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Bayesian inference of hidden corrosion in steel bridge connections: Non-contact and sparse contact approaches

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A R T I C L E I N F O

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A B S T R A C T

This paper describes approaches for inferring the presence and nature of hidden corrosion occurring between connection plies in steel truss bridges. The proposed methods furnish, both non-contact and very sparse contact inspection modalities supporting this goal.

The work is numerical in nature and involves the solution of stochastic inverse problems, in a Bayesian setting, in order to quantify uncertainty in modeling parameter estimation describing hidden corrosion (*i.e.* corrosion that cannot be directly visualized). A non-contact approach, involving a digital infrared camera, is described. Additionally, the paper also describes a means for employing so-called *Gappy Proper Orthogonal Decomposition (Gappy-POD)* in permitting a tiny number of contact temperature sensors to be applied for characterization of the same hidden corrosion.

1. Introduction

In these challenging, resource constrained times, there is a critical need to apply scarce funds in the most impactful way possible. While seemingly obvious, the pursuit of such a vision oftentimes proves complex in theory, as well practice. There is no better economic sector to look to for examples in this regard, than that of transportation; where responsibility for the maintenance of some of society's most critical infrastructure lies. News stories in the media are often heard to quote various statistics concerning structural deficiency and functional obsolescence in our highway bridges, but when pursuing fiscal efficiency it makes sense to identify the critical drivers behind the challenging situation: one such driver is *corrosion*. Indeed, in 2011, the National Association of Corrosion Engineers in the U.S. estimated the direct cost of corrosion in U.S. highway bridges, alone, to be 8.3 billion (USD) annually.

While the economic costs of corrosion on highway bridges are enormous, there is also a vitally important safety consideration implied here: with corrosion expense so high, and maintenance budgets constrained, what is the cost (both additional future economic and in terms of current safety) of under-treating corrosion damage in highway bridges? Indeed, while intentional under-treatment of corrosion damage may be thought of as an economic decision, what is more worrisome is the corrosion that we do not know about (and thus, is not being incorporated into maintenance prioritization decisions) that is also not being treated. The failure of the I-35W bridge, in the U.S., on August 1, 2007 was an important turning point in our understanding concerning the inadequacy of existing inspection methodologies in relation to corrosion detection. While corrosion was not believed to be a primary factor in the failure of the I-35W bridge, the subsequent failure investigation uncovered some alarming facts regarding corrosion in the critical gusset plate connections of the failed steel truss bridge.

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As part of the U.S. *National Transportation Safety Board (NTSB)* led study into the collapse of the I-35W bridge, it was noticed that in the failed gusset plate connection (node L11), a 38% section loss, due to corrosion, was present [27]. This type of hidden corrosion, extended in a line across the entire bottom chord contact area with gusset plate (see Fig. 1), and was not limited to the failed connection: the same corrosion modality was also observed in several other critical connections within the bridge. It is important to note that the presence of this type of extensive corrosion was missed during the previous visual inspection of the bridge; leading the NTSB to conclude that "visual inspections alone, regardless of their frequency, are inadequate to always detect corrosion on gusset plates or to accurately assess the extent of progression of that corrosion…" [27]. The NTSB went on to recommend that bridge owners be required to "…assess the truss bridges in their inventories to identify locations where visual inspections may not detect gusset plate corrosion and where, therefore, appropriate nondestructive evaluation technologies should be used to assess gusset plate condition" [27]. In response to this recommendation the US Department of Transportation released a Technical Advisory in 2010, whose purpose was to "provide recommendations for the use of NDE technologies to supplement gusset plate inspection when visual techniques are inadequate to determine the extent of deterioration due to corrosion" [32]. The Technical Advisory noted that existing *non-destructive evaluation approaches (NDE)* may be inadequate for fulfilling this need, and recommended that *ultrasonic testing (UT) methods* be employed, until better technology becomes available. Such UT methods are "contact" NDE approaches, and thus require an ability to access and "touch" the component being inspected. Additionally, there is considerable user variability with these types of approaches (*i.e.* very well trained and highly experienced personnel are required in operating properly calibrated equipment, so as to furnish useful accuracy).

1.1. Scope and organization

The present paper summarizes research results that are meant to demonstrate two robust and practical approaches for corrosion detection and uncertainty quantification of the same. The proposed non-contact method employs a modestly powerful laser and an inexpensive digital Infrared (IR) camera as part of the practical framework, while the sparse contact approach substitutes three tiny, contact thermal sensors for the camera. At their heart, the proposed approaches rely on the solution of a stochastic inverse problem, aimed at understanding the uncertainty in model parameters used to characterize plausible corrosion scenarios that are hypothesized by the methods. A critical feature of the proposed non-contact method is the ability to operate at large distances (*i.e.* with a large "stand-off" distance) from the connection elements being inspected (*e.g.*35 m, or more). The present study is numerical in nature, with surrogate experimental data generated by simulation and noise contaminated in a manner that is consistent with the measurement processes envisioned as part of the proposed inspection framework.

The present paper presents an algorithmic framework that employs thermographic field imaging data to effect numerical solutions of stochastic inverse problems. After a discussion of previous research work in Sections 2 and 3 rigorously defines the problems considered: both the finite element forward modeling analog of the physical system, and the stochastic inverse problems are treated. Section 4 presents results and analyses from a series of example problems. Conclusions are drawn in Section 5.

2. Background and motivation

Thermal imaging, as a modality for non-destructive evaluation, has been in the minds of researchers for a long time: going back, at least, to the seminal work of de Sénarmount in 1848 [17]. However, it was soon understood by researchers that the physics behind heat transfer created some challenges regarding its application as a basis for inferring material properties, etc. Once the formal theory of inverse problems became more mature [12], it was quickly noticed that, due to the nature of parabolic operators [10], inverse heat problems (*i.e.* problems where information about known heating is combined with field-measured temperatures, in order that unknown boundary conditions, or thermal properties can be

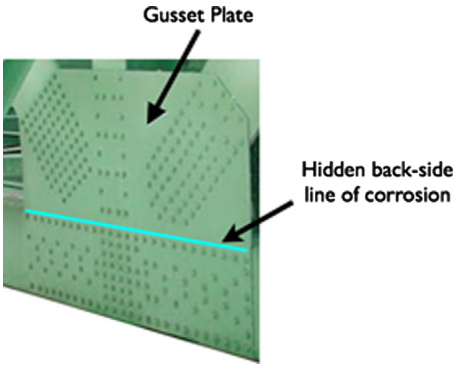

Fig. 1. Depiction of hidden corrosion line in I-35W gusset plate at connection, L11.