Will sustainable development objectives increase the need for structural health monitoring in civil engineering?

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ABSTRACT: The concept of Structural Health Monitoring (SHM) has recently been defined as "a type of system that provides information on demand about any significant change or damage occurring in a structure". Another concept that has also gained a lot of ground in the civil engineering community in recent years is that of Sustainable Development (SD). Both concepts require engineers to think about the the whole-life design of structures in a new manner: the former represents a new tool with seemingly unlimited potential to provide information about the performance of structures and the latter represents a basic philosophical change in establishing criteria for design of structures. This paper discusses a variety of conceptual requirements and strategic issues which need to be understood by SHM engineers to effectively contribute to the decision-making process in a sustainable development context.

1 INTRODUCTION

The concept of Structural Health Monitoring (SHM) has recently been defined as "a type of system that provides information on demand about any significant change or damage occurring in a structure" (ISHMII, 2005). In principle, a useful SHM system would provide the civil engineers with a stream of measured data from the bridges, dams, roads or other infrastructure of interest. This information would in turn be used to alert the users of a given structure about incoming or potential dangers, to predict future behaviour of the structure under observation, to determine its remaining life, and in general, to support policy-makers in taking enlightened decisions on matters related to the repair, rehabilitation or replacement of their infrastructure. Obviously, SHM is of particular interest to owners of a large number of similar or inter-related structures, therefore making administrators of public-owned infrastructure a prime target for its development and implementation.

Another concept that has also gained a lot of ground in the civil engineering community in the recent years is that of Sustainable Development (SD). This concept was introduced to the world community by the World Commission on Environment and Development, also known as the Bruntdland Commission (Brundtland et al., 1987). The principles it advocated eventually reached the engineering community. For instance, the effect of this movement is testified by the adoption of *The Shanghai Declaration on Engineering and the Sustainable Future* by the World Engineers' Convention in November 2004 (Canadian Society for Civil Engineering, 2004). SD is viewed as a means to reduce poverty while maintaining prosperity. A sustainable future has clearly been shown to require a more efficient use the Earth's natural resources; for structural engineers, this translates in an increased responsibilty in the design and operation of long-lasting, material-efficient, and well-maintained structures.

Both concepts require engineers to think about the whole-life design of structures in a new manner: the former represents a new tool with seemingly umlimited potential to provide information about the performance of structures and the latter represents a basic philosophical change in establishing criteria for design of strucutres. Despite very significant technological progress in the last ten years, SHM has far to go to deliver on its advertised promises in civil structural engineering and realize wide-spread implementation. However, the generalized acceptance of sustainable development principles by an increasing number of international regulatory organizations provides a welcome opportunity to promote the benefits of SHM systems. In fact, SHM technology may be essential if SD objectives are to be fully achieved in civil infrastructure. This paper therefore discusses the challenges that need to be addressed to ensure that SHM will contribute effectively to a sustainable future for mankind. The paper does not cover advanced technical issues related to specific measurement devices, communication materials, or characteristics of products for SHM data storage. All of them are bound to evolve significantly during the lifetime of any well-conceived civil engineering structure. The paper will rather examine conceptual requirements and strategic issues which need to be understood by SHM engineers to effectively contribute to the decision-making process in a sustainable development context.

The practice of SD in the civil engineering community has many aspects and dimensions which cane be broadly categorized under ecological sustainability, economical sustainability and social sustainability (Maydl 2004). There are many specifics issues under each of these categories; but within the context of this paper the relevant SD issues are: Ecological – wastes avoidance and efficient use of natural resources; Economic – life cycle costs, reliability and risk management. These issues are very closely linked to the durability and extended service life of structures. Due to the authors' familiarity with bridge structures in particular, bridges will be used as the focal point for discussing the relevant concepts; however, the reader can hopefully extract how the ideas presented are relevant to all structures.

2 DURABILITY OF BRIDGES

Bridge technology has evolved through the centuries, and at a pace faster than ever in the most recent years. The choice of masonry as construction material and the use of compression as the main load bearing system meant that the span of ancient bridges was rather limited. However, the ingenuity of Roman engineers and their desire to build long-lasting structures was such that impressive constructions like the Pont du Gard, in France, have survived until now. Although it may be argued that this particular construction no longer functions as an aqueduct, as it was originally intended, its lower level can still carry limited traffic loads, in part because of restoration work that was carried out between the Middle Ages and the twentieth century.

At the other end of the spectrum, the most spectacular bridges of the twentieth century rely mostly on tension as their main load transmission mechanism and they make use of advanced industrialized materials such as steel. Mastering the technical challenges while minimizing capital costs was often the prime consideration in these designs. However, our modern structures have faced unexpected challenges and many of them show signs of premature ageing, due to material limitations, increasing loads and poor maintenance .

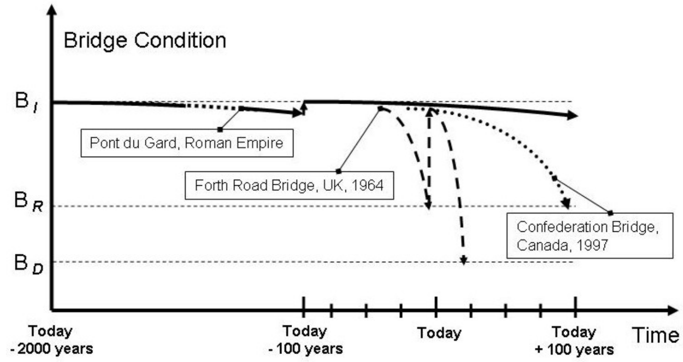

Figure 1. Durability of Bridges

For instance, it was recently reported (COBRAE, 2005) that the combination of traffic increase, load conditions and extent of damages which are already identified on the Forth Road Bridge, a structural icon of the 20th century, is such that despite partial closure and a major reconstruction in the 1990s, it may not be able to survive more than 20 years from now. Some reports even anticipate that a total closure of the bridge may be necessary in no more than 10 years. Figure 1 compares, conceptually, the evolution of these two bridges on a similar time scale. When they entered service, both bridges were state-of-the art for their time. Each bridge's condition was then close to "perfect" or "in agreement with engineering expectations" of the day. In the figure, this corresponds to a descriptive index B_I. Over time, both bridges lost part of their initial capacity. At some point, each underwent repairs or major refurbishment to recover their initial capacity. They could eventually reach a point that forces decommission, when the descriptive index reaches B_D. Due to the high traffic demand on the bridge, it can be argued that the state of degradation of the Forth Bridge was far more critical, relatively speaking, when it was repaired than that of Pont du Gard at any time.

The recognition that relatively recent bridges have reached an advanced state of degradation has encouraged authorities to make provisions to ensure longer life cycles for their new structures. For instance, major structures such as the Confederation Bridge in Canada are expected to survive at least a century before major repairs. An extensive monitoring program has therefore been put in place on this structure to assist in understanding the response to loads and the degradation mechanisms such that early maintenance strategies can be enacted.

The fact that new structures face rapidly increasing demand and that they rely on advanced materials and technologies condemns them, in a sense, to faster degradation than structures from other ages which are no longer adapted to current applications. It is a clear indication, however, of the need to properly assess the condition of bridges and a strong argument for implementation of structural health monitoring for our most advanced constructions.

3 BRIDGE DEGRADATION OVER TIME

The observations arising from the historical bridges discussed above may be generalized to establish a tentative relationship between structural health monitoring and the application of sustainable development principles to bridge engineering.

3.1 *General issues*

Figure 2 summarizes the behaviour of bridges over their life cycle. On its inauguration day, a new bridge has presumably been designed and properly constructed in order to satisfy a set of criteria pertaining to its use and to ensure its long lasting serviceability. If a standardized index were available to describe the condition of the bridge at this time T_0, B_I should normally correspond to the maximum possible value for this structure. Once in service, any bridge index that characterizes the overall condition of the structure will undergo a decrease due to the simple fact that loading and time produce damages. Normally, the initial damages are localized and do not produce significant consequences on the behaviour of the structure. However, over time, the accumulation of minute damages becomes significant. At some point, the index describing the condition of the bridge may be so low, B_D, that it becomes necessary to decommission the structure. On Figure 2, the bridge condition would follow path 1 leading from point “a” at T_0 until it reaches decommission at T_D.

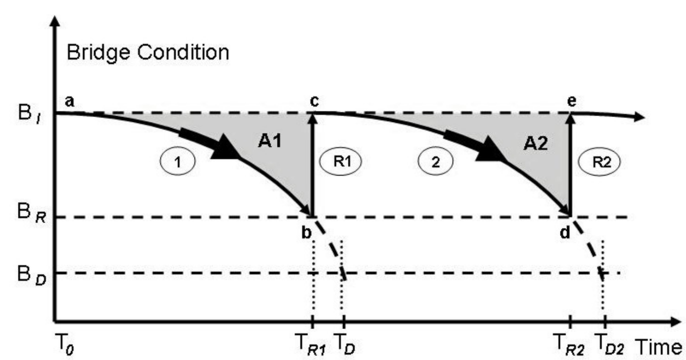

Figure 2. Bridge condition over time

Of course, some time before this critical juncture, the owner may have repaired the structure and restored it to recover its initial capacity. For example, the owner may have decided that once the descriptive index would reach a predetermined value B_R, it would be timely to invest in the rehabilitation of the structure. In the case illustrated, this occurs at time T_{R1}. Once the repair is completed, the bridge recovers its initial descriptive index B_I.

Obviously, major repairs will be more costly and will cause more disturbances to the users than minor repairs. The relationship between the condition of bridge at repair, the amount of repairs and the impact on life cycle costs and service life is complex. However, assuming action is taken before B_D, proper maintenance and frequent repairs will likely be less disturbing and less costly than one major overhaul down the line. It can be imagined that the area A1 enclosed by the path *a-b-c* provides a rough evaluation of the cost of the repairwork needed to bring any given structure to its original condition. In a SD context, this cost should include not only the amount of construction work and materials required but also their associated embodied energy and environmental impact, the amount of waste generated and the value of all social aspects, such as disturbances due to traffic delays and the resulting increase in emissions. Long-term benefits and costs must also be taken into consideration. In fact, one can see that, as T_{R1} gets closer to T_D, the area A1 on Figure 2 increases very rapidly. It is hypothesized that the size of this area is inversely related to the capacity of the structure to operate within sustainable development goals. For the sake of the discussion, we will assume from now on that this area can be measured in “sustainability units” instead of any monetary unit.

At one point, decommissioning the bridge and building a new one may become the only technical solution available. On the other hand, if the decision to repair the bridge is taken soon enough, the existing structure would then undergo a second cycle and follow the path *c-d* until a new overhaul may become necessary again. Theoretically this could go on forever. While this is unlikely, the rehabilitation activity definitely extends the usable life of the structure fulfilling the objectives of SD and providing additional sustainability units.

3.2 *Effect of load variations*

Modern bridges are designed to sustain regulated traffic loads which are clearly identified in codes and standards. However, design loads clearly show a tendency to increase over the lifetime of the bridge, significantly affecting the evolution of its condition over time. This is illustrated in Figure 3.

If the applied loads remain constant, we have already seen that the bridge condition over time would follow a path along the line *a-b*, and then, after repair to the original condition, along the line *c-d*, and so on. However, if the applied loads increase continuously, the bridge degradation will occur faster. This in turn would force the potential decommissioning of the structure earlier than if the initial load conditions prevailed. Instead of following path *a-b* on the bridge condition versus time diagram, the structural behaviour would rather follow path *a-b’*. Instead of T_D, the bridge would reach decommission time at point $T_{D'}$. Likewise, repairs would need to be scheduled at time $T_{R1'}$ instead of T_{R1}.

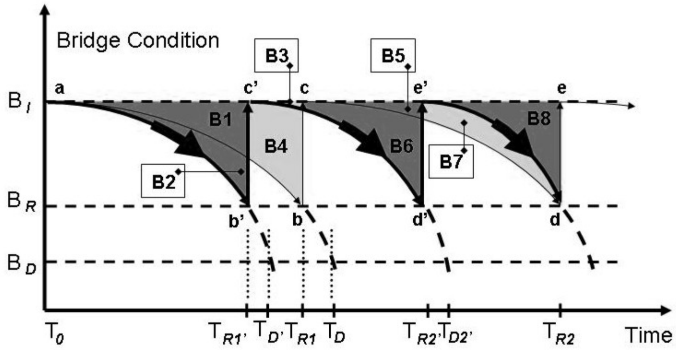

Figure 3. Effect of continually increasing load

Another effect is observed in the frequency of the repair. Under constant loads, repairs would occur at equal intervals. Under continually increasing loads, the repairs would have to be undertaken at continually decreasing intervals. For decision makers, the recommendation to repair the structure in the face of increasing traffic, evolving loading conditions and accelerating degradation, not to mention public awareness, is always a difficult one. While keeping the hypothesis that the sustainable unit cost of the structural repair is actually related to the area enclosed by the paths drawn in Figure 3, three situations faced by structure owners will be discussed.

3.2.1 *The case of a single repair*

We will first assume that the owner of a new structure is interested in following its behaviour until the time of its first repair only. If the load is constant, the structure will undergo normal degradation. The first repair will be recommended at time T_{R1}, and the sustainability unit cost will be related to the area enclosed by path *a-b-c*. In Figure 3, this comprises areas B1, B3 and B4. On the other hand, if the load increases through time, and if the first repair is still recommended when the structure reaches B_R, this will occur earlier at time $T_{R1'}$. The sustainability cost of the operation will be related to the area enclosed by path *a-b'-c'*, consisting of areas B1 and B2. The cost of the repair would then remain smaller than that with constant loads if the sum of areas B2 and B3 is smaller than area B4 in the figure, although the time of repair would be sooner.

This figure illustrates that if the level of the index B_R could be selected, it would influence the relationship between the anticipated and the observed behaviour of the bridge as it modifies the relative areas enclosed by paths *a-b-c* and *a-b'-c'*. This information could be used to support decisions to repair the structure at any given time or to postpone it to a later date.

3.2.2 *The case of successive repairs*

We will now assume that the owner of the structure is interested in the long-term behaviour of the bridge and anticipates the fact that it will likely survive many cycles of repair. Figure 3 also illustrates the case in which two cycles at constant load are of the same duration than to three cycles with continually increasing load. If the load remains constant, the path will follow the lines *a-b-c-d-e*; the entire area enclosed by this path will comprise areas B1, B3, B4, B5, B7 and B8 in the figure. The time between T_{R2} andT_{R1} is the same as the time between T_{R1} and T_{R0}. On the other hand, if the loading conditions increase continuously over time, the bridge condition will follow the path *a-b'-c'-d'-e'-d-e*. This path will then incorporate areas B1, B2, B3, B5, B6 and B8. It this case, it can be seen that the time between each repair goes down. For instance, T_{R2}-$T_{R2'}$ is shorter than $T_{R2'}$-$T_{R1'}$, which is itself shorter than $T_{R1'}$-T_0.

It is suggested that if the sum of the areas B2 and B6 is larger than the sum of B4 and B7, the increasing load conditions will be more expensive than if the load had remained constant over the same service life. Obviously, the ability of the owner of the structure to select an optimal level of B_R would again help decision making. It is suggested that a key tool for this ability may be the availability of a reliable health structural monitoring system.

3.2.3 *The case of partial upgrades*

Another situation that may arise is the partial upgrading of the bridge at any given time. This is illustrated in Figure 4 for the case of constant load.

If a partial repair is made when the bridge descriptive index reaches B_P at time T_U, the net effect will be to push the load path from the line *a-b* up to the line *a-b'*. Although the bridge is not restored to B_I, the main consequence of moving upwards from path *a-b* to path *a-b'* is that it extends the full expected life of the structure from T_D to T_{DU} yielding increased survival time at relatively low investment. Since the effect of the repair was not to reinstate the original strength, it could be hypothesized that its sustainable unit cost would be proportional to area C1 in Figure 4. If full repair then takes place at time T_{R1}, as would have been expected originally, the area C3 correspond to overall savings in the long-term operation of the structure.

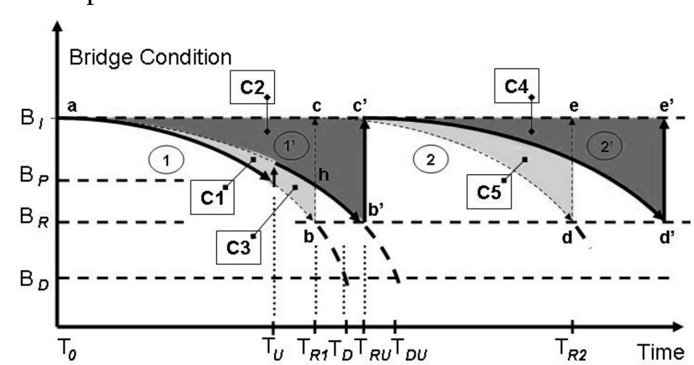

Figure 4. Effect of preventive bridge upgrade

Another option available to the owner is now to postpone any major upgrade to time T_{RU}. However, the previous savings C3 may now be lost due to the addition of area *c-c'-b'-h* in the sustainable unit costs of the operation.

Obviously, the selection of appropriate levels of indexes B_P, B_R as well as repair times T_U, T_{R1} or T_{RU} will have a significant effect on the overall relation between the areas enclosed by the various paths in Figure 4. This, in turn, will lead to a significant increase of the related sustainable unit costs that are presumably associated to them.

4 POTENTIAL IMPACT OF SHM ON SD

The potential impact of SHM technology on the incorporation of sustainable development principles in the whole management process will be discussed from three perspectives.

4.1 *General Support tool for life cycle management*

Decision making in the situations described in the previous section will require the integration of several emerging concepts in the design and management of structures. To achieve the SD objectives through extended service life and optimized repairs, several other advanced tools will be required such as life cycle performance models, probabilistic based assessment and performance based design. The success and effectiveness each of these tools clearly depends on the availability of reliable data on traffic and environmental loads, on material degradation and on structural response of the bridge. With the rapid advances in fibre optic systems, monitoring devices, communication systems and information technology, it can be anticipated that a reliable SHM will be readily available in the future.

4.2 *SHM as a warning tool for existing structures*

The number of bridges and structures that are approaching the end of their expected design life is so large that replacement or upgrade strategies have to be implemented. In this context, any strategy that would allow distribution of the replacement or upgrade work over an extended timeframe would be welcome. In this context, SHM could be implemented on existing structures with the objective of extending its use as much as possible. This concept is illustrated in Figure 5.

Assume that an existing bridge has been allowed to deteriorate to its descriptive index repair value B_R at time T_{R1}. The bridge owner may allow the structure to carry on its duty, most likely under the imposition of reduced traffic loads and of an increasingly severe inspection schedule, until it faces conditions that would lead to final decommission and replacement. Also, the conditions B_R and B_D are normally very conservatively estimated.

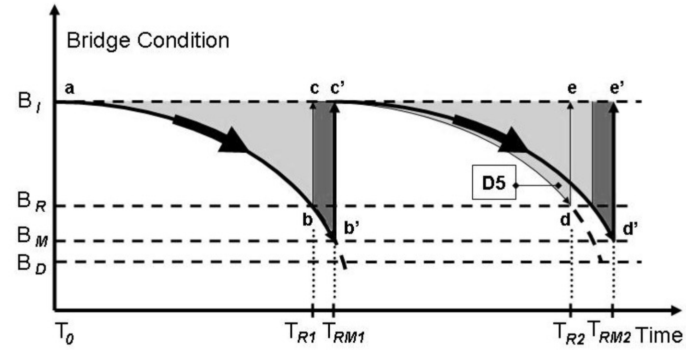

Figure 5. SHM as a warning tool

Alternatively, the installation of a reliable SHM system could be used to extend the life of the structure. By providing a more accurate picture of the structural condition, it would remove uncertainty in the assessment of condition and allow the structure life to be pushed closer to its limit without comprising safety. This leads to the introduction of another descriptive index B_M, as shown in Figure 5, between the index levels B_R and B_D.

This may not be viewed as a strong SD argument since this involves the investment of a significant amount of sustainable units: in Figure 5, they correspond to the area enclosed by *b-c-c'-b'*. However, at time T_{RM1}, the structure could still undergo major repairs and upgrading. In such a case, two full repair cycles would follow the path *a-b'-c'-d'-e'* rather than path *a-b-c-d-e-* for a non-monitored structure. Beyond the total service life extension from time T_{R2} to T_{RM2} and improved resource distribution capabilities, significant sustainable unit costs may be saved over the normal lifetime of the structure; measured by comparing the additional expenses incurred in the area enclosed by *b-c-c'-b'* to the savings in area D5.

4.3 *SHM as a prevention tool in new structures*

The use of a SHM approach is particularly promising in the case of new structures. As proposed in Figure 2, a structure sustaining normal loadings would eventually reduce to B_R at time T_R, represented by path *a-b-c-d-e* in Figure 6. If a reliable SHM system is installed on the structure, improved early evaluation of its condition would be available . Significant but non-critical events would be detected. At some point, corresponding to the descriptive index B_P, their accumulation might be such that the minor damages could be fixed and the structure, restored to its original condition. Figure 6 illustrates that the total sustainability unit costs of minor regular repairs are significantly lower than one-time major repair schemes.

This scenario illustrates how a long-term commitment to regular damage identification and maintenance can produce SD value and savings to society. In fact, the total savings on that particular structure, corresponding to the areas bound by *b'-c'-*

d'-b and *f'-g'-h'-d* in Figure 6, might have a higher SD value than the actual expense units which are bound by the four darker areas similar to *a-b'-c'*.

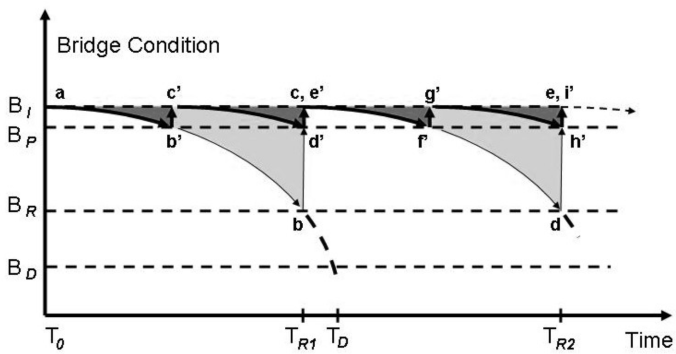

Figure 6. SHM as a prevention tool

5 OTHER SHM ISSUES

In the view of the authors, SHM systems can be designed in answer to two distinct problem categories. First, there are existing structures that need to be monitored closely to extend their working life. In this case, the SHM system is installed quite late in the life cycle of the structure and its objective is essentially to extend its life as much as possible. Secondly, there are systems that may be installed early on, to follow structural behaviour from the construction phase or to assess the performance of a new concept. In this case, the main objectives of the SHM system are to advance engineering knowledge and to improve efficiency of future structural designs. The results of such data gathering may even influence the design of non-monitored structures, for instance by the acquisition of a more detailed knowledge of load distribution and structural behaviour, and by justifying the incorporation of such data in codes and standards.

However, it is possible that the potential generalization of SHM devices and their incorporation into old or new structures may produce social side effects that still need to be investigated. On a minor level are many issues related to ownership and use of SHM data and related privacy laws if video monitoring is incorporated. On a major level, the use of SHM may influence significantly legal issues and could contribute to redefining the legal responsibility of engineers, particularly in circumstances where SHM is being used to extend service life or define safety. The issues are doubled edged: what is the liability of the engineer if the ability to generate a new awareness of structural behaviour and of material degradation exists yet an unexpected failure occurs; or, what if the installation of SHM devices in an existing structure seemingly exhibiting good working states reveals failures, invisible to the naked eye and unknown to the original designer, builder or owner? Either event could trigger series of inappropriate legal actions. Also, what legal actions may be pursued if expensive mitigating measures are taken in response to a monitoring system that wrongly sent a warning to prevent a potentially dangerous event? Altogether, SHM may deeply modify the working environment of structural engineers.

6 CONCLUSION

In recent years, sustainable development has become a defining issue in civil and structural engineering. The need to extend the life of existing structures beyond their initial design has also generated high expectations towards structural health monitoring. In this paper, the authors intended to establish a framework that would illustrate how the two concepts may support each other. Further work is necessary to develop this vision further and to validate the framework through the analysis of actual monitoring data such as those acquired by the authors (Han et al., 2004; Rochette et al., 2002).

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