COST ACTION TU0601
ROBUSTNESS OF STRUCTURES

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SHM-based Robustness: a super-tall structure case-study

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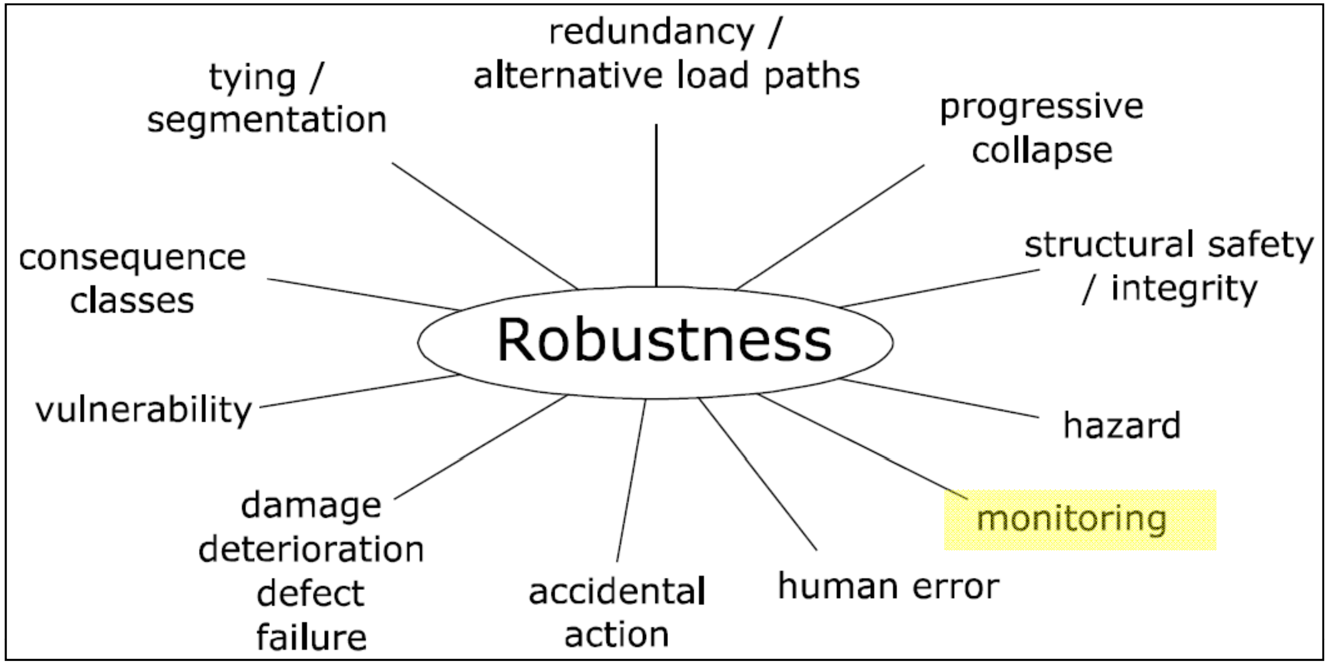
Outlook

- Introduction to monitoring-based robustness
- Case-study : the Guangzhou TV and Sightseeing Tower
- Monitoring the structural response to extreme events
- Assessment of the structural conditions
- The Hilbert-Huang transform (HHT) method improved by filtering
- Conclusions and future work

Introduction

Fink et al. (2009) – Proc. Joint Workshop of COST Actions TU0601 and E55, Ljubljana, Slovenia



Monitoring: Determination and assessment of the condition with the recommendations on steps to be taken (SIA 2004 – Basis of Structural design)

$$P(\text{collapse}) = \sum_i \sum_j \underbrace{P(\text{collapse} \mid D_j \cap EX_i)}\,\underbrace{P(D_j \mid EX_i)}\,P(EX_i)$$

Introduction

The adoption of structural health management (SHM) systems as an integrated part of the structural design can potentially lead to an improvement of robustness by providing the knowledge needed to perform the following actions:

- To statistically characterize and reduce the uncertainties;
- To evaluate the actual loads acting on the structure during its lifetime, included those not considered during design;
- To detect potential mistakes during construction and deviations of the actual performance from the expected one;
- To support in detecting faults and damaged elements, which may result from the manufacturing process or from the natural material deterioration phenomenon;
- To update the residual life estimates and to efficiently schedule maintenance and interventions, thus reducing costs while preserving or improving the structural design performance;
- To enable a prompt response to emergencies;
- To gather knowledge and experience about the actual operational performance of a structure. This knowledge can be integrated into the design practice, resulting in an evolution of the structural criteria and technologies.

- Various **damage identification algorithms** have been developed for structural assessment and identification purposes. Although there has been much development in this area, many difficulties need to be overcome in practical applications, such as the treatment of **measurement uncertainties**, the presence of **inadequate test data**, etc.
- Also, another important difficulty stems from the difference between the analytical models and the real structures. Generally, the **error in analytical models** is related to several aspects, such as:

(1) the approximation in the **boundary conditions** of the analytical models, which may make the analytical stiffness matrix deviate from the practical one,

(2) the **connectivity conditions** of the elements in analytical models, which cannot reflect the real connective state of structural members,

(3) some important **material parameters** in analytical models, e.g. Young's modulus, which may not represent the real ones,

(4) the presence of **many stiffness sources** in practical structures, which are ignored in analytical models due to computational capacity;

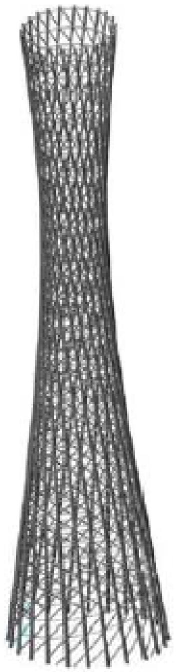
(5) a **coarse mesh** or the selection of **unsuitable element types**, which can cause errors in the analytical models.

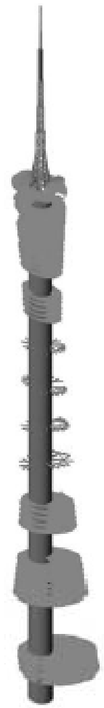
- For these reasons, in practical applications, it may be preferable to avoid employing too much information of the analytical models. Hence, the kinds of algorithms presented are **not dependent on analytical models**, but they are rather dependent on the modal parameters, i.e., natural frequency, damping ratios, and mode vectors, which are obtained by the **operational modal analysis** that deals with the output-only measurements of a structure subjected to external forces.

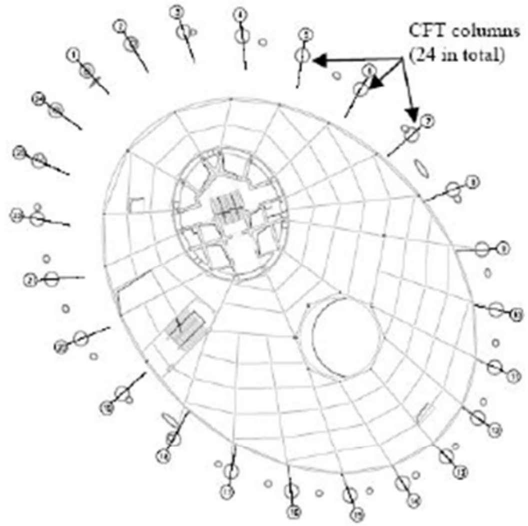
Canton Tower (former Guangzhou TV and Sightseeing Tower)

The tallest structure in China (followed by Shanghai World Financial Center), the Canton Tower is the seventh tallest structure and the third tallest freestanding structure in the world.

It was designed by the Dutch architects Mark Hemel and Barbara Kuit of Information Based Architecture together with Arup.

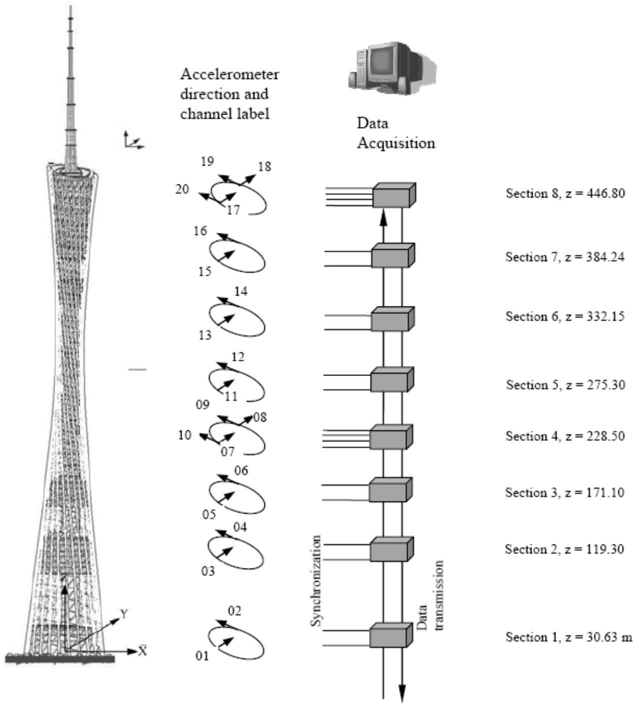


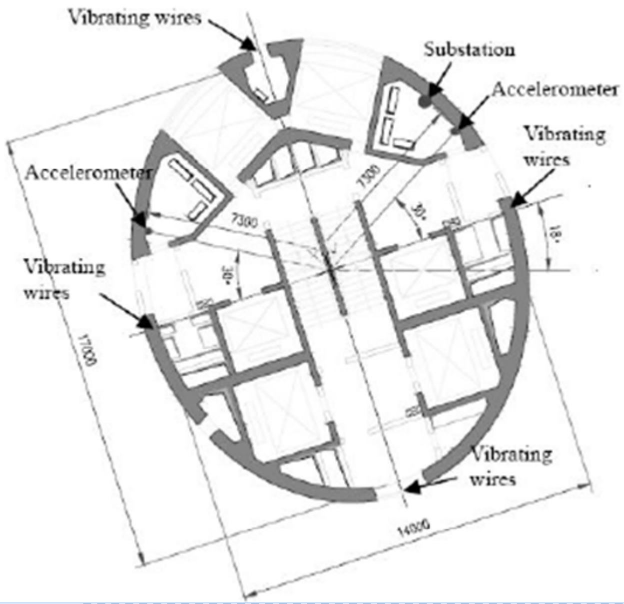




Oval concrete inner tube with constant dimensions of 14 m × 17 m

Construction begins in February 2007
and is completed in October 2010.





Long-term Structural Health Monitoring (SHM) System

No.	Sensor type	Monitored quantities	Number of sensors		Manufacturer
			In-construction monitoring	In-service monitoring	
1	Zenithal telescope	Inclination of tower	2	0	LAT LASER JZC-G
2	Tiltmeter	Inclination of tower	0	2	LEICA GEOSYSTEMS NIVEL 210
3	Level sensor	Leveling of floors	2	0	LEICA GEOSYSTEMS SPRINTER 200
4	Theodolite	Elevation	2	0	KOLIDA ET-02
5	Total station	Inclination, leveling, elevation	1	0	LEICA GEOSYSTEMS TCA 1800
6	Anemometer	Wind speed and direction	2	2	R M YOUNG 05103L
7	Wind pressure sensor	Wind pressure	0	4	KANGYU KYB11
8	Seismograph	Earthquake motion	0	1	TOKYO SOKUSHIN SPC-51C
9	Thermometer	Temperature of structure	96	60	FUMIN MEASUREMENTS PT100
10	Vibration wire gauge	Strain, shrinkage and creep	416	60	GEOKON GK4000, GK4200
11	Fiber optic sensor	Strain and temperature	0	120	MICRON OPTICS OS 310S, SM 130-200
12	Accelerometer	Acceleration	0	22	TOKYO SOKUSHIN AS-2000C, AS-2000S
13	GPS	Displacement	2	2	LEICA GEOSYSTEMS GPS1230
14	Digital video camera	Displacement	3	3	PROSILICA GE2040C
15	Corrosion sensor	Corrosion of reinforcement	0	3	S+R ANODE LADDER
16	Weather station	Temperature, humidity, rain and air pressure	1	1	VAISALA WXT510

Benchmark problem launched in 2008, under the auspices of the Asian-Pacific Network of Centers for Research in Smart Structure Technology (**ANCRiSST**).

Goal: to monitor the tower dynamical behavior in various weather conditions and under exposure to extreme events, and to analyze this response by the aid of several algorithms to reach a full **performance assessment in real time**.

Monitoring the structural response to extreme events

•The response of the tower under **5 typhoons and 2 earthquakes** was recorded at different times and at different stages of the tower construction.

•Three of these typhoons (named Kammuri, Nuri, and Hagupit) occurred in 2008, before the total completion of the tower height, while the last two typhoons (named Molave and Koppu) occurred after it.

• The two earthquakes both have a Ritter magnitude of 6.4 (MMM VI – strongly perceived, light damage) and occurred off the coast of Taiwan, in 2009, and in southwestern Taiwan, in 2010, respectively.

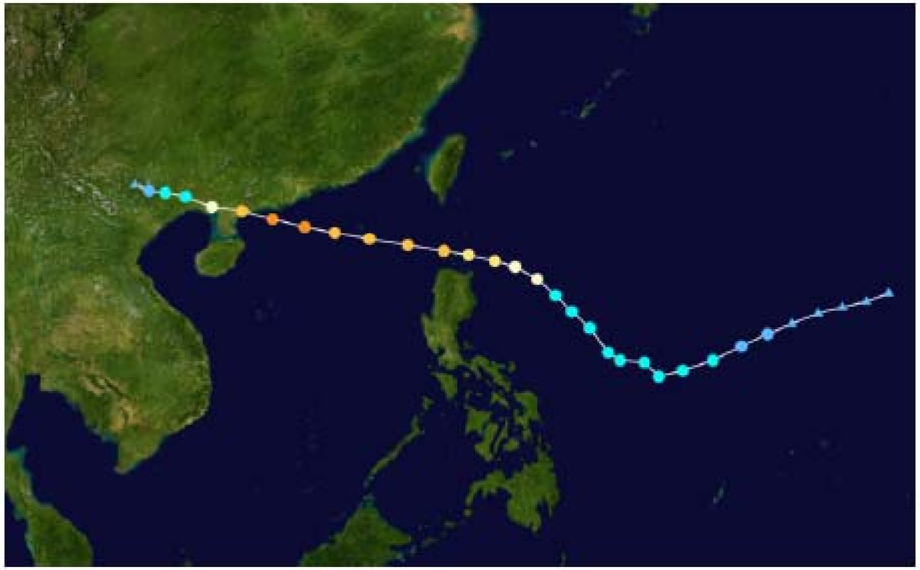
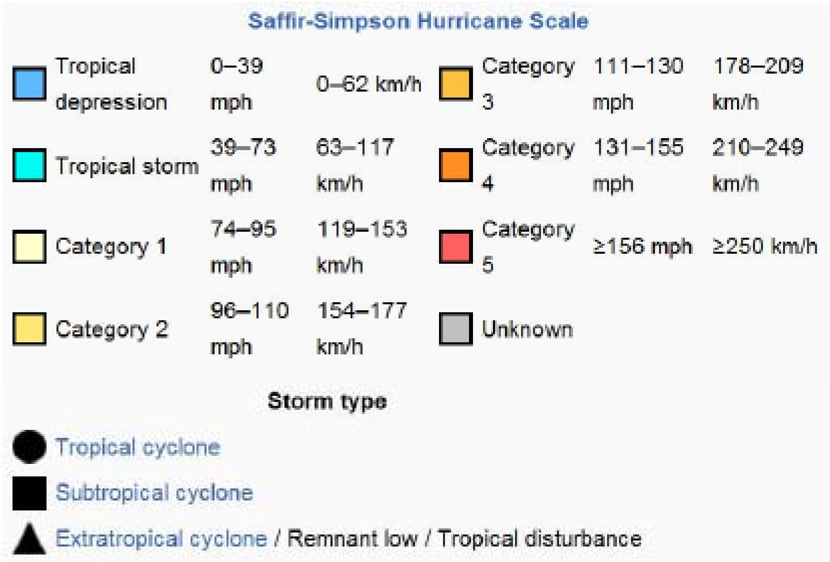
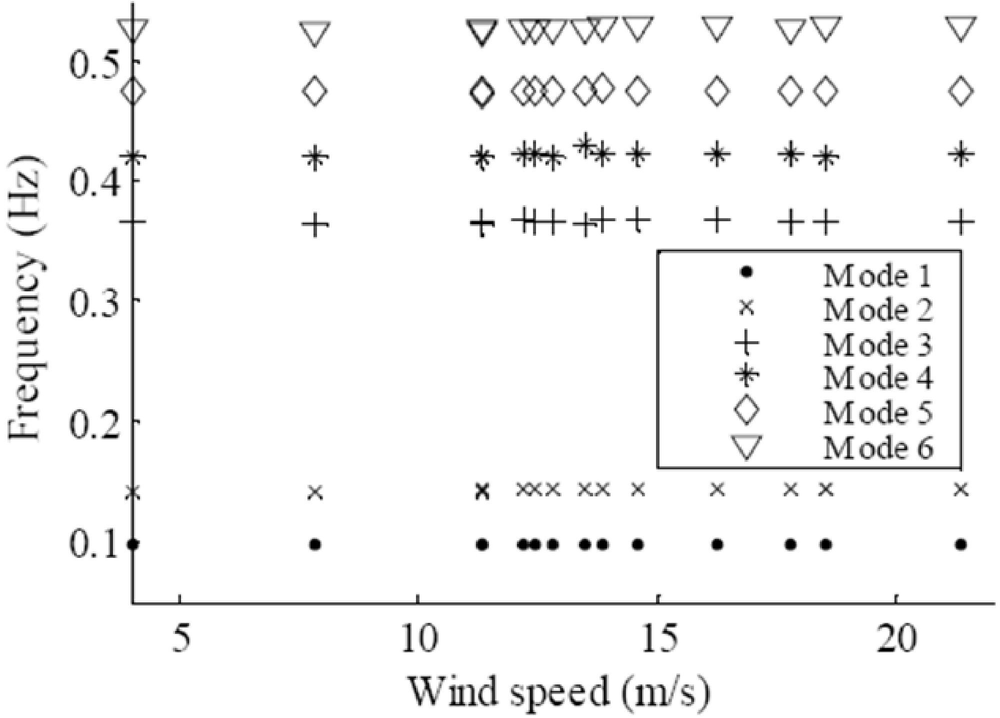
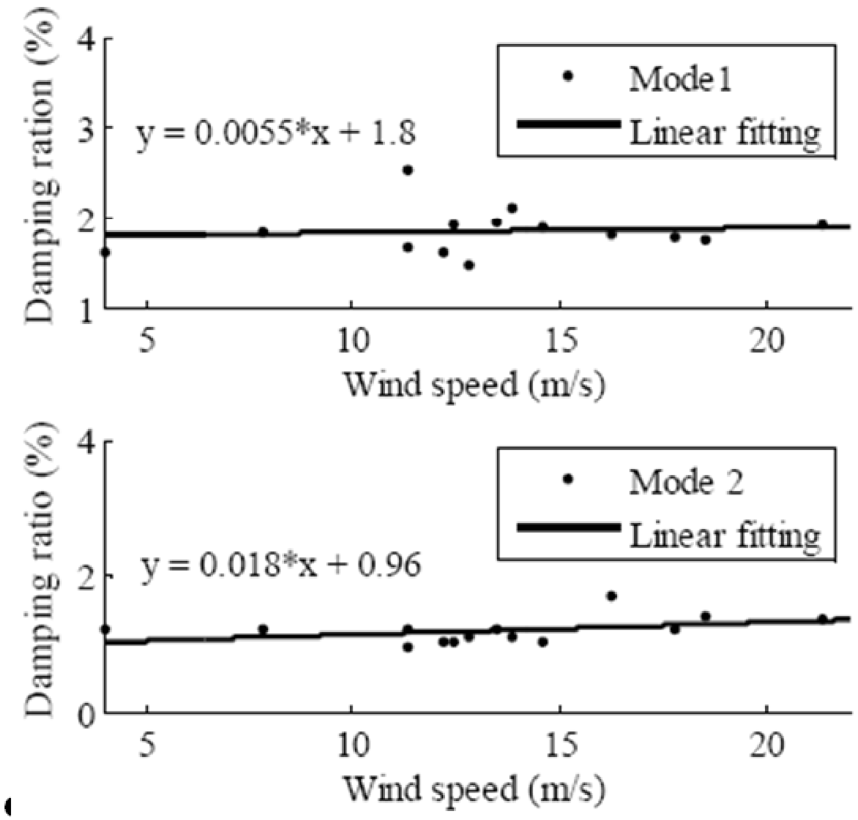


Figure 1.14. Hagupit typhoon path.

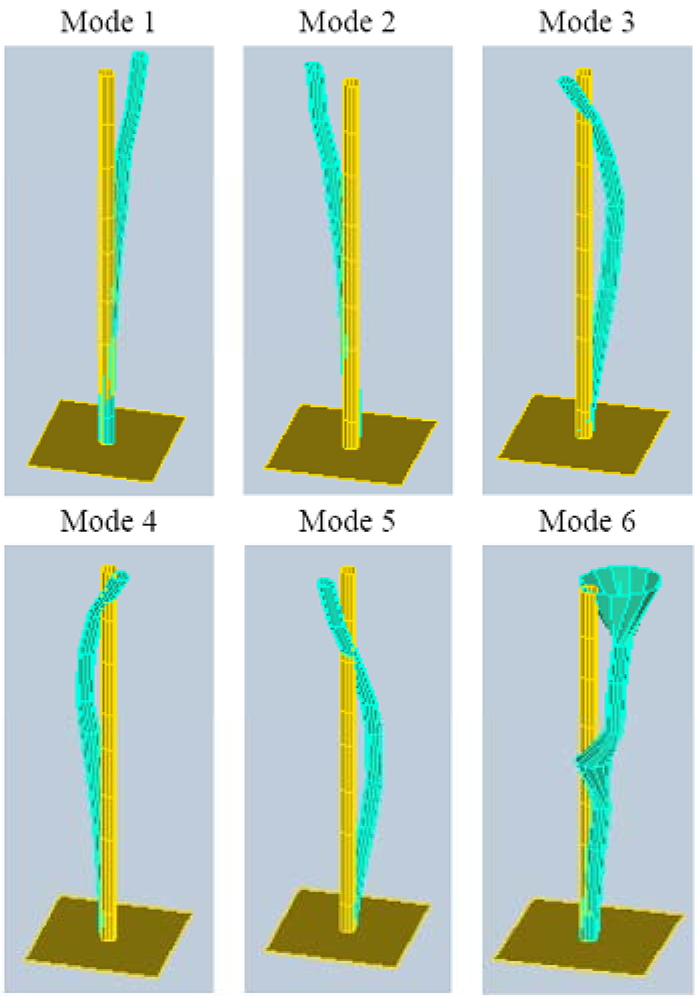


(Frequency Domain Decomposition) → Modal Parameters





•The frequencies remain nearly constants with wind speed variations, not only for the first mode but also for the higher ones.
•The damping ratio slightly increases with the mean wind speed and the rate of increase differs from one direction of the structure to the other depending on the geometry of the structure and the wind direction.



Structural condition assessment

Frequencies: 0.094, 0.14, 0.36, 0.42, 0.47, and 0.52 Hz

Mode	Typhoons						Earthquakes			
	Nuri		Hagupit		Molave		TH		ST	
	MAC	MCC	MAC	MCC	MAC	MCC	MAC	MCC	MAC	MCC
1	1.00	0.98	1.00	0.99	1.00	1.00	1.00	0.96	1.00	0.91
2	1.00	0.99	1.00	0.99	0.99	0.92	1.00	1.00	1.00	0.99
3	0.99	0.90	1.00	0.98	1.00	0.92	1.00	0.99	1.00	0.99
4	1.00	0.99	1.00	0.98	0.99	0.90	0.99	0.95	0.99	0.89
5	0.99	0.92	1.00	0.94	1.00	0.86	1.00	0.99	1.00	0.98
6	1.00	0.99	1.00	0.96	0.96	0.83	0.99	0.98	0.99	0.99

$$MAC(x,p)=\frac{\left[\sum_{j=1}^{N}(\phi_x)_j.(\phi_p)_j\right]^2}{\left[\sum_{j=1}^{N}(\phi_x)_j^2\right].\left[\sum_{j=1}^{N}(\phi_p)_j^2\right]}$$

$$COMAC(j)=\frac{\left[\sum_{L=1}^{L\max}\left|({}_j\phi_{x,l})({}_j\phi_{p,l})\right|\right]^2}{\left[\sum_{L=1}^{L\max}({}_j\phi_{x,l})^2\right].\left[\sum_{L=1}^{L\max}({}_j\phi_{p,l})^2\right]}$$

Sensor	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Nuri	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	N.A.	N.A.	N.A.	N.A.
Hagupit	N.A.	N.A.	N.A.	N.A.	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	N.A.	N.A.	N.A.	N.A.
Molave	N.A.	N.A.	0.90	0.99	1.00	0.99	0.98	N.A.	1.00	N.A.	1.00	0.97	0.92	0.99	N.A.	N.A.	N.A.	N.A.	1.00	1.00
TH Eq.	0.82	0.85	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
ST Eq.	0.84	0.89	1.00	1.00	1.00	0.99	1.00	0.99	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.99

The Hilbert-Huang transform (HHT) method improved by filtering

- It is based on the assumption that each signal is composed of different simple intrinsic oscillatory mode functions (IMFs) associated with energy at different timescales.
- First, the tower principal frequencies are approximately estimated by manually picking the peaks of the Power Spectrum Density (PSD) of the signal obtained by FFT.
- Each detected peak is then separately considered to extract the associated monocomponent function from the signal made of multiple dominant harmonic components. For this purpose, a band-pass filter with central frequency set equal to the corresponding natural frequency of the tower and a frequency bandwidth of 0.001 Hz is applied. This filtering procedure ensures that completely isolated IMFs are obtained also when narrowband multi-harmonic signals are treated. The derived monocomponent function in then calibrated so that the energy is preserved.
- Finally, the Empirical Mode Decomposition (EMD) method (Huang et al., 1998) is employed to extract the first IMF, $c_j(t)$, from the jth calibrated monocomponent function, $j = 1, \ldots, n$, with n the number of the selected principal frequency components in the PSD.
- The resulting signals are symmetric about the local zero-mean line and do not contain any riding wave.

After taking the HHT of each computed IMF, $c_j^*(t)$, the original time history, $y(t)$, can be expressed as:

$$y(t) = \mathrm{Re}\left\{\sum_{j=1}^{n} A_j(t)\exp\left[i\theta_j(t)\right]\right\} \qquad (1)$$

where Re indicates the real part. The instantaneous amplitude, $A_j(t)$, and the phase angle, $\theta_j(t)$, are given by:

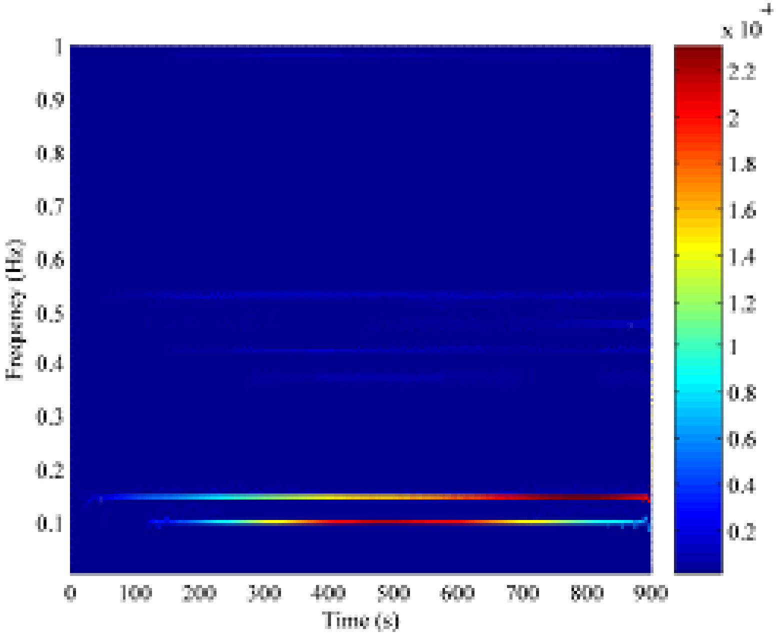
$$A_j(t) = \sqrt{\left[c_j(t)\right]^2 + \left[c_j^*(t)\right]^2} \qquad (2)$$

$$\theta_j(t) = \tan^{-1}\left[c_j^*(t)/c_j(t)\right] \qquad (3)$$

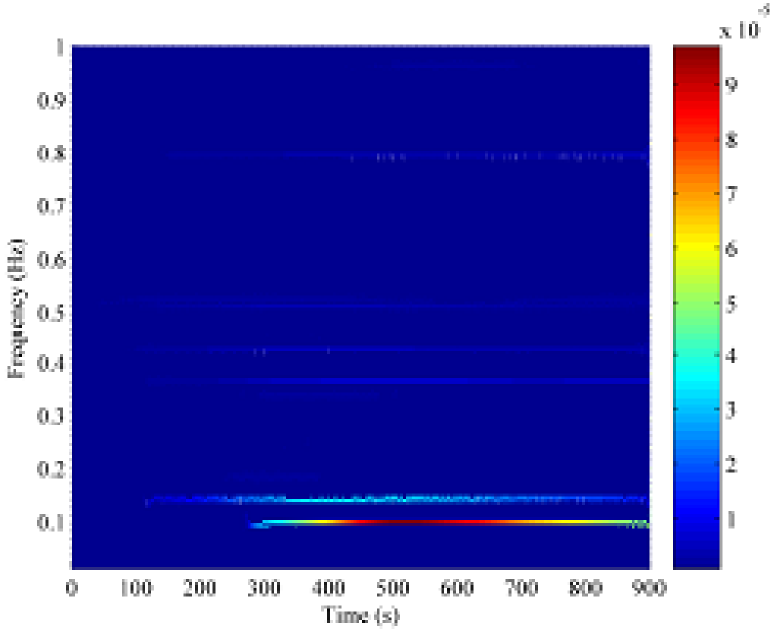
respectively. These quantities are functions of both time and frequency. In particular, the frequency-time distribution of the amplitude during some extreme events that interested the GNTVT site is represented by the Hilbert spectra in Figure 9. A measure of the energy associated to the jth IMF is then defined as:

$$E_j = \int_0^{t_d}\left[A_j(t)\right]^2 dt \qquad (4)$$

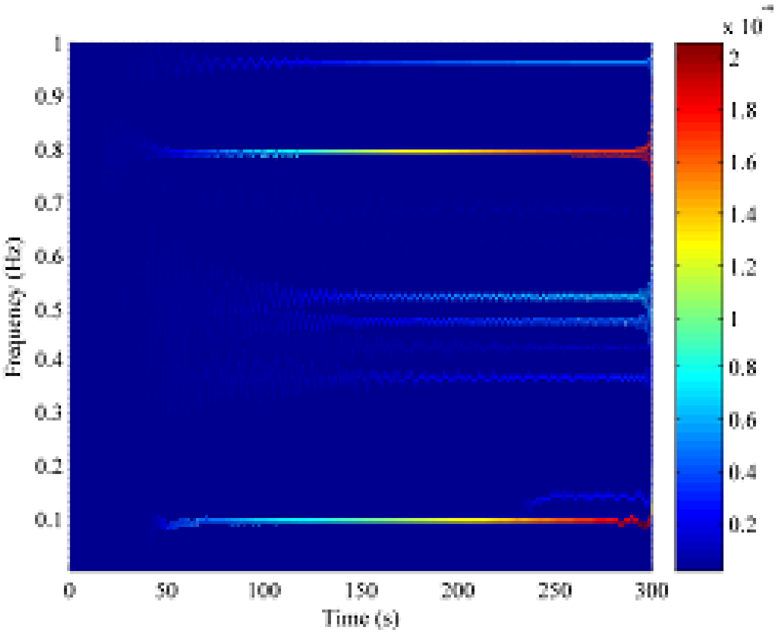
where t_d is the duration of the considered time history.



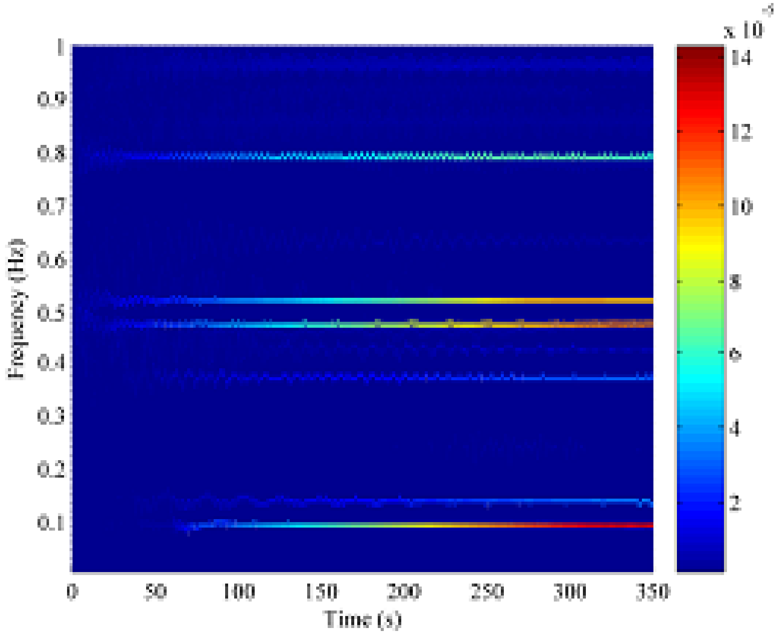
(a) Sensor 11, Molave typhoon



(b) Sensor 12, Koppu typhoon

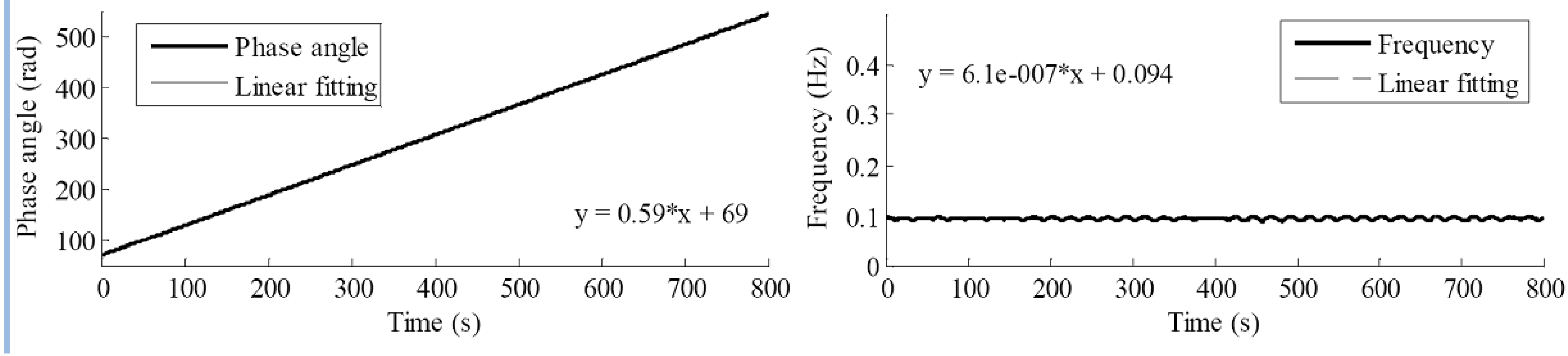


(c) Sensor 17, 2010 Taiwan EQ



(d) Sensor 14, 2009 Sothern Taiwan EQ

$$f_1(t) = \frac{1}{2\pi}\frac{d\theta_1(t)}{dt}$$



With the aim of detecting any commencement of structural damage and introducing a **damage metrics** based on the results of the HHT method improved by the filtering approach, the following essential phenomena are investigated: (1) **the spread of vibration energy between near modes**, such as an energy intensity decrease, suggests the presence of structural nonlinearity; (2) **a reduction in the modal frequencies** may indicate the loss of structural stiffness, and hence it is a sign of structural deterioration; (3) Physically, any damage in a structure alters the speed at which the energy traverses the structure; once the wave passed through the damage, the energy speed is no longer affected. **The Hilbert phase** behaves in the same manner. Furthermore, the **slope change** appears to be dependent on the size of the damage so that the energy speed propagation would be altered in a different way depending on the size of the damage. This implies that one can track increasing amount of damage as a function of phase. Thus, the Hilbert phase should enable to determine the size and the location of damage.

Conclusions and Future Work

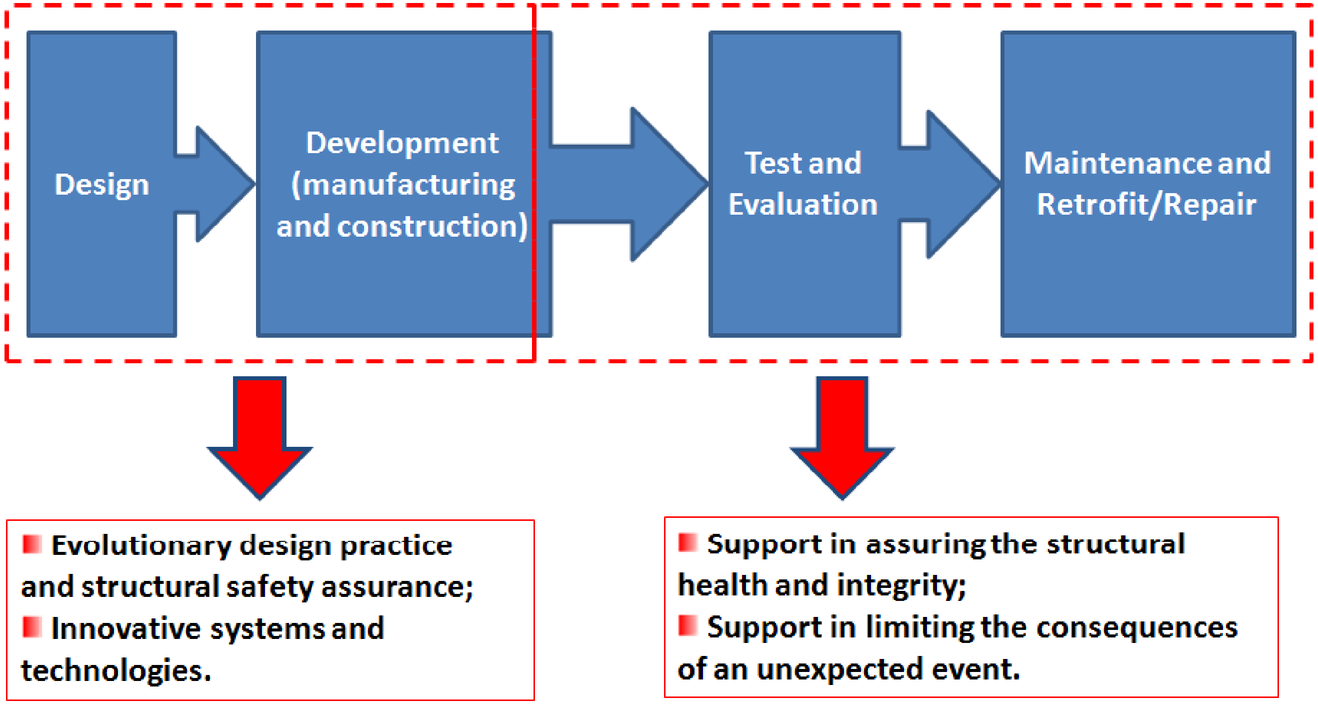
- Whereas the FFT spectrum of a signal cannot give any local time information, the energy content can be captured **in both the time and frequency domains** by adopting the improved HHT method and the resulting natural frequencies coincide quite well with those of the FFT spectrum. When investigating the response to earthquakes, the improved HHT method clearly identified the **high energy imparted to the dominant higher modes** of the tower.
- Furthermore, it was possible to detect the time at which the tower started to have a significant response to the ground motions by tracking the point at which the energy started to have a sudden increase in the tower various vibration modes. **The capability to detect the occurrence in time of the consequences of an extreme event on the structural response** is mostly useful not only in the case of earthquakes, but also upon the occurrence of a vehicle collision with the structure or a nearby explosion. This valuable information **would enable to send, in real-time, an alarm about the structural conditions** to the responsible persons who could take a suitable decision in order **to avoid or limit the catastrophic consequences of a failure**
- Different **damage metrics** have been proposed based on the HHT method improved by the filtering procedure. Nevertheless, a reliable judgment of the performance of the different damage assessment criteria would require their application to the data from an experimental model which actually underwent some damage. The selected case-study offers, however, the unique possibility to advance the long-term SHM studies from laboratory investigations to practical applications.

Conclusions and Future Work

"Smart" systems for civil structures are described as systems that can automatically adjust structural characteristics in response to external disturbances and/or unexpected severe loading toward structural safety, extension of the structure's life time, and serviceability
(Otani et al. 2000 – Proc. SPIE)

Measures to increase robustness
defined as the ability of a stucture or its members to withstand events like fire, explosions, impact or consequences of human error, without being damaged to an extent disproportionate to the original cause (CEN 2006 - Eurocode 1-1-7 – Actions on structures)

$$P(\text{collapse}) = \sum_i \sum_j \underbrace{P(\text{collapse} \mid D_j \cap EX_i)}\,\underbrace{P(D_j \mid EX_i)}\,P(EX_i)$$



The evaluation of the overall system performance provides the basis to adopt performance-based design criteria for certain types of structures. Design practices can then evolve as the ability to collect in-service knowledge about the operational performance of the structural concepts is gained. Technological advancements for future constructions can be identified from the experience gathered on the existing structures. By periodically evaluating the experience gathered through tests and in-service monitoring and by transferring it back into the design process through new "standard technology", the assurance of structural safety can be approached as an evolutionary accomplishment. The lifetime for which new structures are designed can be increased, and the service life of existing structures can be extended. In conclusion, design criteria and innovative structural systems can evolve together by benefitting directly from the advancements in sensors and data processing technology.

Aknoweledgements

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