# Civionics A New Paradigm in Design, Evaluation, and Risk Analysis of Civil Structures

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# Civionics – A New Paradigm in Design, Evaluation, and Risk Analysis of Civil Structures

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**ABSTRACT:** This article discusses the reasons why civil engineers are very conservative in the design of new structures and the evaluation of existing structures. It is argued that structural health monitoring (SHM) will assist in providing data that could be used to fine-tune the calibration of load and strength factors leading to more efficient and economical designs and better utilization of the strengths of existing structures. For major changes in design, construction, and evaluation to be accepted, it is necessary that innovative structures be monitored for their health so that the required data bank can be developed. To assist in achieving this goal, civil engineers in Canada are developing a new discipline, which integrates civil engineering and electrophotonics under the combined term 'civionics'.

*Key Words:* civionics, conservative, data, decision, designs, efficient, evaluation, risk, safety index, structural engineers, SHM.

## RISK ASSOCIATED WITH CIVIL STRUCTURES

WITH respect to the topic of this article, civil engineers should ask themselves two important questions:

- Are civil structural engineers 'risk-averse'?
- Can structural health monitoring in the field be useful in managing the risk?

Before trying to answer these two questions, the authors would like to examine various human endeavors and the degree of risk involved in each of them that is 'accepted' by society. For example, the table of the risk of death involved in various activities, as proposed by Melchers (1987), is reproduced in Table 1.

Notwithstanding the accuracy of the risk values given in Table 1, it is clear that the risk involved in the failure of completed civil structures is significantly smaller than that involved, for example, in air travel. It is recalled that civil structures include bridges, public buildings, dams, offshore platforms, and power plants. The glaring differences between the risks involved in various human endeavors lead to another set of questions:

- Are the low levels of risks associated with completed civil structures fixed by society?
- Or are these risk levels fixed by the designers of civil structures themselves because they are wary of taking undue risks?

It is true that the public does not expect civil structures to ever fail. However, the authors suspect that the low risk levels associated with completed civil structures are a result of a combination of both the demands of society and also the awareness of the structural engineer that, unlike manufactured machines with usually well-tested prototypes, each structure is unique and nearly always without means to monitor its performance during its service life under loads and circumstances, which are more difficult to forecast than those for machines. The authors would like to make a case for the structural health monitoring (SHM) of important civil structures, such as large bridges and public buildings. They could be monitored on a continuous basis, thus eliminating

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Los Angeles, London, New Delhi and Singapore

*Table 1. Risk of death involved in various activities.*

| Activity | Risk (/Million/year) |
|---|---|
| Alpine climbing | 1500–2000 |
| Swimming | 120 |
| Smoking | 1000 |
| Air travel | 24 |
| Car travel | 200 |
| Coal mining | 300 |
| Construction | 150–440 |
| Manufacturing | 4000 |
| Building fires | 8–24 |
| Structural failures | 0.1 |

certain unknowns about their performance, which could and do change with time. In making a case for the SHM of important civil structures, the authors foresee a slight increase in the notional or theoretical, rather than the actual, risk of failure in these structures, but a significant reduction in the capital cost that society has to incur partly to construct and largely to maintain its infrastructure.

## CIVIL STRUCTURAL DESIGN PROCESS

Traditionally, structural components were designed by the working stress method, which requires that the maximum stress due to nominal dead loads and live 'service' loads is a fraction of the maximum stress that the component can withstand. The ratio of the failure stress to the 'actual' stress was and is still known as the factor of safety. As long as the factor of safety was a sufficiently large number, such as 2 or 3, the design was deemed to be safe. While the working stress design has served the engineering community well for a long time, it has led to structures with non-uniform margins of safety. For example, if long- and short-span components were designed to the same design specifications, or codes, the long-span components would have considerably larger margins of safety than their short-span counterparts. This would be so because the designs of large span components are largely governed by dead loads, which can be forecast with more certainty than live loads. On the other hand, the design of short-span components is usually governed by live loads.

The works of researchers such as Cornell and Lind in the late 1960s and early 1970s laid the foundations for modern structural design codes, which are based on the concept of structural reliability (Nowak and Collins, 2000). In Canada and some parts of Europe, the probabilistic-based design method is referred to as the limit states design method. In the USA, the same method is referred to as the load and resistance factor design (LRFD) method. The first limit states design code for bridge design in Canada was the Ontario Highway Bridge Design Code introduced in 1979, followed by its two editions, and then by the Canadian Highway Bridge Design Code (2000). The LRFD method was first introduced for bridge design by the AASHTO Specifications in 1994.

It is important to note that the working stress method, which is still practiced in many parts of the USA as well as in many other countries, was used to design a very large part of the current stock of infrastructure in practically every country. The earlier working stress design methods, requiring manual calculations and based on simplifying assumptions usually led to structures with large reserves of strength. By careful use of SHM, the conservatism of civil structural engineers can be reduced. This reduction will lead to economies in the design and building of safe and innovative structures. The use of SHM is also expected to encourage innovative structures.

The level of safety of a structural component is determined by the probability of its strength exceeding the maximum load effect it would receive during its lifetime. Such a determination requires knowledge of the statistical distribution of both the strengths of the component and the maximum loads to which the component would be subjected. For designing new components, the statistical distribution of strengths necessarily includes very low – even zero – strengths. For a component of an in-service structure, however, such low strengths need not be included in the strength distribution. A method proposed by Bakht et al. (2002) allowed advantage to be taken of the fact that a component of an in-service bridge has already been proof tested by traffic, therefore, its strength cannot be below the load effects due to the corresponding maximum traffic load. By utilizing the proposed method, the evaluated live load capacity of a component can be upgraded significantly, if the strength under consideration has a large statistical variation.

Safety margins in a structural component are measured by the probabilistic-based safety index, $\beta$. Although the term 'safety index' has been around for quite some time (for example, OHBDC, 1979; CHBDC, 2000), it has not yet gained currency with many engineers who are still uncomfortable with probabilistic methods in structural engineering. In order to explain the safety index in simple terms, consider a three-lane bridge with four simply supported spans and a total of 28 reinforced concrete girders (Figure 1). Further, assume that the point of interest is the moment capacity of the girders at their midspans. It is well known that, if all the reinforced girders were tested to failure, the likely finding would be that each girder has a somewhat different moment of resistance than those of the others. A few girders are likely to have a very small moment capacity, while a few others would have a very high moment capacity. The majority of girders would perhaps have their moments of resistance within a

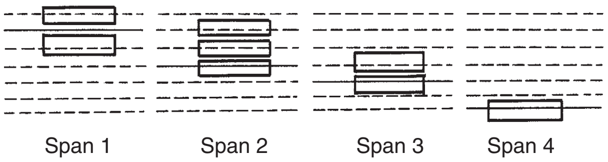

***Figure 1.*** *Girders of a four-span bridge shown in plan.*

narrow band. The histogram of the moments of resistance of the girders can be represented by a continuous distribution curve, denoted in Figure 2 as $R$ (resistance). The mean and standard deviation of $R$ are denoted as $\mu_R$ and $\sigma_R$, respectively.

During the lifetime of the bridge, each girder is likely to be subjected to a different maximum live load moment. For example, as illustrated in Figure 1, a girder in Span 1 shown in solid line, might receive its maximum live load moment from two exceptionally heavy trucks, present on the bridge at the same time. Similarly, a girder in Span 2, also shown in solid line in Figure 1, might experience its maximum moment under three different heavy trucks simultaneously present on the span, and so on. These lifetime maximum moments are designated as $S_1$, $S_2$, $S_3$, $S_4$, etc. A normal distribution is assumed for these moments, denoted by $S$ in Figure 2; for simplicity, it is also assumed that these moments include the effect of both dead and live loads. The mean and standard deviation of $S$ are denoted as $\mu_S$ and $\sigma_S$, respectively.

The overlapping area of the $R$ and $S$ curves, shown shaded in Figure 2, is a qualitative, although not quantitative, measure of the fact that there is a probability that the moment of resistance of some girders would be exceeded by the maximum applied moments. The reduction of maximum applied moments – for instance, by enforcing stricter weight regulations – would have the effect of moving the $S$ curve to the left, thus reducing the area of overlap, and thereby in effect reducing the probability of failure.

A quantity $g$, defined by $g = R - S$, can be used to assess safety quantitatively; the frequency distribution of this quantity is shown in Figure 3, in which it can be seen that a certain portion of the $g$ curve, shown shaded, lies in the negative region. As is also shown in Figure 3, the zero value of $g$ lies at a distance $\beta \times \sigma_g$ to the left of $\mu_g$, where $\sigma_g$ and $\mu_g$ are respectively the standard deviation and mean of $g$. The quantity $\beta$ is the quantitative measure of the probability of $S$ exceeding $R$; it is referred to as the safety index. The safety index for individual components is given by:

$$\beta = \frac{\mu_R - \mu_S}{\sigma_R^2 + \sigma_S^2}. \qquad (1)$$

Similar to several other modern limit state design codes, the Canadian and American bridge design codes relate only to the notional safety index $\beta$.

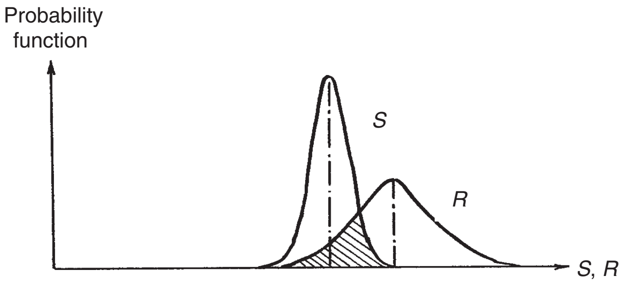

***Figure 2.*** *Distributions of maximum moments and moments of resistance.*

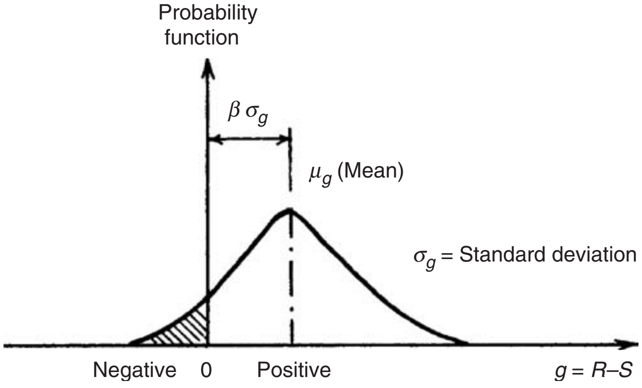

***Figure 3.*** *Distribution of g.*

After determining by back calculations, that the value of $\beta$ for components of existing bridges is 3.5 or greater, it was agreed amongst the experts in the field that components of new bridges should be designed for $\beta$ equal to $\approx 3.5$. Both the Canadian and American bridge design codes are generally calibrated to $\beta = 3.5$, which corresponds to the notional, i.e., theoretical, probability of failure of a component of 1 in nearly 2000 during the lifetime of the bridge (Figure 4). Considering the lifetime of a bridge to be 75 years, the probability of failure corresponding to $\beta = 3.5$ translates to one failure in about 150,000/year. The fact that this probability of failure is significantly larger than the probability of failure of one in 10 million/year for completed structures (Table 1), underscores two very important points with respect to bridges, in particular:

- $\beta$ relates only to the theoretical failure of a component; the failure of the combination of components, being a system, has a much smaller probability of failure; and
- since most failures are caused by extreme events, such as those relating to hydraulics, $\beta$ should not be taken as the real measure of the safety of a structure.

The resistance of a structure, such as a bridge, can decrease with time due to environmental and other time-dependent effects, with the result that the $R$ distribution shown in Figure 2 moves to the left. Similarly, the live loads that a bridge is called upon to carry can also

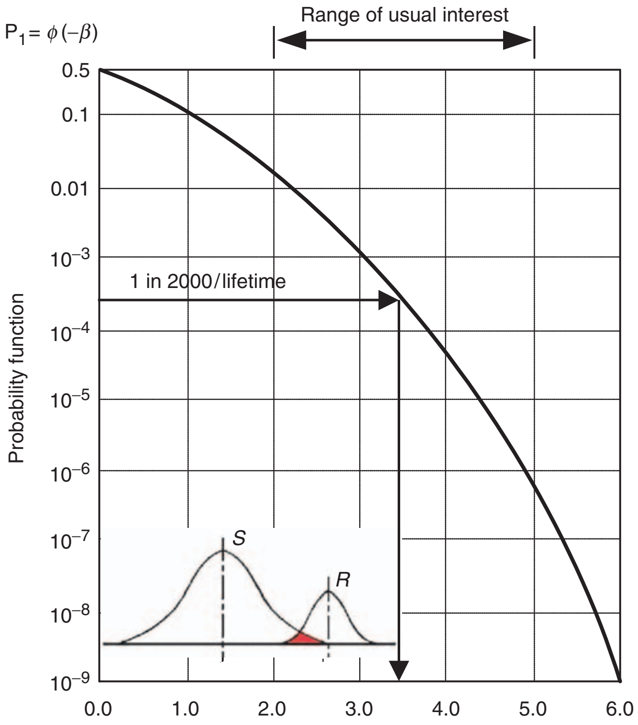

***Figure 4.*** *Safety index $\beta$ and probability of failure.*

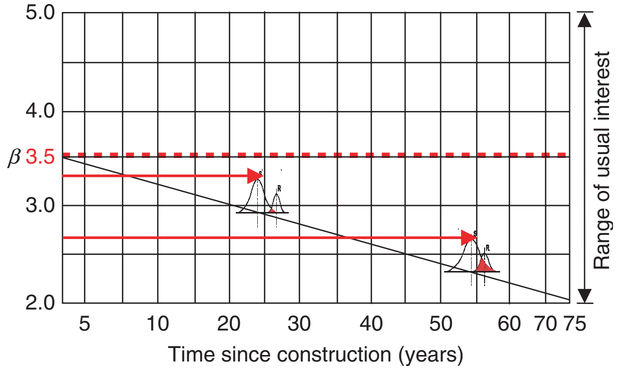

***Figure 5.*** *Reduction in value of safety index with time.*

increase with time, as has been experienced in Canada with the changes in vehicle weight regulations demanded by the economics of weight hauling by highway trucks. The increase in vehicle weights causes the *S* curve in Figure 2 to move to the right. As illustrated in Figure 5, the net result of the decrease of resistance and increase of loads over time is an increase of overlapping areas for the two curves.

Hence, it can be seen that the notional safety indices of the components of a bridge can decrease with time. Should such a reduction in the safety index always give engineers a cause for concern? Fortunately, a bridge can still be used even if its safety index is smaller than 3.5, but only if there is reliable knowledge about the structure. Bakht and Jaeger (1990) have shown that each time a bridge was tested surprising results were observed. The actual behavior of bridges was found to be usually different than that of the mathematical model used in the original design. In most cases, the actual strengths of bridges were considerably higher than the theoretical strengths.

## STRUCTURAL HEALTH MONITORING SYSTEMS

The second question posed at the beginning of this article – Can structural health monitoring in the field be useful in managing the risk? – is also answered affirmatively by the foregoing discussion. The term ‘civionics’ was coined recently (Mufti, 2003) to be parallel to ‘avionics,’ which is defined in American English language dictionaries to denote the application of electronics to aviation and astronautics. The term ‘civionics’ refers to the application of electronics to civil structures for the purpose of determining the state of their health. The use of sensors to monitor the response of a structure or its model to applied loads is not new, nor is bridge evaluation by field testing, which includes both diagnostic and proof testing. What is new, however, is the use of SHM through civionics. The purpose of SHM, according to Mufti (2001), is to monitor the *in situ* behavior of a structure accurately and efficiently to determine its health or condition. SHM is the integration of a system of sensors, a data acquisition system, a data processing system, an archiving system, a communications system, and a damage detection and modeling system to acquire knowledge, either on demand or on a continual basis, regarding the in-service performance of structures (Figure 6).

In the past, civil engineers have gained knowledge about the integrity of civil structures largely by means of manual inspections, and rarely by nondestructive evaluation (NDE) and interpretation of data using conventional technologies. The structural engineering profession has relied heavily on evaluation parameters given in codes of practice that lead to conservative and often costly conclusions about the strength of existing structures. The current practice has resulted in a North American stock of the civil structures whose health is not easy to monitor. For example, many bridges and large buildings constructed in earthquake-prone areas cannot be opened for public use immediately after a seismic event due to the time and cost involved in performing extensive safety checks. Quite often, after such extreme events the safety of these structures cannot be ascertained with certainty, hence it is difficult to know whether they should continue to stay in service.

In order to remain competitive in today’s global economic environment, the owners of civil structures

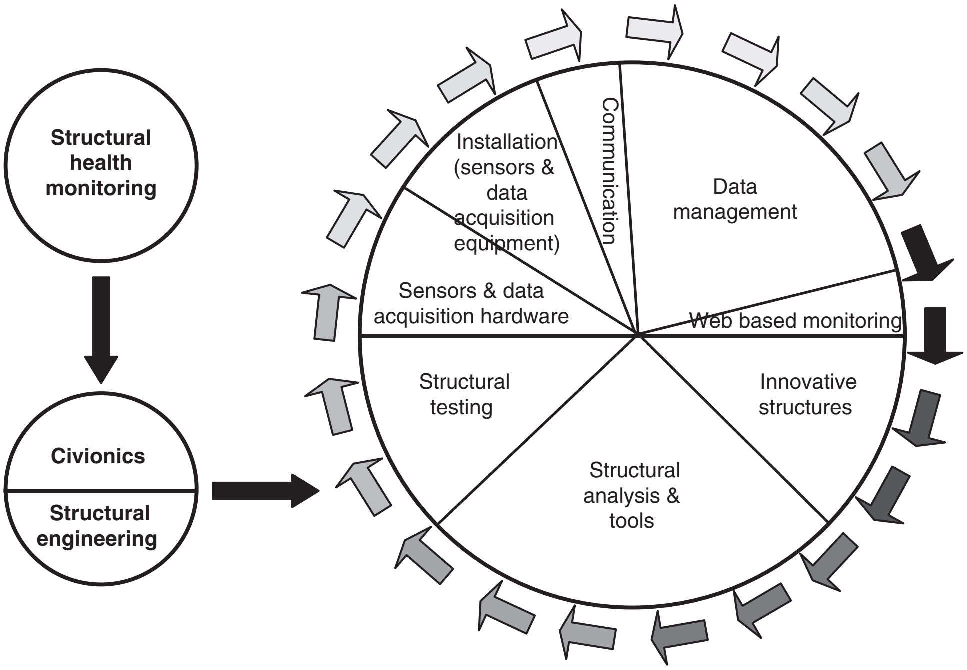

*Figure 6. The basic components of an SHM system.*

need to minimize the user costs involved with the unnecessary closing of the structures and the service disruption caused by outdated and time-consuming inspections following extreme events, such as strong-motion earthquakes, hurricanes, or flash floods. In the evaluation of any structural system, it is important to be able to assess specific performance issues related to serviceability, reliability, and durability. To effectively quantify the system's performance requires a means to monitor and evaluate the integrity of these large civil structures with minimal interruption of service. The SHM data, besides allowing owners to better allocate their resources toward repair, replacement, or rehabilitation of the structures, will also be useful in future projects in estimating the life cycle costs of the structural system compared to the initial cost. An efficient SHM system should be autonomous and capable of continuous monitoring, inspection, and damage detection of structures. Reports regarding the integrity of a structure should be automatically relayed through a local network or to a remote monitoring center. Clearly, the development of major SHM systems will involve many disciplines including structures, materials, damage detection, sensors, data collection and intelligent processing, computers, and communication (Figure 6).

Although conventional NDE can be considered to be within the framework of SHM, there is a difference in terms of data interpretation between the traditional NDE and SHM. The traditional NDE techniques tend to use direct measurements at discrete time intervals to determine the physical condition of structures. For example, bridge testing could either be diagnostic or involve proof loading. For evaluation by bridge testing, historical data are generally not required. SHM techniques, using continuous monitoring, assess changes in the condition of a structure. Hence, a history of data is crucial to the technique. The direct benefits from SHM systems are very large and include:

- monitoring and evaluating structures in real-time under service conditions;
- reducing downtime;
- improving safety and reliability; and
- reducing maintenance costs.

With the reduced downtime and improved reliability, in-service structures can be used more productively with less cost.

## CIVIONICS INTO PRACTICE

For SHM to become part of civil structural engineering, it should include civionics. The new discipline of civionics must be developed by civil structural engineers and electrophotonics engineers to lend validity and integrity to the process. Civionics includes the hardware and physical installation of the sensors, wires, conduits, termination and control boxes. SHM complements civionics and includes the collection and interpretation of data. A parallel for this process exists in the medical profession where a doctor requires medical instruments and technology to permit him, or her, to monitor and assess the health of the human body. In this same manner, civil engineers need civionics and SHM to monitor the health of a structure. Civionics and SHM will provide engineers with the means and the knowledge to build 'smart' structures containing the necessary equipment to provide much needed information related to the health of a structure before things go wrong.

Realistically, it is true that consulting engineers and contractors will only invest in the development of the expertise created by graduates of the civionics discipline when they can be assured that the prospects for business are good in this field. The experience of ISIS Canada in integrating fiber optics sensors and fiber reinforced polymers into innovative structures, built across Canada, has demonstrated that such opportunities do exist.

The CHBDC (2000) has a section on the strength evaluation of existing bridges; the section is based on the concept of a target reliability index that can change with (a) system behavior, (b) component behavior, and (c) the level of inspection. The system behavior relates to the effect of the failure of a component to the failure of the whole structure; the component behavior corresponds to the ductility of its failure; and the inspection level refers to the degree of confidence in the inspection process in determining the actual condition of the bridge and its components. The effect of the three factors on the target reliability index can be explained with the help of two examples.

In the first example, the component under consideration is critical to the safety of the entire structure. It can fail suddenly, such as in shear or by buckling. The component cannot be inspected, possibly because it is inaccessible. For such a component, the target reliability index $\beta$ is required by the CHBDC (2000) to be 4.00. For normal traffic, the live load factor $\alpha_L$ corresponding to a $\beta$ of 4.00 is 1.77.

For the second example, the component is such that its failure does not affect the failure of the whole structure. In addition, it is subject to gradual failure with advance warning of impending failure. The inspection of the component is carried out by the evaluator and the calculations for the final evaluation account for all the information gathered during this inspection. For such a component, the target reliability index $\beta$ is required by the CHBDC (2000) to be 2.50 with the live load factor $\alpha_L$ for normal traffic being 1.35.

Depending upon the system and element behavior and confidence in the inspection, the difference between two useable live load capacities can be as large as about 24%. If the condition of a component of a structure were determined with the help of sensors in an SHM system, the degree of confidence in the determination will be greater than in any visual inspection, with the consequence that the evaluator of the component will be able to utilize a larger portion of its live load capacity.

The concept of the target reliability index changing with the inspection level does not exist in the design of new structures. Yet, it can be appreciated that if the designer of a structure were confident that the condition of the structure and the load that it receives would be determined continuously and accurately by an SHM system, he/she can afford to be less conservative, thus reducing the capital cost of the structure. Drawing upon the comparison between a fully instrumented aerospace structure and a civil structure without any sensors to report on its health, it can be stated confidently that the designers of civil structures are risk-averse to an extent because of the absence of information about the field performance of these structures.

## CONCLUSIONS AND RECOMMENDATIONS

The answer to the question, "Would SHM help to change the 'risk shy' culture of civil structural engineers?" is a conditional yes. However, the civionics discipline needs to be further developed.

As mentioned earlier, ISIS Canada would like to change significantly the design, construction, and evaluation of civil engineering structures (ISIS, 2003). For such changes to be accepted, it is necessary that innovative structures be monitored for their health so that the required data banks can be developed. To assist in achieving this goal, ISIS Canada is developing civionics, which integrates civil engineering and electrophotonics under the combined term 'civionics'. In addition, ISIS Canada has developed Civionics Specifications (Rivera et al., 2004) and guidelines for construction engineers.

The authors also believe that a change in civil engineering culture to take risks in using new construction materials, design processes, and analytical methods would lead to innovations in civil engineering technologies and methods. However, civil engineers should manage these risks, by monitoring the structures.

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