# STRUCTURAL HEALTH MONITORING OF HYDRAULIC STEEL STRUCTURES

by

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**Keywords:** fatigue, hydraulic steel structures, risk-based inspection planning, dynamic Bayesian networks, structural health monitoring

**Mots-clés :** fatigue, structures hydrauliques en acier, planification des inspections basée sur le risque, réseaux bayésiens dynamiques, surveillance de la santé structurelle

## 1 INTRODUCTION

Hydraulic steel structures, such as navigation lock gates, play a significant role in keeping navigation traffic continuously moving, and their reliability is essential to the navigation infrastructure. They are usually large steel structures working (partly) underwater and their lifetime is 50-100 years or even more in the future. Currently, in Europe, there are a lot of hydraulic steel structures in operation along inland waterways, as well as all over the world. Many of them were fabricated a couple of decades ago and they are near or having reached their design life (> 50 years).

There are a lot of factors leading to the extensive degradation of hydraulic steel structures including fatigue failure caused by cyclic loading, effects of environmental conditions, increasing load or design requirements overtime. Therefore, it is required to use continuous monitoring system for hydraulic steel structures to provide a regular update of the structural status as a function of time using real-time data. Based on these data, the failure probability of the structure can be updated and optimum maintenance plan can be defined.

This study provides an overview of structural health monitoring and its application in structure monitoring. A specific application using structural health monitoring of the Greenup mitre gate USA) is presented.

# 2 STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) provides the basis for an optimal schedule of inspection and maintenance for hydraulic steel structures. Thus, the health monitoring of structures and its applications is now an attractive issues for hydraulic steel structures.

Structural health monitoring is a modern technology and is considered to be crucial for the future. It is being applied in many fields, for example in bridges, e.g. Collins et al. [1], Ko and Li [2] and Reid [3] for more than 30 years. Successful applications were found in offshore structures, see Kim and Stubbs [4], Mourad et al. [5].

For hydraulic steel structures, Commander et al. [6] performed tests using monitoring strain at over 30 locations on the Emsworth mitre gate to assess the condition of the gate. This research provided additional information to further identify irregular lock gate behaviour. Treece et al. [7] presented SHM use to detect degradation between the quoin and wall boundary on the downstream mitre lock gates at lock N° 27 on the Mississippi River, USA.

Recently, the United States Army Corps of Engineers (USACE) [8] has developed an SHM programme to monitor for changes in behaviour of lock gates and this study utilises SHM data of the Greenup mitre gate. Measured data are collected and extracted every 15 seconds.

Figure 1 shows a strain gauge response at different locations on the Greenup mitre gate in 2014 (over a 12-months duration).

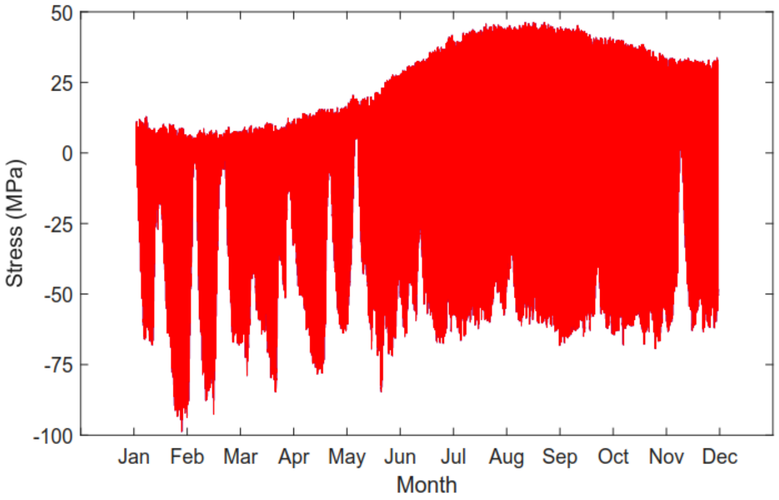

*Figure 1: Stress measurements on Greenup mitre gate*

# 3 METHODOLOGY

A fatigue assessment has been performed for the Greenup lock gate, which is an upstream horizontally framed mitre gate. The selection of potential crack locations are limited to the areas exposed to a strong response under fatigue load and its frequency.

This study utilises fatigue crack growth, a model based on fracture mechanics to analyse the crack propagation through the thickness under fatigue loading and evaluates the fatigue life by integrating the crack growth law. The most widely used model is the Paris-Erdogan law [9]. Crack depth at time t can be calculated by Eq. (1).

$$a_t = [a_{\mathrm{t-1}}^{1-\frac{m}{2}} + \left(1 - \frac{m}{2}\right) C B_{\mathrm{m}}^{m} B_{\mathrm{y}}^{m} Y^{m} B_{\mathrm{s}}^{m} \pi^{m/2} \sum_{j=1}^{k} \left(\Delta\sigma_j^{m_{SN}} n_j\right)]^{2/(2-m)} \tag{1}$$

where $a_0$ (t =1) is the initial crack size; Y is geometry function; C and m are material parameters; $\Delta\sigma_j$ is stress range and $n_j$ is number of cycles corresponding. $B_m$, $B_s$, $B_y$ are, respectively, measurement, load and geometry uncertainties.

A Dynamic Bayesian network (DBN) is a special class of Bayesian network, that represents the temporal evolution of variables over time. DBN allows temporal connections between time slices can be incorporated with condition probabilities among variables to create different time-dependence slices. A DBN framework for stochastic modeling of deterioration process and updating the failure probability is proposed in Straub [10]. In this study, DBN is used to determine degradation modelling for a welded joint. By instantiating the inspection variables $I_t$ in the DBN with the observed events at the times of inspection, the failure probability is updated considering the inspection outcomes, Eq. (2).

$$\mathrm{p}(\mathrm{a_t}, \mathrm{q_t} | \mathrm{I_0}, \dots, \mathrm{I_t}) \propto \mathrm{p}(\mathrm{a_t}, \mathrm{q_t} | \mathrm{I_0}, \dots, \mathrm{I_{t-1}}) \mathrm{p}(\mathrm{I_t} | \mathrm{a_t}) \tag{2}$$

The DBN representation including inspection results $I_t$ is shown in Figure 2.

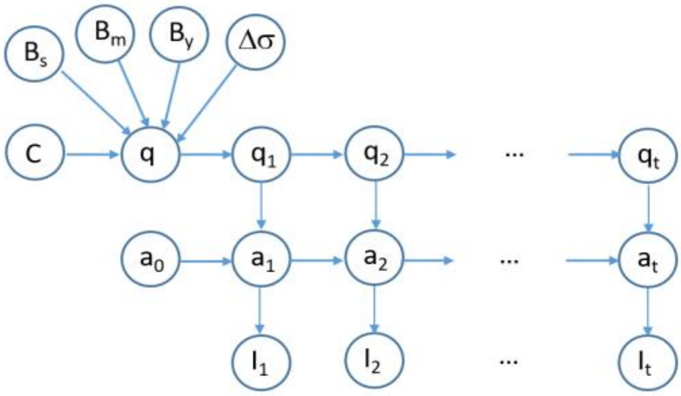

*Figure 2: Fatigue crack growth as a DBN*

# 4 RISK-BASED OPTIMAL INSPECTION STRATEGIES USING DYNAMIC BAYESIAN NETWORKS

Risk-based inspection (RBI) is an interesting topic for hydraulic steel structures due to the increase of aging structures where many failures may be detected. The risk-based optimal inspection strategies are identified according to the collected SHM data for the heuristic decision rule *“inspection performed when failure probability threshold is reached”* [11].

The total expected cost during the lifetime $E_{tot}$ may be written as Eq (3).

$$E_{tot} = \sum_{t=1}^{T} C_f P_f(t) \frac{1}{(1+\alpha_r)^t} + \sum_{i=1}^{T_{insp}} \frac{C_r P_r(T_i) + C_{insp}}{(1+\alpha_r)^{T_i}} + C_{SHM} \tag{3}$$

where $P_f$ denotes the annual failure probability in year t and $P_r$ is the probability that a repair is performed in year t after an inspection done in the same year. $P_{fc}$ is the cumulative failure probability. $C_f, C_r, C_{insp}$ and $C_{SHM}$ are failure, repair, inspection and SHM costs.

The different unitary costs are provided in Table 1. The discounting rate αr is 3 % and the total time period is 100 years.

| Unitary cost | Value US$ |
|---|---|
| Inspection cost, $C_{insp}$ | $0.0025C_f$ |
| Repair cost, $C_r$ | $0.04C_f$ |
| Failure cost, $C_f$ | $12{\cdot}10^6$ |
| SHM cost, $C_{SHM}$ | $5{\cdot}10^4$ |

*Table 1: Cost characteristics*

Figure 3. shows that the optimal annual failure probability threshold is $P_f$ = $3{\cdot}10^{-4}$ and the expected costs is $E_{tot}$ = $1.21 \cdot 10^5$ (US$).

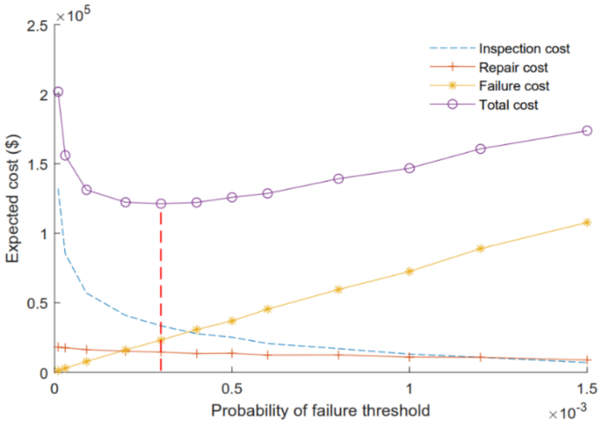

*Figure 3: RBI Results – with inspection at failure probability threshold*

Figure 4. shows the change of expected cost for three cases (‘Do nothing’, optimal based on ‘periodic inspection’ and optimal based on ‘failure probability threshold’) after 50, 60, 70 and 80 years.

In this study, the benefit of using SHM is analysed and SHM is recommended when the Green up mitre gate is expected having a long-term service (≥ 70 years).

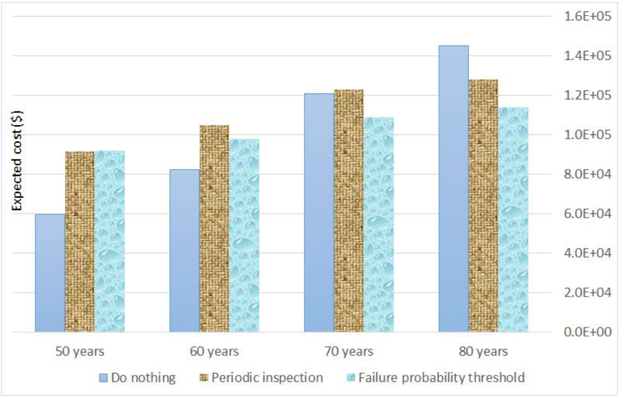

*Figure 4: Results for RBI – with inspection at failure probability threshold*

## 5 ACKNOWLEDGEMENTS

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## SUMMARY

Hydraulic steel structures, such as navigation lock gates, play a significant role in keeping navigation traffic continuously moving, and their reliability is essential to the navigation infrastructure. They are usually large steel structures working (partly) underwater and their lifetime is 50-100 years or even more in the future. Currently, in Europe, there are a lot of hydraulic steel structures in operation along inland waterways, as well as all over the world. Many of them were fabricated a couple of decades ago and they are near or having reached their design life (> 50 years).

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## RESUME

Les structures hydrauliques en acier, telles que les portes d'écluses de navigation, jouent un rôle important pour maintenir le traffic de navigation en mouvement continu, et leur fiabilité est essentielle pour l'infrastructure de navigation. Il s'agit généralement de grandes structures en acier travaillant (partiellement) sous l'eau et leur durée de vie est de 50 à 100 ans, voire plus à l'avenir. Actuellement, en Europe, il y a beaucoup de structures hydrauliques en acier en service le long des voies navigables, ainsi que dans le monde entier. Beaucoup d'entre elles ont été fabriquées il y a quelques décennies et sont proches de leur durée de vie nominale (> 50 ans) ou l'ont déjà atteinte.

De nombreux facteurs conduisent à la dégradation importante des structures hydrauliques en acier, notamment la rupture par fatigue causée par les charges cycliques, les effets des conditions environnementales, l'augmentation de la charge ou des exigences de conception au fil du temps. Par conséquent, il est nécessaire d'utiliser un système de surveillance continue pour les structures hydrauliques en acier afin de fournir une mise à jour régulière de l'état de la structure en fonction du temps en utilisant des données en temps réel. Sur la base de ces données, la probabilité de défaillance de la structure peut être mise à jour et un plan de maintenance optimal peut être défini.

Cette étude donne un aperçu de la surveillance de la santé structurelle et de son application dans la surveillance des structures. Une application spécificale utilisant la surveillance de la santé structurelle de la mitre Greenup gate (Etats-Unis) est présentée.

## ZUSAMMENFASSUNG

Stahlwasserbauwerke wie Schleusentore für die Schifffahrt spielen eine wichtige Rolle bei der Aufrechterhaltung des kontinuierlichen Schiffsverkehrs, und ihre Zuverlässigkeit ist für die Schifffahrtsinfrastruktur von entscheidender Bedeutung. Es handelt sich in der Regel um große Stahlkonstruktionen, die (teilweise) unter Wasser arbeiten, und ihre Lebensdauer beträgt 50-100 Jahre oder sogar noch länger. Gegenwärtig sind in Europa und in der ganzen Welt zahlreiche Stahlwasserbauwerke auf Binnenwasserstraßen in Betrieb. Viele von ihnen wurden vor einigen Jahrzehnten gebaut und stehen kurz vor dem Erreichen ihrer Lebensdauer (> 50 Jahre) oder haben diese bereits erreicht.

Es gibt viele Faktoren, die zu einer weitreichenden Verschlechterung der Stahlwasserbaukonstruktionen führen, wie z.B. Ermüdungsversagen durch zyklische Belastung, Auswirkungen der Umweltbedingungen, zunehmende Belastung oder steigende Konstruktionsanforderungen im Laufe der Zeit. Daher ist es erforderlich, ein kontinuierliches Überwachungssystem für Stahlwasserbauten einzusetzen, um den Zustand der Struktur in Abhängigkeit von der Zeit anhand von Echtzeitdaten regelmäßig zu aktualisieren. Auf der Grundlage dieser Daten kann die Ausfallwahrscheinlichkeit der Struktur aktualisiert und ein optimaler Instandhaltungsplan festgelegt werden.

Diese Studie gibt einen Überblick über die Zustandsüberwachung von Bauwerken und ihre Anwendung in der Bauwerksüberwachung. Es wird eine spezielle Anwendung für die Überwachung des Strukturzustands des Greenup-Gatters (USA) vorgestellt.

# RESUMEN

Las estructuras hidráulicas de acero, como las compuertas de las esclusas de navegación, desempeñan un papel importante a la hora de mantener el tráfico de navegación en continuo movimiento, y su fiabilidad es esencial para la infraestructura de navegación. Suelen ser grandes estructuras de acero que funcionan (parcialmente) bajo el agua y su vida útil es de 50 a 100 años o incluso más en el futuro. Actualmente, en Europa hay muchas estructuras hidráulicas de acero en funcionamiento a lo largo de las vías navegables interiores, así como en todo el mundo. Muchas de ellas se fabricaron hace un par de décadas y están cerca o han alcanzado su vida útil (> 50 años).

Hay muchos factores que conducen a la degradación extensiva de las estructuras hidráulicas de acero, incluyendo el fallo por fatiga causado por la carga cíclica, los efectos de las condiciones ambientales, el aumento de la carga o los requisitos de diseño con el paso del tiempo. Por lo tanto, es necesario utilizar un sistema de monitorización continua de las estructuras hidráulicas de acero que proporcione una actualización periódica del estado estructural en función del tiempo utilizando datos en tiempo real. A partir de estos datos, se puede actualizar la probabilidad de fallo de la estructura y definir un plan de mantenimiento óptimo.

Este estudio proporciona una visión general de la monitorización de la salud estructural y su aplicación en la monitorización de estructuras. Se presenta una aplicación específica que utiliza la monitorización de la salud estructural de la puerta de inglete Greenup (Estados Unidos).