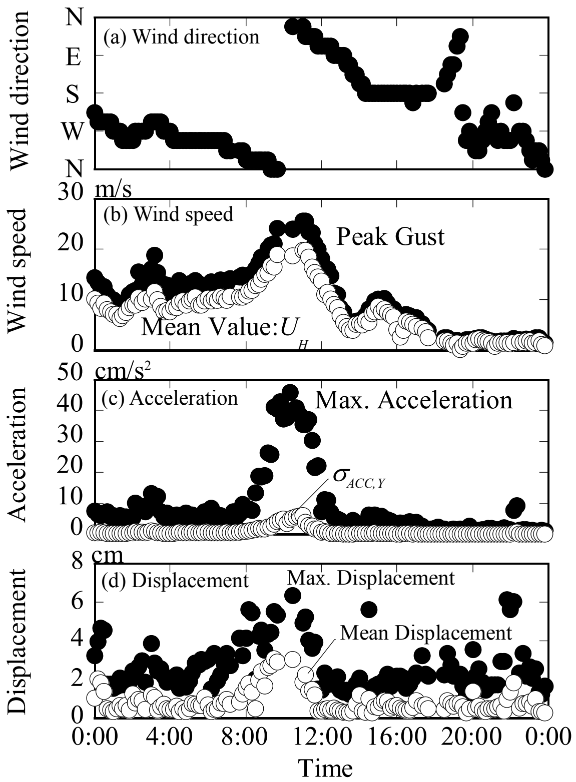
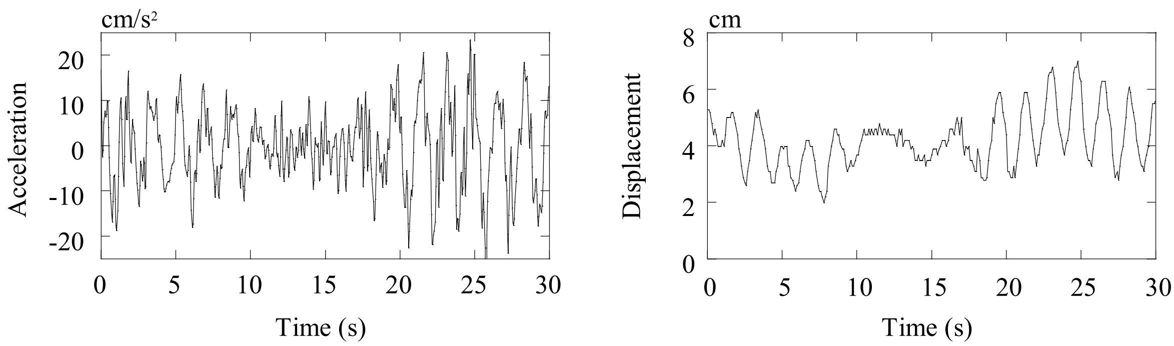


Fig.5 Temporal variations of the wind and the response data every 10min during a typhoon

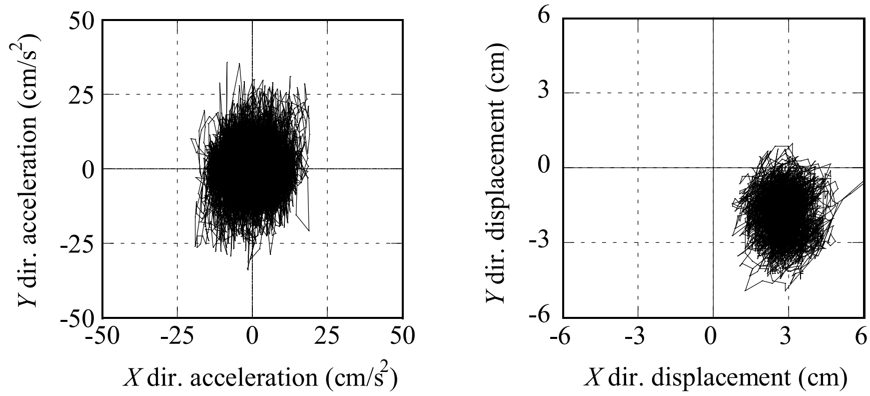


(a) Accelerometer (b) RTK-GPS

Fig.6 Example of temporal variations of wind-induced responses of the tower during a typhoon (Tamura et al. 2001) the displacement by RTK-GPS.

Both spectra have a peak at 0.57 Hz corresponding the lowest natural frequency of the tower, although that of the displacement by RTK-GPS shows almost constant energy in the higher frequency range, which is attributed to the background noise of RTK-GPS.

The vibration characteristics are estimated by the RD technique. Figures 9(a) and (b) show the random decrement signature obtained by this technique from the acceleration record and the RTK-GPS displacement record, 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 0.94% for the acceleration record and 0.87% for the RTK-GPS displacement.



(a) Acceleration (b) RTK-GPS

Fig.7 Example of the tip locus during a typhoon

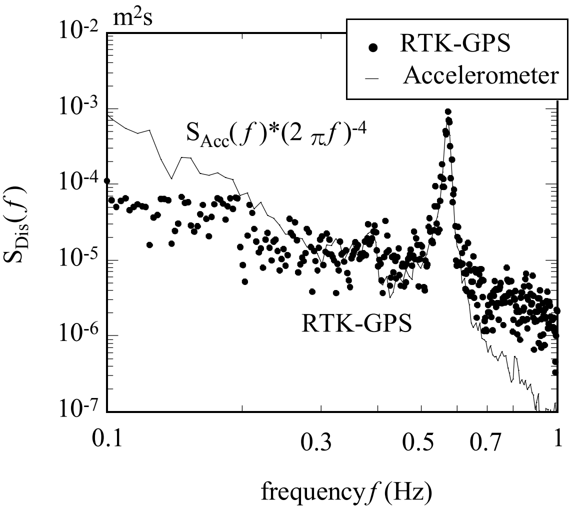


Fig.8 Power spectra of tip displacement

Since RTK-GPS can measure the static displacement, the deformation of the tower caused by the solar heating effect could also be detected. Figure 10 shows the tower deformation caused by solar heating on a calm and on a clear day. Each plot indicates a preceding hour's mean displacement of 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.

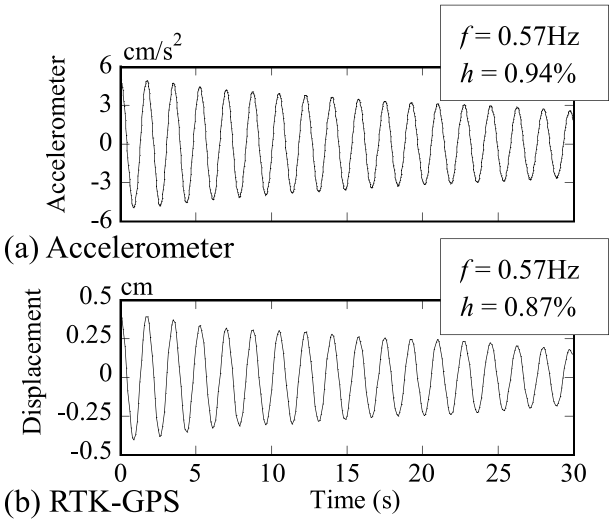


Fig.9 Random decrement signature obtained by RD technique

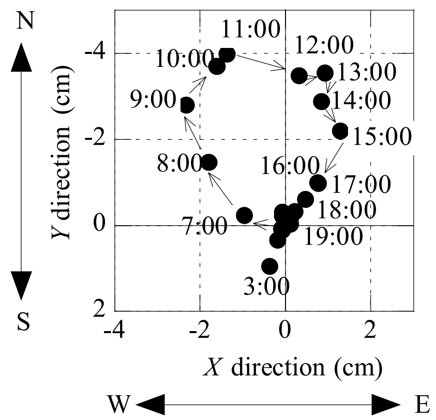


Fig.10 Tower deformation caused by solar heating effect

FEM ANALYSIS OF TOWER

An FEM tower model based on the design documents was created in the computer. SAP2000 was used for its 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 are shown in Fig.11. Figure 12 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 by $F_z = \rho U_z^2 CA/2$, where the mean wind speed U_z was estimated assuming the power-law index $\alpha = 0.2$, and the wind force coefficient C was estimated by the following equation (ASCE, 2000).

$$C = 4.0\phi^2 - 5.9\phi + 4.0 \qquad (1)$$

Here, ρ is air density, A is projected area, and ϕ is solidity ratio. Figure 12 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, which 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, was used for the analysis.

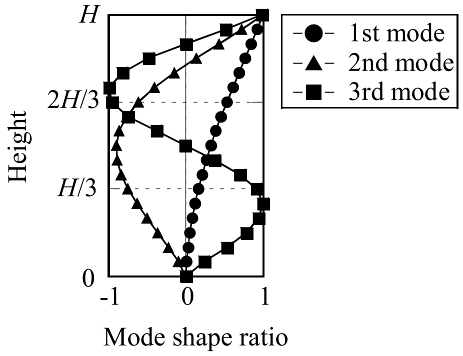


Fig.11 Mode shape obtained by FEM

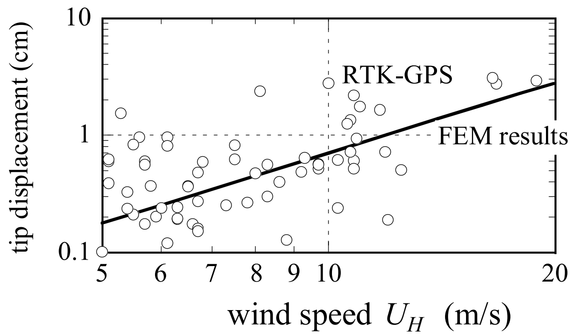


Fig.12 Mean displacement and mean wind speed

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. The system can monitor the stresses of 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 of members at the tower base shown in Fig.13 were calculated from the temporal variation of the GPS tip displacement. Figure 14 shows the temporal variations of stresses virtually monitored by hybrid use of the FEM and RTK-GPS. The results shown in Fig.14 were member stresses converted from GPS displacement during Typhoon 0115. They include the stresses caused by tower dead load. These members, i.e. inner column, outer column and diagonal member shown in Fig.13, were compressive members as shown in Figs.14(a), (b), and (c). Reflecting the fluctuation of wind forces, the outer column (Fig.14(a)) and diagonal member (Fig.14(b)) fluctuated. However, the inner column (Fig.14(c)) fluctuated much less than the outer column and diagonal member, and it bore mainly vertical load.

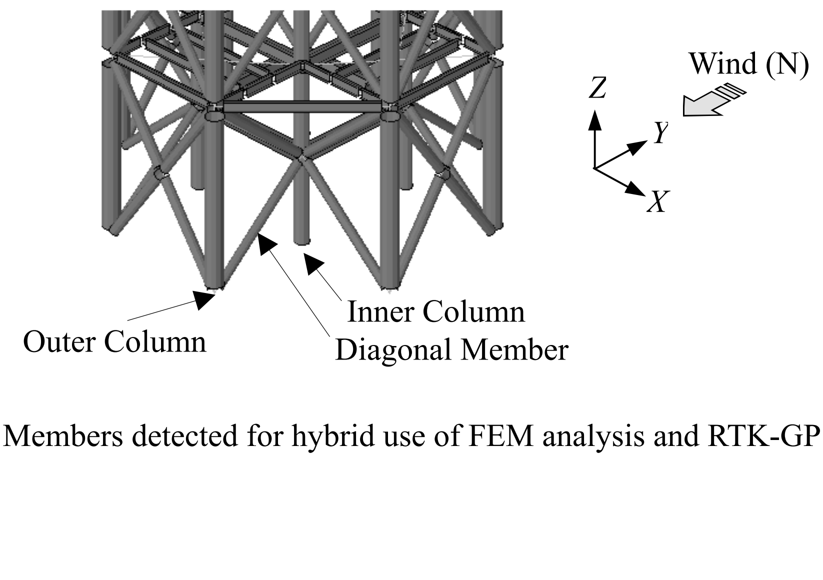
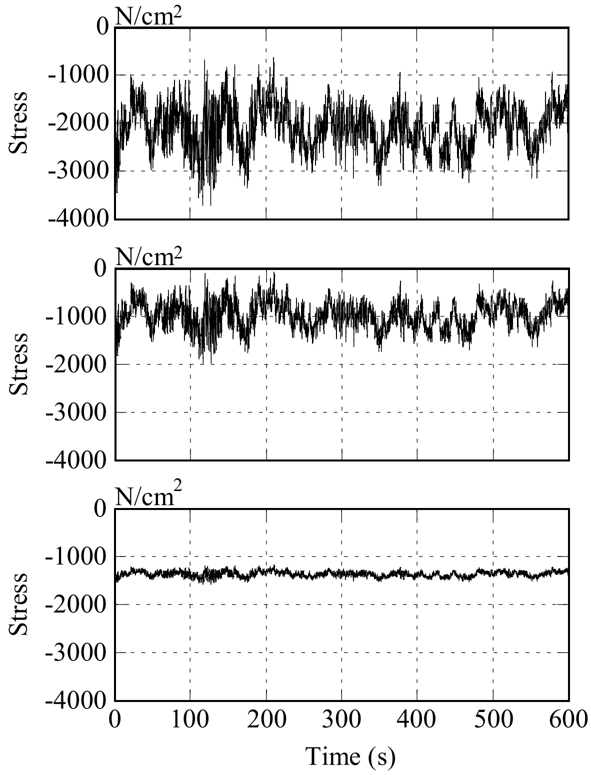


Fig.13 Members detected for hybrid use of FEM analysis and RTK-GPS



(a) Outer Column

(b) Diagonal Member

(c) Inner Column

Fig.14 Temporal variations of stresses by hybrid use of FEM analysis and RTK-GPS

CONCLUDING REMARKS

Based on the feasibility study of RTK-GPS for measuring wind-induced responses of buildings, the responses with amplitudes larger than 2cm and natural frequencies lower than 2Hz can be detected by RTK-GPS. Thus, evaluation of 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 is proposed.

REFERENCES

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

Tamura, Y., Matsui, M., Uchiyama, M., Hibi, K. and Ishihara, K. (1999), "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*, B-1, 203-204 (in Japanese)

Tamura, Y. (2000), "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*, 1-7 (in Japanese)

Tamura, Y., Matsui, M., Pagnini, L.C., Ishibashi, R. and Yoshida, A. (2001), "Measurement of wind-induced response of buildings using RTK-GPS", *Proc. of APCWE V*, 93-96