INTELLIGENT INFRASTRUCTURE HEALTH MONITORING BASED ON FUZZY ANALYSIS

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ABSTRACT: This paper presents evaluation of BART - **B**ridge **A**ssessment and **R**ating **T**ool, an intelligent decision support tool for analysis of reinforced concrete, pre-stressed concrete and steel/concrete composition type of bridges based on fuzzy arithmetic and fuzzy reasoning. BART relies on data obtained from field measurements and observations on bridges to predict a "safe" window within which maintenance can be carried out. The use of fuzzy reasoning permits knowledge gained from human experts, through research and experience to be incorporated into the decision making process. The parameters analysed are bridge type, dead loads, type of vehicle loading, bridge dimensions and cross-section, material properties, reinforcement details, and existing physical condition of the bridge. Although BART has been proposed for use in evaluation of existing infrastructure, it is envisaged that the analysis and evaluation framework can be built into new construction projects.

.keywords: Intelligent Systems, Intelligent Structures, Fuzzy Systems, Infrastructure Monitoring, Bridge Assessments, Bridge Maintenance.

INTRODUCTION

Most constructed structures including, buildings, roadways, and bridges, require regular inspection and assessment so that proper actions can be taken to maintain their usefulness. This could be in form of Principal Bridge Inspections (every six years) or general inspections which are done annually and monitored by the Highways Agency (UK) A previous study carried out in the U.S estimated that the failure of civil infrastructure systems to perform at their expected level can reduce the national gross domestic conducted within the UK showed that the cost of correcting defects in buildings and civil engineering structures was £1000m annually which is a sum greater than the total profits of all UK construction companies [2]. For this reason, in many developed countries, where many of the infrastructure systems have become old and deteriorated, the need for efficient maintenance strategies has become crucial. Thus, on one hand, maintenance of highways and associated structures, such as, bridges is a pressing issue. On the other hand, local authorities who own the infrastructure are reluctant to carry out costly maintenance, such as strengthening works. Making good maintenance decisions is therefore important and requires years of practical experience.

Computer-aided solutions for maintenance of highways networks are now available, which analyse quantitative information obtained from site inspections [3,4]. Although these computer programs can be accurate and consistent their assessments are, in general, conservative and parsimonious, which can lead to untimely maintenance schedules. Expert systems [5,6] have provided decision support in many activities relying on human expertise, such as, medicine and manufacturing and, therefore, have potential in highway maintenance [7,3]. Intelligent systems, as opposed to classical expert systems, are designed to learn and cope with imprecision's of the real world, and thus, provide more robust and cost-effective solutions [8]. In fact, different research groups are currently investigating infrastructure of the future that should incorporate intelligent systems, comprising embedded sensors, hardware and software to monitor the use and serviceability of the infrastructure [1,9].

OVERVIEW OF THE ASSESSMENT PROCESS

Assessments can be defined as "inspection and determination of the load carrying capacity of a structure in terms of either full construction and use loading or specified gross vehicle weights". From this definition, its apparent that the decision making process in assessment borders on deciding when to carry out an inspect and how to determine the load capacity. Inspections are necessary to verify the form of construction, the dimensions of the structure and the nature and condition of the structural components. Structures are inspected to determine the materials and the dimensions needed to calculate to calculate an estimate of the dead and superimposed dead loads.

The initial assessment process normally has three phases (as illustrated in Figure 1). The first phase is called a desk top assessment in which all available and relevant information is examined. This includes:

- As built drawings; Bridge register;
- Records of strengthening works;
- Any ground or soils information's, if relevant.

The second phase is the inspection and involves the usage of information obtained from the desktop study to plan what data is required from a site inspection, and what equipment is necessary to enable a survey to be carried out expeditiously.

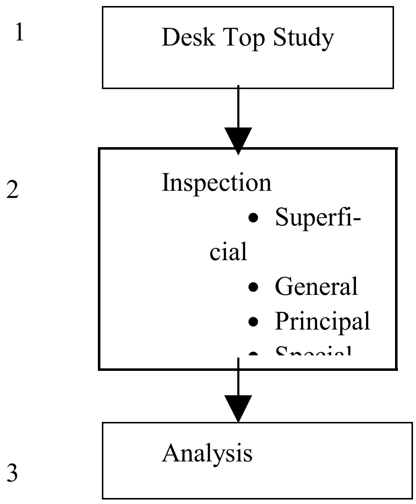

Fig 1 : Assessment Process

The third phase is a combination of information and data from the first two phases, resulting in the structural analysis.

This paper addresses the second phase of the assessment process. The inspection phase can be classified into two groups: *Inspection for Resistance* and *Inspection for Loading.*

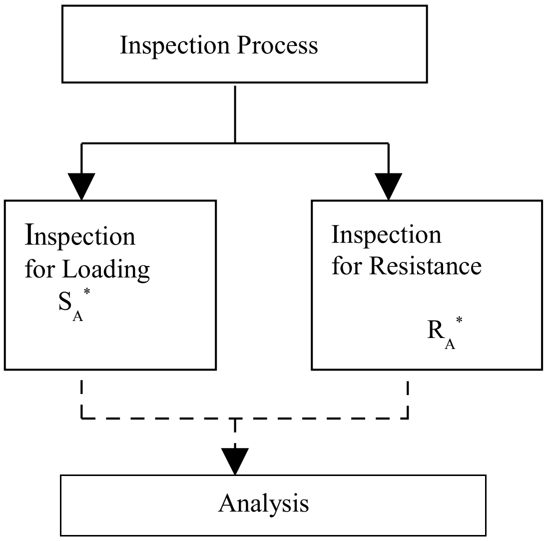

Fig 2: Inspection Process

Inspection for Loading involves the determination of materials and dimensions so as to calculate the dead and superimposed dead loads. The combination of the dead, superimposed and the live loads is known as the loading effect (S_A^*). The Inspection for Resistance is necessary in order to identify the parameters required to determine the actual resistance capacity

of the structure (R_A^*), given by the dimensions and strength of materials used in construction of the structure. Structures are deemed to be capable of carrying a specified level of assessment loading when,

$$R_A^* > S_A^* \quad (1)$$

In the event of structural inadequacy one of several actions can normally taken, such as, regular monitoring of condition, weight or lane restriction and strengthening works. Thus, the accuracy and reliability of the inspection analysis is crucial to efficacy of the assessment process. Recent studies indicate that the use of expert systems in structural assessment can aid the management of infrastructure. In particular, the use of fuzzy expert systems to handle the uncertainty and imprecision of available information is seen as important. Fuzzy reasoning can also be used to offer explanability to the decision-making process, which increases confidence in the assessment results. Furthermore, it introduces a qualitative, but, objective criteria for determination of assessment results.

FUZZY LOGIC OVERVIEW

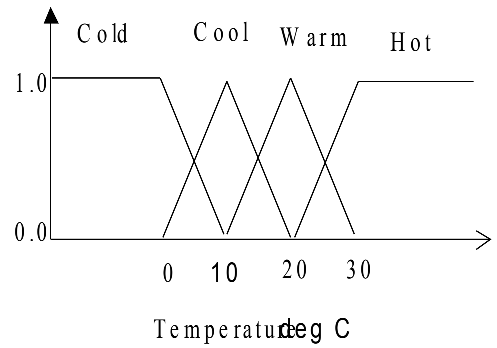

Figure 3: Membership functions for "temperature"

Problems that involve ambiguity and imprecision are successfully solved by humans in complex situations where computerized algorithms most often fail. Fuzzy logic aims to imitate the imprecise models of human reasoning and decision-making, which are essential to our ability to make rational decisions in situations of uncertainty, vagueness and incomplete information. This ability is dependent on the fact human reasoning can utilize imprecise propositions and also infer imprecise consequences, a facility that machines do not, as yet, have.

The fundamental aspect of fuzzy logic that plays the major role in fuzzy decision-making systems is the so-called linguistic or fuzzy variable. A fuzzy variable is a variable whose values are expressions (or words) taken from a natural or constituted language. A well known example is the fuzzy representation of a temperature scale, where dependent on the context and application, temperature can be classified into the values, "Cold", "Cool", "Warm" and "Hot". Each of these values is represented by a range of temperature, with variable degrees of belonging as shown in Figure 3. Now, while the shape of the membership functions for these values will in general be the same, the universe and ranges of the values will depend on the context. Thus, if on the one hand, the values should happen to apply to operation of a blast furnace, "Hot" would be probably refer to temperatures in the neighborhood of 1000 ºC. On the other hand, if these were room temperatures then a temperature of 30 ºC is "Hot". The vagueness of these values is also immediately apparent, because any two people will most likely not agree on what "precisely" a "Hot" room temperature is. On the other hand, they would certainly agree on a range of values that could be referred to as "Hot".

A linguistic (or fuzzy) value, thus, represents a possibility distribution of values that could be described by the fuzzy term. Formally, a fuzzy value is a duple {T, M}, where T is an interval [a,b] of the real number line and M is a membership function, m(t) such that:

$$\begin{array}{ll} 0.0 < m(t) < 1.0; & \text{for } a < t \in T < b; \\ 0.0; & \text{otherwise.} \end{array} \qquad (2)$$

m(t) can be any general analytic function, however, for simplicity triangular or Gaussian functions are preferred.

APPLICATION OF FUZZY ANALYSIS TO INFRASTRUCTURE MONITORING

The fuzzy approach to infrastructure monitoring has been proposed to deal with uncertainties including, inaccurate assessment of the effects of loading, such as, unknown stress distribution in the structure, inherent inaccuracies in the calculation models, and variations in the dimensional accuracy from measured values. Structural adequacy is based on the assessment load effect, S_A^* and the assessment resistance, R_A^*. In order to compensate for the uncertainties above, a fuzzy comparison has been proposed. This is in contrast to conventional analysis, which relies on deterministic calculation models using generalised partial factors to compensate for the inaccuracies.

Nominal values of both R_A^* and S_A^* are obtained using standard calculation model. These are then converted to approximate quantities by fuzzification. There are several ways by which membership functions can be assigned to variables. These include: fuzzy statistics, machine learning (neural networks and genetic algorithms), inductive reasoning and heuristics. The heuristic approach is founded on the capacity of humans to derive functions based on their expertise and experience, and has been applied in this research.

Applying the heuristic approach, a fuzzy membership function is formed centered on the nominal values of R_A^* and S_A^*, in order to take into account the anticipated inaccuracies and uncertainties. The fuzzification may also known distributions of uncertainty, such as, observed statistical deviations in measurements or standard partial factors. Where appropriate conditional deterioration can be taken into account. All these consideration result in the membership functions being skewed, either to the left or to the right. For ease of representation, piece-wise linear, monotonic (triangular) membership functions were assumed, instead of Gaussian distributions. The fuzzified values of R_A^* and S_A^* are then be used in a reasoning or inference mechanism to provide a rating and recommendation for the assessment carried out.

PROPOSED MODEL

Fuzzy arithmetic was used to determine the rating of a structure based on a "safe window" scale of assessment. From equation (1), a satisfactory rating of assessment is given by,

$$(R_A^* - S_A^*) \geq 0.0 \qquad (3)$$

A linear operation on two triangular membership functions, generates another triangular function. The case of the arithmetic difference of two functions is shown in Figure 3. As with most applications of fuzzy reasoning, it is then required to obtain a crisp deterministic outcome. A normalised outcome of the operation is provided, in this case, based the area of the fuzzy membership function. Thus, a normalised of the fuzzy functions is obtained, which also takes into account the possibility distribution of the values of R_A^* and S_A^* . In other words, it is necessary to determine when equation (3) can result in an unsatisfactory outcome.

Assuming the triangular membership functions, let R_A^* be represented by the triple of vertex points $\{R_{Al}, R_{Am}, R_{Ah}\}$, and similarly, S_A^* by $\{S_{Al}, S_{Am}, S_{Ah}\}$. The difference between the two fuzzy values is another membership function given by the triple, $\{R_{Al} - S_{Ah}, R_{Am} - S_{Am}, R_{Ah} - S_{Al}\}$.This is illustrated in Figure 3. The rating is given from the areas the difference membership function (**bold**) as:

$$\Phi = \frac{\int_{R_{Al}-S_{Ah}}^{R_{Ah}-S_{Al}} \operatorname{sgn}(t)\ m(t)\,dt}{\int_{R_{Al}-S_{Ah}}^{R_{Ah}-S_{Al}} m(t)\,dt} \qquad (4)$$

Dependent on the value of Φ (where $-1.0 \leq \Phi \leq 1.0$), one of several recommendations was provided:

$-1.0 \leq \Phi \leq -0.75$ **Bridge Closure**
$-0.75 \leq \Phi \leq 0.0$ **Restrict Loading**
$0.0 \leq \Phi \leq 0.75$ **Re-Assess**

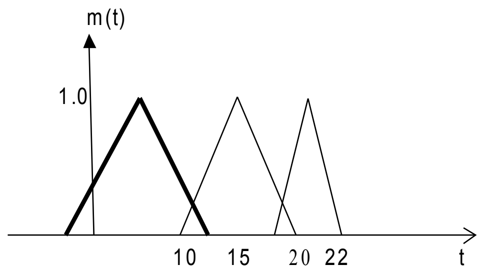

Figure 4: Fuzzy arithmetic difference of two func

$0.75 \leq \Phi \leq 1.0$ **Pass**

CONCLUSIONS

An application of fuzzy reasoning to bridge assessment has been presented in this paper. Initially, we have sought to provide an alternative approach to using partial factors to account for the inaccuracies and uncertainties in the assessment. This we consider to be a realistic approach because it is possible to take account of uncertainties that are not measurable quantitatively. The tool has been evaluated in pilot studies against conventional procedures as specified by British Standards Codes of Practice, and has achieved recommendation that were admissible. While this paper has applied simple fuzzy arithmetic to provide an assessment, work in progress is investigating an integrated approach that incorporates qualitative observations and predictive techniques in the overall assessment strategy.

GLOSSARY

Assessment: evaluation of load carrying capacity, determination of material strength or classification of current condition.

Dead Loads : The weight of the materials and parts of the structure that are structural elements.

Live Loads : Loads due to vehicle or pedestrian traffic.

Strengthening : increasing the load carrying capacity of the structure to a level higher than that intended in the original design.

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