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Improvement of robustness through monitoring and smart materials/devices

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Summary

This paper reports on how technological advances in structural health monitoring techniques and smart structural systems and materials can be usefully deployed to enhance the robustness of a structure. An integration of these aspects with robust design criteria is envisioned for the future to enable an evolutionary concept of structural safety in the design and maintenance practice, eventually leading to the realization of innovative robust systems. For this purpose, a disciplined approach that flows from the data acquisition to the decision making process is outlined and the need of multidisciplinary engineering principles is emphasized. At the basis of such an approach is the understanding of the structural needs in order to maintain its service. These needs will drive the selection of the data that must be a priori known and those that should be monitored during the operational life of a structure.

Keywords

Robustness, structural health management, smart structures.

Background / Introduction

By providing the structures with an over-strength so that they do not reach their limit states by a large safety margin, the current design practice overcomes the difficulties related to an incomplete knowledge about the state of the materials due to processing and manufacturing and the environment and usage that the structures will actually experience during their operational lifetime. Since the current design practice requires to consider only the worst scenario, important information about the history, the usage and the events likelihood deriving from the experience gained on the existing constructions are ignored. Furthermore, the resulting structures have a fixed capacity of load resistance and energy dissipation, so that they cannot adapt to changes in the environmental excitation. Structural robustness criteria need to be put in place in order to cover these aspects and to assure the structural integrity following likely scenarios that are not directly considered in the design process.

Problem statement / Key issues

The challenge consists of developing a system that provides the information to make decisions well in advance of an event. The following questions should be answered in order to assess the structural robustness and to provide an opportunity for technology advancements:

- What data should be a priori known?
- What assumptions should be made about quality?
- What allowances should be made for usage or abusage during service?
- What new data could be gathered and processed to provide knowledge of state throughout a structure's service life?

Increased knowledge during the operational lifetime of a structural system can reduce the quantity of a priori needed information and provide more latitude during the design and maintenance processes. In order to make decisions on how to maintain, manage and improve the performance of a structure during its operational lifetime, data must provide a complete picture of the structural state in a timely manner. Methods to diagnose the data and to retrieve information that provides the knowledge needed to make decisions must be developed and implemented within a disciplined approach.

Methodology

The adoption of structural health management (SHM) systems as an integrated part of the structural design (Figure 1) 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.

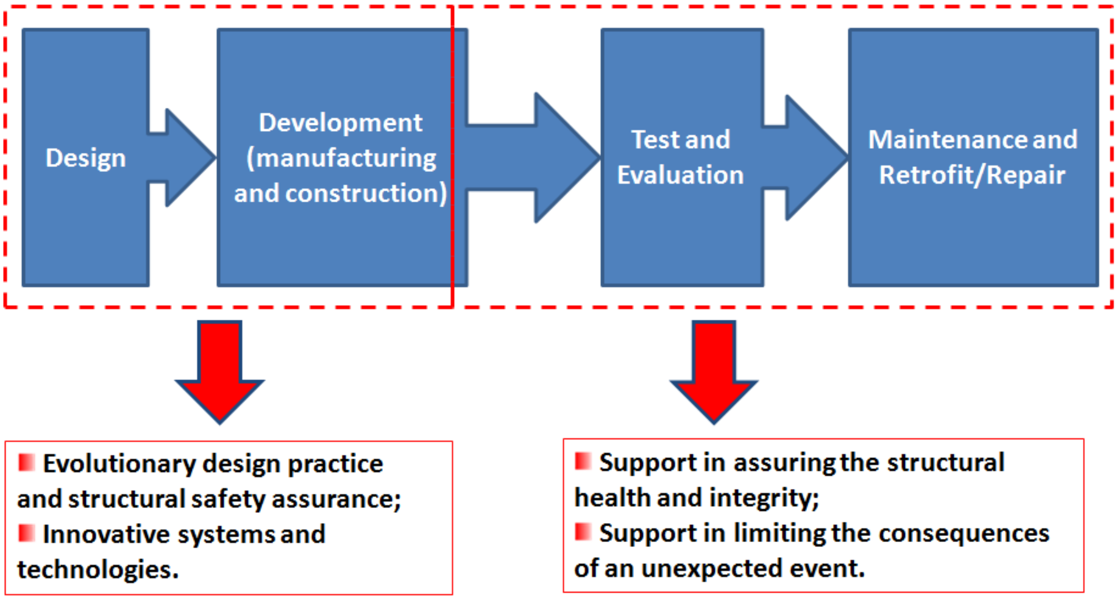

Figure 1: Influence of SHM technology new capabilities help all phases of a design life cycle

In the past decade there have been significant improvements in software, computer capability, diagnostics hardware, and engineering methodologies. However, the implementation of advanced SHM technologies into operational platforms has been limited. There have been advancements in nondestructive inspection techniques, but integration with and impact on the design practice has also been limited. An integrated solution, where structural systems and design criteria are developed with advanced SHM technologies in mind, and SHM technologies are developed by evaluating them in the context of new criteria and advancements in other design tools and practices, is a perspective envisioned for the future (Young et al., 2009). 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. Some applicative examples where advanced SHM technologies could be integrated, at varying levels, as part of the design criteria and the maintenance practice of a structure, are shown in Figure 2.

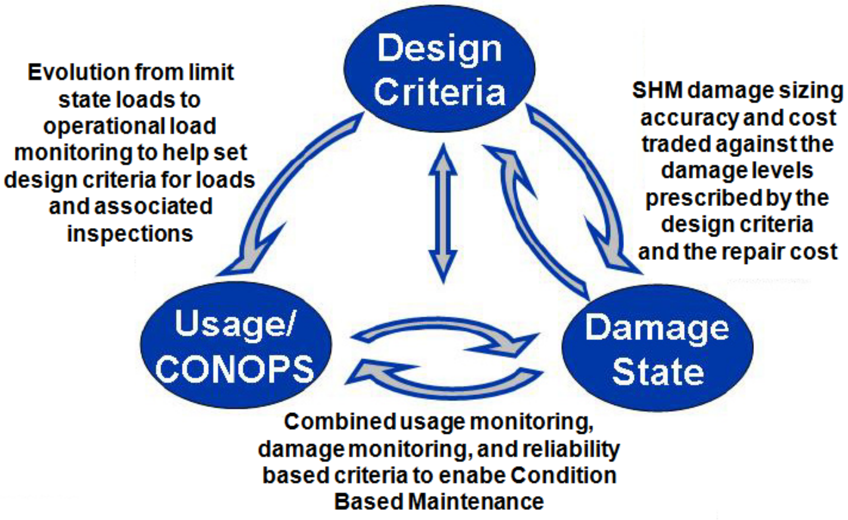

Figure 2: Applicative examples of integrating SHM, design and maintenance

For example, condition based maintenance (CBM) combines the concepts of operational load monitoring, with in service damage monitoring, in the context of reliability based criteria. The calculation of an Equivalent Initial Flaw Size (EIFS) along with operational loads collected by an in-service monitoring system of an individual network component (e.g., a single bridge of a transportation network) are key pieces of information needed to enable a reliability based approach. Sufficient crack data is collected during fatigue testing to develop initial EIFS probability distributions. The EFIS distributions are then used during operations along with load monitoring data to predict damage growth information. An additional and continued improvement to this approach can be accomplished by collecting critical crack length detection data during operational usage. Indeed, a probability distribution for crack length detection in time can then be used to further update the EIFS distributions and thereby to further improve the reliability based estimates for damage growth. This is a very illustrative example as it brings together advanced SHM technologies in the context of the reliability based criteria that are needed to provide the kind of knowledge that enables a CBM approach. It also offers the ability to update knowledge as operational data are collected over the structure’s lifetime. However, it should be noted that inspection intervals might not be defined based on fatigue loading alone.

At the base of the overall process is the identification of the structural needs in order to maintain its service based on the CONOPS (Concept of Operations), which is the document describing to the stakeholders the objectives of the system and the processes for its initiation, development, maintenance and dismissal. The identified needs will drive the decision that will be made about the integrity of the structural system (Ratay 2005). The data and first hand information needed to develop knowledge about the state of the material and the structure used in the design must be identified in the context of the CONOPS. These data are then processed with analytic methodologies that best fit the targeted design to obtain the most knowledge of state, and to allow for changes in criteria and CONOPS that optimize the safety and performance of the system. The SHM flow from data to decision making is summarized in Figure 4, where the main challenges of an SHM approach integrated with design and maintenance practices are also listed.

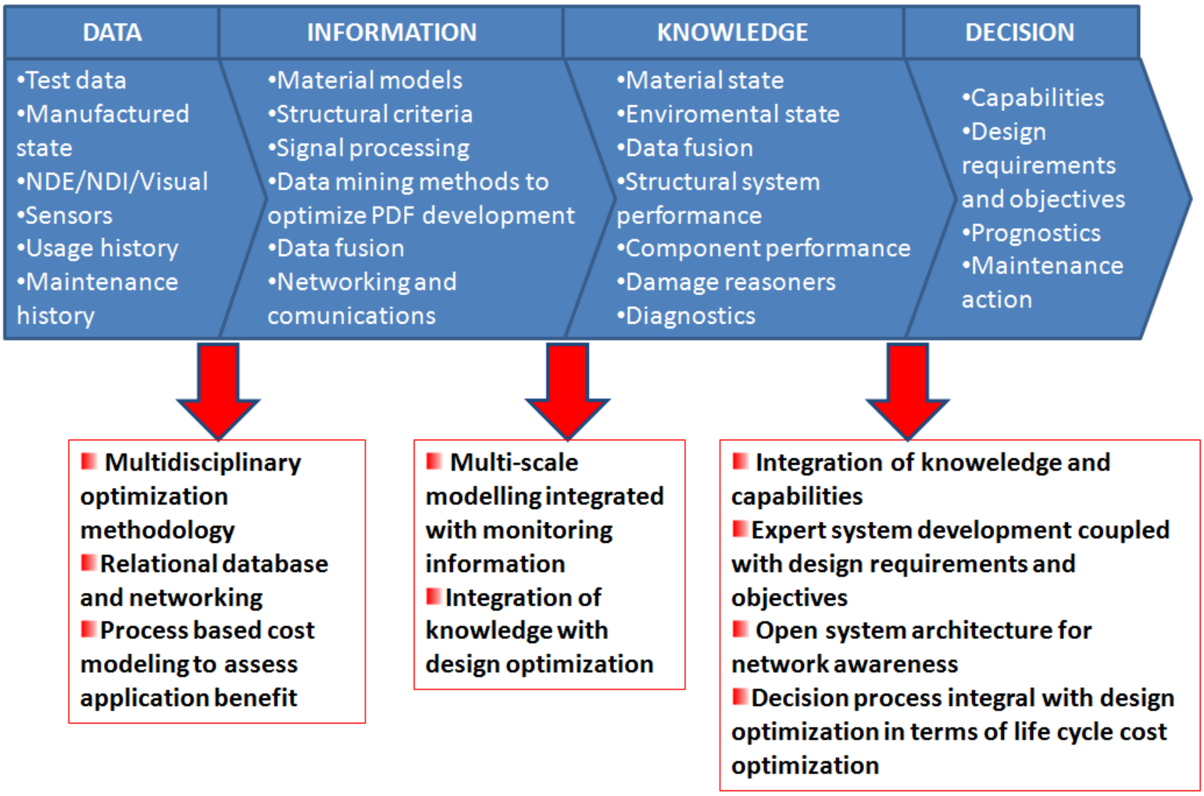

Figure 3: Disciplined approach for integration of SHM with design and maintenance practices

System integration can lead to an evolution from off-board SHM systems, where only sensors network are permanently attached to the structure, to on-board SHM sysytems, where sensors network, hardware and software are all integrated with the structure. Further developments are oriented toward the implementation of “autonomic or intelligent structures with bio-inspired sensory network” (Shoureshi and Faravelli, 2008) . The concept of smart structure originated from the discovery of natural or man-made materials with unusual properties (smart materials), and systems that can automatically adjust themselves to environmental changes (adaptive systems). With adaptive systems and/or smart materials and devices added to the structure, the structure becomes smart because it can monitor itself and adapt to the environment. A smart structural system has the ability to sense any change in the environment or system, diagnose any problem at critical locations, store and process monitored data, and command appropriate actions to improve system performance and to preserve structural integrity, safety (strength and stability) and serviceability (stiffness).

Main findings / Discussion

The smart structure concept has been applied to aerospace and mechanical industries, such as aircraft crack monitoring systems and automobile vibration absorbers. Application of this concept to large civil engineering structures is still a cutting-edge technology under research and development. Civil engineering structures designed using the traditional approach have limited capacities of load resistance and energy dissipation. Such structures totally rely on their own stiffness to resist the load and on their own small material damping to dissipate dynamic energy. These structures are “passive” in that they cannot adapt to ever-changing and uncertain environment excitation. In earthquake resistant design, an increase of structural strength and ductility is required, but high-strength and ductile construction materials are usually expensive. Increasing strength by enlarging the cross-sections of partial constituents members of an indeterminate structure actually attracts more demand force on these members, subsequently requiring even greater strength. This approach can then result in a fruitless spiral design. Moreover, there are no means to improve damping for common construction materials, such as reinforced concrete or steel. These observations led to the interest of developing innovative smart structure technologies for civil engineering applications. With smart structure technology, devices or systems are added to the structure so that it does not have to rely only on its own capacities, but also on these devices and/or systems to withstand the loads and to dissipate the energy. Smart structure systems can save materials and construction work, consequently reducing structural weight as well as construction cost.

The earliest smart structure technology for civil engineering applications was developed to control the dynamic response of a structure in either a passive, active, semi-active, or hybrid manner (Casciati et al., 2006). Basically, devices are added to the structure for vibration suppression or mitigation. In this way, loadings are counteracted not only by the structural members, but also by an “error-activated” control force which enables to automatically vary the structural system behavior in accordance with unpredictable variations in the loading as well as environmental conditions, and thereby produces desirable responses under all possible loading conditions. Today, such systems have been applied to specific classes of civil engineering structures that are either flexible and particularly sensitive to dynamic excitation (towers, tall building, long-span roofs or bridges), or have a critical function and consequent high safety requirements (hospitals, fire stations, power plants, government buildings).

Advances have been made also in the application of smart materials. Electrorheological or magnetorheological materials, piezoelectric layers, shape memory alloys (Casciati and Hamdaoui, 2008), and optical fiber sensors were the objects of many studies for civil engineering applications. They are used to develop sensors, dampers, and structural members with embedded smart material layers for sensing and actuation. Structural components with smart materials, dampers, and sensors are applied to civil engineering structures so that these structures are capable of responding spontaneously to the external excitation in order to minimize the undesired effects.

Novel sensors technology led to the development of cement-based composites, fatigue sensors, corrosion sensors, and others. The cement-based composites (Ou and Li, 2009) contain one or several conductive materials to convert cement from an insulant to a semi-conductive material with piezoresistive or piezoelectric properties. They are used to fabricate strain and acoustic emission sensors which are compliable with the matrix of the structure and have an identical strength and the same service life. The sensors initially developed to be wired need to be further improved to become wireless to enable the long-term applicability of the monitoring systems. A smart sensor is an enhanced integrated sensor with wireless and computational capabilities embedded with an on-board microprocessor. Smart sensors with high resolution data acquisition, large memory of the microprocessor, and power harvesting features are currently under development.

Limitations / Outlook to further research

The following issues must be addressed in order to enable the development of the proposed methodology of integrating SHM with structural design and maintenance:

- False negatives and false positives;
- Local versus global coverage;
- Wireless updating of existing wired monitoring systems;
- Assessing viable operational concepts that provide value;
- How to best transition new technology without proven reliability (addition of new technologies must ensure safety under existing certification);
- The impact and cost of integrating and maintaining SHM sensors and supporting hardware.

Recommendations

In order to perform structural health management for a structure in the future and to enable technological advancement and standardization, a disciplined approach that makes use of multidisciplinary engineering concepts is needed. Diagnostic techniques cannot preclude from considering hardware limitations, structural variations, and real operational constraints of the structure. Their aim is to provide a quantifiable result with a high degree of confidence (Probability of Detection, POD). Therefore, the challenge is to develop the right model with the right set of inputs so that it is reliable and technically and economically feasible. Direct measurements of load-related quantities (e.g., strain and/or acceleration) at every significant structural item might be costly. High-fidelity, physics based dynamic models may exist and be validated, but they must be quite detailed in order to provide such a high fidelity. Thus, they require significant computational resources to run. As it would not be feasible to field a practical solution with such a complicated model, an alternative solution must be pursued which consists of developing a lower fidelity model that can approximate the response of the detailed model using readily available data and information, including both the structural features assumed as deterministic (geometry, weight, etc.) and the sensors measurements (e.g., strain gage, accelerometer, temperature, etc.). The model can be trained for different inputs and topologies. Model performance is ranked by the ability to perform correct predictions, with limited false positives and no false negatives. The “tolerance” for false positives is traded against adding dedicated structural sensors.

Prognostic models are used to predict damage growth and to estimate the residual strength and remaining useful lifetime of a structure (Inman et al., 2005). In order to yield accurate predictions and estimates, a key issue is to create a proper link between the diagnostic outputs and the prognostic inputs (Mueller et al., 2009). Prognosis relies on a reliability-based predictive tool that makes use of a physics-based model to represent the progressive damage evolution. The data-based and physic-based portions of the process are not independent. The diagnosed damaged area first needs to be mapped to the structure finite element model. The next step of characterizing the diagnostic outputs with failure modes is crucial and future research needs to be conducted to overcome the difficulties. Future loading models are derived from usage monitoring that provides the actual loading and operating conditions and/or from design loads and environments. Progressive failure analysis is then performed within a Monte Carlo simulation scheme in order to achieve an estimate of the structural reliability and its evolution in time. Response surface methods to approximate the limit state function can be used to reduce the computational burden. However, the many uncertainties involved make the prognostic problem of difficult solution. The solution process is iterative, relying on the experience gained from past predictions to improve future predictions.

Example / Illustration / Case studies

The main stimulus for progress in the outlined research topics comes from innovative architectural solutions, such as the “rotating tower” by Arch. David Fischer (Casciati et al., 2009), which is currently under construction in Dubai. It consists of a luxury residential building with floors independently rotating around a central circular tower made of reinforced concrete. The motion is powered by wind turbines located in the gaps between the floors. Solar panels are also mounted at the top of each floor. The static concept of civil structures has turned into moving adaptable devices. Each rotating floor is *de facto* a machine which requires a monitoring system and a driving controller. Furthermore, all the units have to communicate with each other through wireless links. Maintenance becomes a key-aspect inherent to the structural design and not only limited to some of its tecnological components, thus paving the way to structural health management and to the adoption of fully adaptive active or hybrid control solutions.

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