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Photograph: Detail from 'Bridge No. 2' from the series *Rust Never Sleeps*, John Moore, 1996

AN INTEGRATED STRUCTURAL HEALTH MONITORING SYSTEM FOR THE PRESERVATION OF THE HISTORIC FIREBOAT ALEXANDER GRANTHAM

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Abstract

The structural integrity of a metal artifact is always of concern to conservators and curators, particularly if the object is very large and intended for permanent display outdoors. Being the first vessel preserved as a historical relic in Hong Kong, the Fireboat Alexander Grantham was lifted from the sea and has been on public display since 2006. Given the unfavorable, yet uncontrollable outdoor environment, the fireboat will inevitably suffer from degradation and perhaps structural failure, which may not be easily detected or identified at an early stage through visual inspection. For the sake of her long-term preservation, the Central Conservation Section in Hong Kong has pioneered the development of an integrated Structural Health Monitoring system to monitor the structural stability of the vessel on exhibition. This paper will discuss the conservators' experience in devising the system and the preliminary findings obtained from the program to illustrate the merits and limitations of its application on historic vessels.

Keywords: integrated structural health monitoring, extreme events, structural behavior, strain, hull convergence, historic vessels

Introduction

Being the largest in the fleet of local fireboats during her service, the Fireboat *Alexander Grantham* (AG) was an icon embodying the achievements of the fire service as well as the glorious history of the shipbuilding industry in Hong Kong. With the objective of preserving this unique piece of cultural heritage, the Leisure and Cultural Services Department, the Government of the Hong Kong Special Administrative Region, undertook to fund and lead the Fireboat AG project. As soon as the fireboat was decommissioned in 2002 after some 50 years of service, she was given a series of intensive restoration treatments to arrest specific preservation problems, to ensure her structural well-being for the lifting operation onto dry land, and to provide protection against weathering and possible damage when she was set for open display (Tse et al. 2008). The fireboat is perched on the waterfront of the magnificent Victoria Harbour in Hong Kong, with a small gallery built around her hull showcasing Hong Kong's sea salvage history of the past 100 years.

Overview of the structure

Constructed in the 1950s, the Fireboat AG is a steel twin-screw diesel driven vessel for fire-fighting and sea

salvaging operations. The hull was constructed from Lloyd's grade-A steel plates (Hong Kong & Whampoa Dock Co., Ltd 1950) supported by 67 transverse frames with watertight bulkheads also made of grade-A steel. The steel plates were butt-welded in non-critical areas and complemented with traditional riveting at all the seams and frames. The bulkheads not only increase the overall structural rigidity, but also divide the hull into various functional compartments, such as engine room, pump room, etc.

As the boat is displayed on land, it is now supported by a cradle system (see Figure 1), which was designed with input from cross-disciplinary professionals, including architects, structural engineers, marine engineers, ship-builders and conservators. All factors, such as her static load distribution, dynamic load to be imposed by visitors and the wind load effect were considered in the cradle system's design. Nevertheless, structural systems are inevitably subject to age-related deterioration, causing concerns over their stability, maintenance, public safety, and environmental and cost implications. The fireboat is no exception. Therefore, the role of conservators is to manage the possible changes incurred upon the fireboat and to prolong her life for future generations.



Figure 1. Cradle system supporting the Fireboat *Alexander Grantham*.

Current inspection practice for ships

As a general practice, structural assessments of ships are conducted by professional surveyors to assess functionality. The survey is normally a process of visual inspections, sometimes with supplementary thickness measurements and Non-Destructive Evaluation (NDE) for specific areas, such as welds and joints (Wang et al. 2008). Although these techniques reveal structural information, the process can be time-consuming and costly over a long-term, especially when many of the structural members are normally covered by wall panels and machinery (Salvino and Collette 2009). Moreover, these assessments are basically on-the-spot surveys and targeted for ships that are still serviceable to identify their fitness for continued use as a floating structure. Current monitoring techniques, primarily related to operational safety and stability, are not applicable to the fireboat as her use has now been significantly altered. Given her current exhibition status, a proactive, rational, and integrated approach is warranted to monitor the structural integrity of the whole display. With this approach, monitoring is more than a visual inspection as it requires that continuous structural checks are performed. With technical advice from various experts, a structural health monitoring (SHM) system has been developed for the fireboat that involves monitoring various parameters in order to integrate and evaluate all the findings for data analysis and interpretation (Rizzo 2008). The principles of SHM are based on the SHM program for fixed land-based structures, such as bridges. By collecting and analyzing data over time, the conservators hope to assess the prevailing condition of the display, and project the likelihood of any structural failures prior to their development into significant issues that threaten the integrity of the structure.

Concept of integrated SHM

The concept of SHM has been widely researched in the past few decades for its potential to reveal the structural stability of road facilities, bridges and high-rise buildings. It is aimed at providing accurate and in-time information concerning structural stability and dynamic behavior. SHM monitors for unusual behavior that may indicate a malfunctioning structural condition. When detected, the unusual behavior necessitates a detailed inspection and diagnosis/prognosis of the structure, and typically calls for immediate maintenance to rectify the failure (Glisic and Inaudi 2007). Core activities of the integrated SHM program for the fireboat include (Wong and Ni 2009):

- risk assessment and setting monitoring scopes
- identifying representative monitoring parameters
- designing integrated monitoring systems and the sensor network
- data acquisition, processing and interpretation

Risk assessment and setting monitoring scopes

In adoption of a risk-based approach^[1] (Serratella et al. 2008), the following potential risks to the structure of the fireboat are identified to determine the scope of the program and the areas to be studied include:

- Failure of the structural components due to degradation will lead to the collapse of the fireboat. It is necessary to understand her structural behavior under various service patterns and weather conditions
- As the fireboat is now established as an accessible collection for public visitation, the dynamic load applied is significantly different from what she was originally designed for. Therefore, it is desirable to identify the anomalies in her load distribution and other dynamic behavior in order to assess the possible damages that may have incurred
- Although natural disasters have not been a real threat to Hong Kong, there are a number of typhoons every year. The severity of the damage is often difficult to establish without appropriate assessment means. Therefore, it is essential to evaluate the structural integrity immediately after the occurrence of extreme events.

The result of adopting this approach will allow resources to be focused on the structural components where they are most needed. The integrated SHM program can provide the necessary information and analytical tools for planning, evaluating and designing a long-term inspection program and effective maintenance strategies, and hence re-direct the maintenance from a corrective to a preventive approach.

Selection of monitoring parameters

Load pattern of the fireboat

In the past, the fireboat was supported by water buoyancy pressures and therefore her static and dynamic loads (e.g. vibratory loads from machinery) had been duly spread over the frames. With the vessel now mounted on land, all loadings are shared by the cradle members. Therefore, any change in the load pattern of the vessel could have a direct effect on the structural reliability of the cradle, which in turn affects the structural behavior of the whole display.

Deformation of the hull structure

The cross section of the hull can be regarded as a tunnel and its geometry has a direct relation with the structural reliability of the ship. Therefore, it is necessary to measure the hull convergence, which would be calculated as the degree of hull deformation.

Tilting and acceleration

During extreme events, such as a typhoon, the fireboat will be subject to severe external forces that may affect her overall structural stability. The related changes in stability parameters can be duly reflected by the measurements of overall tilting and acceleration.

Foundation settlement

The fireboat is now sitting on a stretch of reclaimed land that was not intended to take massive loads. Though piles were embedded in association with the construction of a foundation plinth for the fireboat, differential settlement may still take place and affect the reliability of the data gathered from the SHM program, particularly the change of load pattern. Therefore, settlement measurement is essential for data verification.

Wind speed and direction

To differentiate the readings caused by damage due to variations in environmental conditions in data normalization, environmental parameters such as wind speed and direction also are logged (Farrar and Sohn 2000).

Description of the monitoring system

With reference to the proposal of the engineering consultants, an integrated SHM system has been developed in phases to measure the identified parameters. Except for the strain gauges that were installed in March 2006, extensive instrumentation has been deployed as per the system requirements for implementation of the program in March 2009. The current setup (see Figure 2) can be categorized into three sub-systems:

- Continuous monitoring system — vibrating wire strain gauges, anemometer, accelerometer, tiltmeter
- Periodic monitoring system — reference points for tape-extensometer,
- settlement markers
- Data acquisition management system — devices for continuous logging of data from sensors.

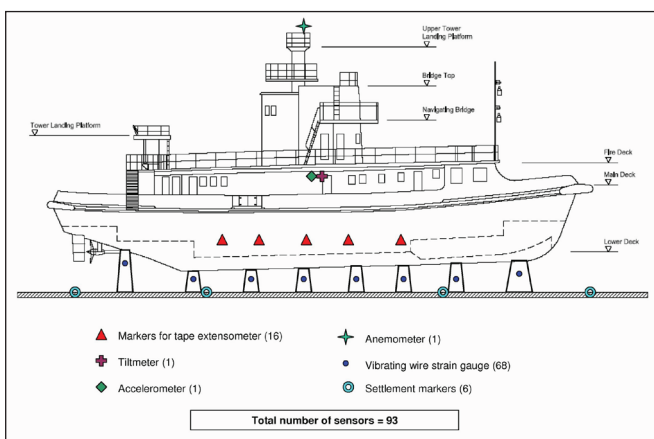


Figure 2. Location of monitoring sensors on the Fireboat *Alexander Grantham*.

Vibrating wire strain gauges

Sixty-eight sets of vibrating wire strain gauges, Gauge

Technique model TSR/5.5/T, were installed onto the cradle before the installation of the fireboat. The gauges measure the strain/stress levels acting on each cradle member at hourly intervals so that the change of load pattern of the fireboat can be determined through engineering calculations.

The Anemometer

Installed at the highest point on-board, the RM Young 05106MA anemometer (see Figure 3a) will capture the data of wind speed and direction acting on the vessel and will not be affected by the turbulence transferred from the shipboard structures. Data has been logged at 5-minute intervals and the anemometer has been connected to the accelerometer and the tiltmeter in order to over-ride their pre-set sampling frequency during extreme events.

The Accelerometer

The accelerometer, Kistler 8330A3, mounted to a structural member inside the pump room casing (see Figure 3b) is used to measure the dynamic movement across the vessel. It normally takes readings hourly but will sample at 10Hz when the 5-minute mean wind speed is greater than 40 km/hour.

The Tiltmeter

The Durham Geo Slope Indicator EL Monopod tiltmeter (see Figure 3c) is deployed to measure changes in orientation of the vessel caused by deformation of her structure, wind load effect or differential settlement of the foundation slab. The frequency of data sampling is the same as that obtained by the accelerometer.

Reference points for tape-extensometer

Due to the arrangement of machinery and superstructures on-board, hull sections within the main engine room and the pump room are more susceptible to deformation. Therefore, 16 sets of reference points have been installed onto frames inside these compartments for repeatable measurement with tape extensometer. Apart from the regular measurements to be conducted monthly, supplementary measurements will also be carried out within two days of the occurrence of extreme events for rapid condition screening to provide, in near real time, reliable information on the overall integrity.

Settlement markers

Six settlement markers have been installed on the foundation slab to assess differential settlement that may affect the structural stability of the fireboat and the readings collected by other on-board instruments. Optical surveying techniques (see Figure 3d) have been deployed for the assessment, using a Leica NA3003 digital level, once every three months.

Data management system

The data management system is composed of three categories of equipment, namely data acquisition units (for collection of data from the sensors), data transmission units (the cable network for transmission of signals) and storage device (for temporary storage of data until retrieval). The data is then downloaded to a computer and the project Structural Engineer deals with the analysis and interpretation.

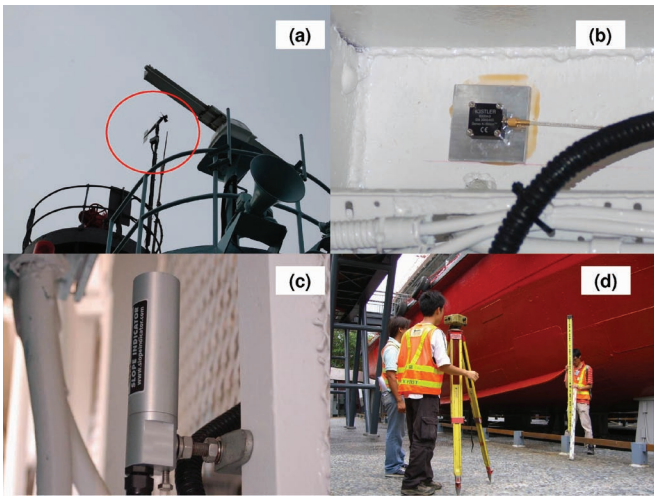


Figure 3. (a) The anemometer is fixed on top of the fireboat; (b) The Kistler 8330A3 accelerometer measures dynamic behavior of the fireboat especially during the occurrence of extreme events; (c) The tiltmeter is installed inside the pump room casing; (d) An Optical surveying technique has been deployed for settlement measurement.

Preliminary findings

Change of load pattern

The load pattern measurements obtained between March and July 2006 are shown in Figure 4. Measurements of the force acting on the cradle member supporting frame 21, the heaviest part located at the centre of the vessel, show a change after the installation of the fireboat in March 2006. The drop of force over time depicts a compressive force generated by the static load of the vessel acting on the cradle. This force gradually increased from the end of March apparently because the fireboat had started to sag. Continuous monitoring has been conducted over the past few years, and readings on the same cradle from April 2007 until December 2009 (see Figure 5) illustrate that the change of strain was within 3-5%. This result is within the instrumental and measurement error, as determined by the project structural engineer, and thus considered as insignificant. This implies that the sagging of the fireboat largely settled at an early stage before April 2007. The strain gauges were installed with an individual temperature sensor and therefore all the readings were corrected for temperature effect. Readings on the same cradle in 2009 (see Figure 5) illustrated that the change of strain was almost insignificant, which implied that the sagging of the fireboat has largely settled.

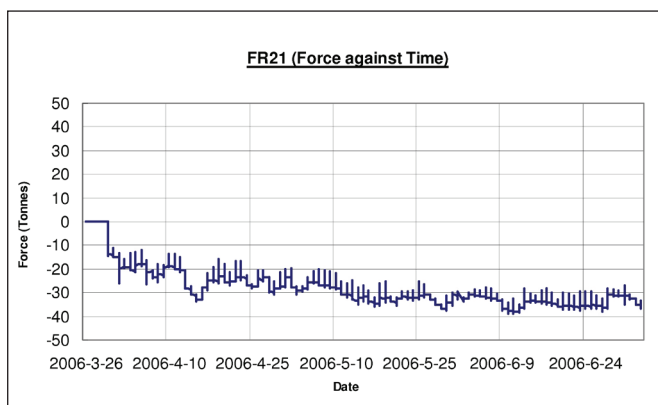


Figure 4. The amount of force acting on frame 21 during the period from 26 March 2006 to 4 July 2006.

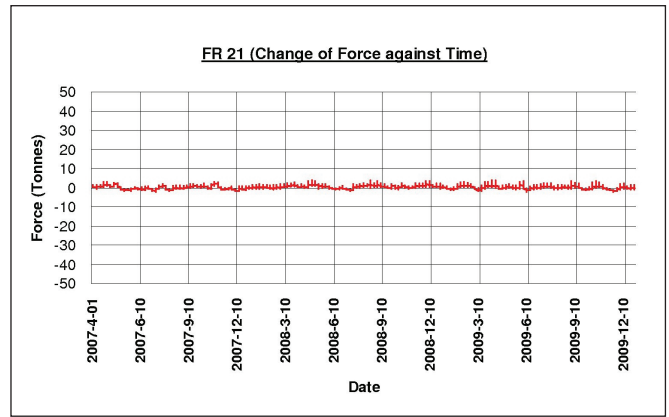


Figure 5. Change of force acting on frame 21 during the period from 1 April 2007 to 10 December 2009. The readings along the zero level indicate that the change of force acting on the cradle was almost insignificant over the period.

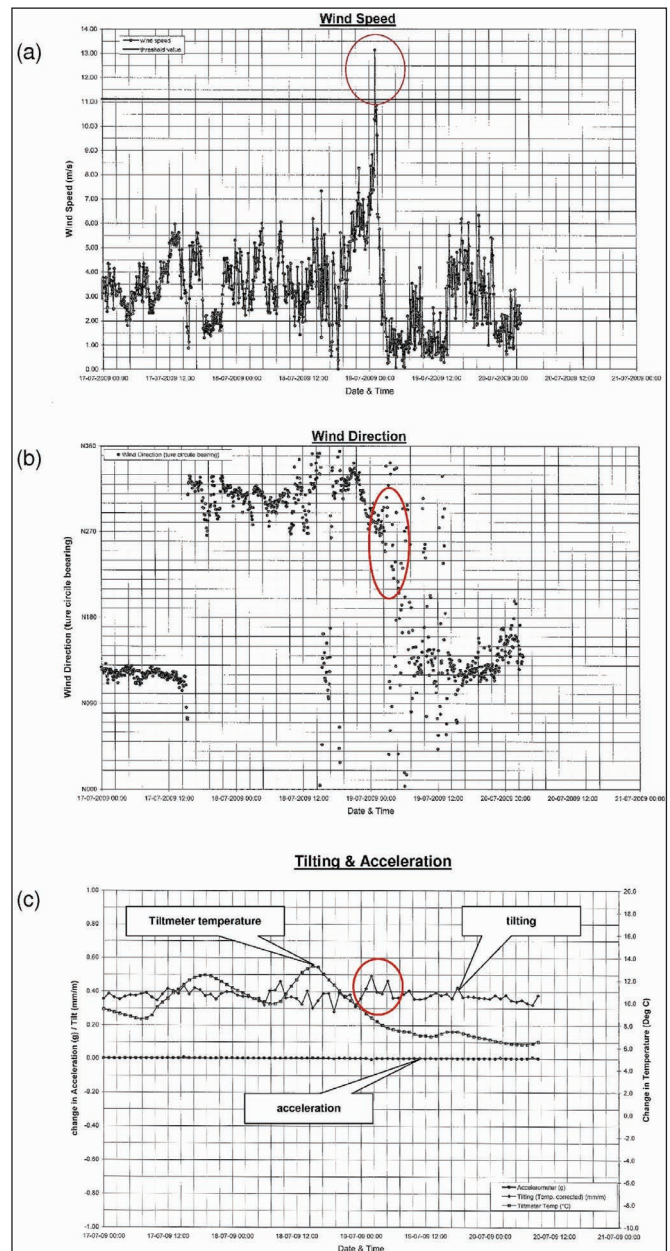


Figure 6. (a) The wind speed plot indicates the maximum wind speed that was recorded after midnight on 19 July 2009; (b) The wind direction changed from west to south-west during the period with highest wind speed; (c) The maximum transient tilt was recorded during the period with maximum wind speed, while acceleration was negligible.

Tilting and acceleration

The impact of a typhoon is illustrated in Figure 6. A maximum wind speed of 13m/s (see Figure 6a), with direction from west to south-west (see Figure 6b), was recorded around 1 a.m. on July 19, 2009, while the typhoon signal no. 9 was in force^[2]. It is evident from the chart that the maximum transient tilt of Fireboat AG was also detected simultaneously. Fortunately, the event did not lead to any permanent tilt and the reading resumed to normal shortly afterwards (see Figure 6c). Therefore, the wind load effect was not very significant. This can be explained by the phenomenon that the wind direction was almost parallel to the fireboat, which is aligned in an east-west direction, hence only a small part of the vessel was subject to the wind load. The acceleration recorded was negligible, which implied that the tilting movement had been relatively slow.

Hull convergence and foundation settlement

Up to January 2010, data collected in the program indicates that hull deformation and foundation settlement are both insignificant, but continuous monitoring will be carried out.

Limitations and future challenges

Though the SHM technique has been well developed for assessing the condition of new structures, its use for assessment of the Fireboat AG is, in fact, a pioneering attempt to apply the system to an historic vessel. The difficulties or challenges to be overcome include:

- While the Finite Element Modeling (FEM) is a typical component of a SHM programme for predicting the behaviour of new structures, lack of available information for the Fireboat AG meant that an FEM was not feasible. (Clemente and Buffarini 2009)
- The mechanical properties of historic structures may vary, due to workmanship, obsolete techniques, deterioration and corrosion
- There may be significant changes in the constitution of structural elements in the course of time, a consequence of the object's past service history (Lourenco 2001).

In most cases, an observational approach has been adopted in this project to determine the thresholds of the readings that give an early warning regarding the integrity of the fireboat and her cradle. Apart from the useful results, the project has provided the conservator with a good opportunity to assess the potential of applying SHM as a monitoring tool for the long-term preservation of historic vessels or large metal artifacts. Moreover, further studies on the following aspects will need to be carried out so that a more sensitive system with structural evaluation and appropriate diagnostic and prognostic capabilities can be developed. Future areas of interest are:

- The use of fiber optic sensors to provide more sensitive measurement, especially concerning the structural deformation;
- Development of a FEM to further verify the structural

stability of the vessel, and to determine the life expectancy of the whole display

- A real-time monitoring system be devised so that the structural behavior of the fireboat can be evaluated instantly, especially during extreme events
- Statistical models to be developed to differentiate undamaged features from damaged structures so that algorithms can be implemented to quantify the degree of damage of the vessel.

Conclusion

Display of objects in an outdoor environment is always difficult and metal objects in these situations are subject to degradation that will inevitably reduce their long term structural stability. A corrective approach, which is based on structural health monitoring that incorporates periodic inspections, and at times, instrumental tests or non-destructive analysis, was recently previously adopted to preserve the historic Fireboat *Alexander Grantham* in Hong Kong. After several decades of research and development in the engineering field, structural health monitoring is now considered a proven process for damage detection in structures. Providing adequate information on the structural performance over time ensures the overall safety and stability of the structure. Having pioneered this technique for the preservation of the Fireboat *Alexander Grantham*, conservators in Hong Kong believe that it can bring a new dimension to the inspection, maintenance, and repair strategy for other historic structures.

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Endnotes

[1] Risk-based approaches to inspection, maintenance and repair (IMR) strategies originated in the nuclear industry in the 1970s and have progressively migrated into other industries over the years, including the shipping industry for marine and offshore structures. It is a proactive approach and gives a balance between risk and inspection effort by including risk assessment of the asset coupled with the understanding of degradation mechanisms and consequences of failures for development of an optimum IMR programme.

[2] In accordance with the Hong Kong Observatory, typhoon signal no. 9 indicates the sustained wind speed is between 63-117 km/h, the gusts may exceed 180 km/h, and the wind strength is expected to increase significantly.

Materials

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