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Deriving the transition probability matrix using computational mechanics

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Abstract

Purpose – The combined effects of several complex phenomena cause the deterioration of elements in steel hydraulic structures (SHSs) within the US lock system: corrosion, cracking and fatigue, impact and overloads. Predicting the future condition state of these structures by the use of current condition state inspection data can be achieved through the probabilistic chain deterioration model. The purpose of this study is to derive the transition probability matrix using final elements modeling of a miter gate.

Design/methodology/approach – If predicted accurately, this information would yield benefits in determining the need for rehabilitation or replacement of SHS. However, because of the complexity and difficulties on obtaining sufficient inspection data, there is a lack of available condition states needed to formulate proper transition probability matrices for each deterioration case.

Findings – This study focuses on using a three-dimensional explicit finite element analysis (FEM) of a miter gate that has been fully validated with experimental data to derive the transition probability matrix when the loss of flexural capacity in a corroded member is simulated.

Practical implications – New methodology using computational mechanics to derive the transition probability matrices of navigation steel structures has been presented.

Originality/value – The difficulty of deriving the transition probability matrix to perform a Markovian analysis increases when limited amount of inspection data is available. The used state of practice FEM to derive the transition probability matrix is not just necessary but also essential when the need for proper maintenance is required but limited amount of the condition of the structural system is unknown.

Keywords Corrosion, Finite element modeling, Markov chain, Miter gates, Multivariate samples of statistical distributions, Navigation steel structures

Paper type Research paper

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Introduction

Information on current and future conditions of navigation or flood control steel hydraulic structures (SHSs) is essential for the maintenance and rehabilitation of navigation infrastructure. Current conditions of navigation infrastructure are measured by periodic and detailed inspections following recommendations from Engineer Regulation (ER) 1110-2-100, Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures [Headquarters, USA Army Corps of Engineers (HQUSACE), 1998]; ER 1110-2-8157, Responsibility for Hydraulic Steel Structures [Headquarters, USA Army Corps of Engineers (HQUSACE), 2009]; and Engineer Manual 1110-2-6054, Inspection, Evaluation and Repair of Hydraulic Steel Structures [Headquarters, USA Army Corps of Engineers (HQUSACE), 2001].

The accuracy of these conditions depends on the type of inspection performed. Periodic inspections on SHS are primarily visual inspections. The inspection procedures are designed to detect damage, deterioration or signs of distress to avert any premature failure of the structure and to identify any future maintenance or repair requirements. In recent years, critical repairs have been avoided with the development of condition states and deterioration models for SHS and general infrastructure (Riveros and Arredondo, 2010a, 2010b, 2011, 2014; Sauser and Riveros, 2009; Frangopol *et al.*, 2004; Bocchini *et al.*, 2013). Riveros *et al.* (2014, 2016) used deterministic models in which no randomness is involved in the development of future deterioration states of the system. These models calculate the condition of the system as a precise value based on mathematical formulations of the actual deterioration (Riveros *et al.*, 2014; Ortiz-Garcia *et al.*, 2006; Frangopol *et al.*, 2004; Casas, 2004). However, the main challenge arises in the accurate development of deterioration models for which the system condition is often measured on a discrete time scale, such as inspector's ratings (Frangopol and Liu, 2007, Riveros *et al.*, 2014).

The main disadvantages of these methods are that they require the ability to collect inspection data at reasonable intervals of time. However, SHSs in its majority are submerged and inspections are conducted at large time intervals or when there is a concern about a problem. Headquarters, USA Army Corps of Engineers (HQUSACE) (2009) requires that every fracture critical member be inspected every five years. In general, each SHS must be thoroughly dewatered and inspected at least every 25 years. This is the major drawback of the methodologies that use the Markovian process and are dependent of inspection rate data (Wang *et al.*, 2006; Riveros and Arredondo, 2010a; 2010b, 2011, 2014); however, this paper presents a methodology using three-dimensional (3D) finite element models that are deteriorated at different rates for a particular deterioration case, and then are used to define the transition probability matrix to be used in the Markovian prediction model. Bocchini *et al.* (2013) acknowledged that simulation-based approaches are the only truly universal way to address complex and strong nonlinear probabilistic problems, which is the intend of this paper.

Condition states for steel hydraulic structures

Sauser and Riveros (2009) developed a condition rating system for SHS that uses an ordinal, integer value scale from 1 to 5. This system indicates relative health of the infrastructure elements for the four most common deteriorations encountered in SHS: protective systems, corrosion, fatigue and fracture and impacts or overloads.

The following stages describe corrosion and section loss:

- A protective coating protects the member or other means or it has not been subjected to corrosive action. The member is in like-new or as-built condition and has no deterioration.
- The member has lost some of its protection or has been subjected to corrosive action and is beginning to deteriorate (corrode), but it has no measurable section and is

bounded minimally by the onset of corrosion and maximally by section loss that is not measurable, for example, pitting not measurable by simple hand tools.

- The member continues to deteriorate and measurable section loss is present but not to the extent that it affects its function. The upper bound of this state is, for example, pitting to a depth less than 1.5875 mm (0.0625 in.) or total loss of section thickness less than 3.175 mm (0.125 in.).
- The member continues to deteriorate, and section loss increases to the point where function may be affected. An evaluation may be necessary to determine if the structure can continue to function as intended, if repairs are necessary or if its use should be restricted. The upper bound is a function of member strength, member load and member use, but it could be capped at 10 per cent of the total section loss for ease of and consistency in reporting.
- The member continues to deteriorate, and section loss increases to the point where the member no longer serves its intended function and affects the safety. An evaluation may be necessary to determine whether the structure can continue to function safely.

The five general condition states are listed in Table I (Sauser and Riveros, 2009). The use of this system provides a structured approach to identifying, documenting and tracking deficiencies in SHS. Collecting SHS condition state inspection data provides the means to predict its future condition (by use of the Markov chain model) for prioritizing maintenance and replacement funding.

Although the applicability of this rating system seems promising, due to the time frame from proposal to implementation, there is a lack of condition state inspection data available. Hence, the use of subsequent tools that feed from this information to statistically predict the future condition of SHS is limited. The lack of inspection information is a consequence of the time frame for which SHSs are inspected as described above.

State of practice to determine transition probability matrices

Transition probability estimation literature. Wirahadikusumah *et al.* (2001) used an exponential model in the regression analysis for establishing the relationship between the overall structural grade and sewer age, which was used in the development of a Markov chain-based deterioration model for large combined sewers in Indianapolis, IN. They adopted the nonlinear optimization-based approach commonly used for pavements and bridges (Jiang *et al.*, 1988; Jiang and Sinha, 1989) to derive the transition probability among the five different structural grades.

Riveros and Arredondo (2010a, 2010b, 2011, 2014) developed a statistical approach to derive the transition probability matrix for navigation steel structures where the available

Table I. Condition states description

No.	Condition	Description
1	Protected	Member is sound, functioning properly and absent of the deficiency
2	Exposed	Member shows beginning signs of the deficiency but is still sound and functioning properly
3	Attacked	Deficiency has advanced and function is becoming affected
4	Damaged	Deficiency has advanced to the point that serviceability is suspect
5	Failed	Member no longer serves intended function

Source: Sauser and Riveros (2009)

data containing condition states are limited, the development of a probabilistic method using Markov chain and multivariate samples of statistical distributions that allow the outcome of the Markovian simulation to be updated as more data become available. This allows the method to be used confidently to predict future deterioration of hydraulic steel structures.

The most common methods used to derive transition probabilities are based on linear regression (Carnahan *et al.*, 1987; Jiang *et al.*, 1988). These models suffer from several methodological limitations and practical inconsistencies that have been pointed out by Madanat and Wan Ibrahim (1995). First, the use of linear regression is not appropriate when the dependent variable (condition rating) is a discrete variable. Second, these models, by linking causal variables to facility condition rating directly, do not recognize the latent nature of the infrastructure deterioration process. Finally, the method used to estimate the transition probabilities from the deterioration model imposes limitations on the number of parameters that can be estimated.

Madanat *et al.* (1995) introduced the application of the ordered probit model for the estimation of transition probabilities from the inspection data. The ordered probit model has come into fairly wide use as a framework for analyzing responses where the dependent variable is discrete and ordinal. The model assumes the existence of an underlying continuous random variable and therefore allows the latent nature of infrastructure performance to be captured. Although the application of these modeling methods has advanced the state-of-the-art in infrastructure deterioration modeling, these have not adequately accounted for the presence of heterogeneity and have provided few insights into the validity of the Markovian assumption.

Madanat *et al.* (1997) presented incremental models that are used to compute infrastructure transition probabilities, and predict changes in conditions over time as a function of a set of explanatory variables, such as traffic, age, environmental factors and design and material characteristics. The state-of-the-art discrete infrastructure deterioration models (Butt *et al.*, 1987; Feighan *et al.*, 1988; Jiang *et al.*, 1988; Scherer and Glagola, 1994; Madanat *et al.*, 1995; Madanat and Wan Ibrahim, 1995) have typically been developed using panel data sets of in-service facilities but these have not accounted for the presence of heterogeneity, which is likely to exist in such data.

Finally, DeStefano and Grivas (1998) estimated a time-based model motivated by the need for state transition probabilities. However, the time-based modeling approach has a serious limitation. A restricted specification is adopted so that the complex structure of the deterioration process reflecting the significant effects of the multitude of explanatory variables is not captured.

The consequences of the limitations associated with the various methods discussed above are biased estimates of the state transition probabilities, as shown in Madanat *et al.*'s study (1995). This will lead directly to poor predictions of future infrastructure condition, thus, compromising maintenance and rehabilitation decision-making.

The available methodologies to derive an accurate transition probability matrix are a function of the amount of inspection data that is collected at predefined time intervals. This aspect is difficult for SHS considering the infrastructure systems are under water and inspections are sparse. Therefore, it is not just necessary but also essential to develop a methodology where condition states can be obtained without the need of constant inspections. The methodology presented in this paper shows that advances in numerical modeling can serve as a vehicle to obtain the necessary condition states to perform an accurate Markovian analysis.

Solution

Advances in high-performance computing have enabled the development of technologies capable of modeling and simulating computationally demanding models that closely resemble real conditions. By use of numerical methods, software is now able to build and analyze geometrically complex models to the point of which the true in-service response can be predicted. The use of this powerful tool allows for the capability of generating reliable numerical data that would be congruent with that expected in field conditions.

Through this concept of using a previously calibrated, detailed 3D miter gate numerical model developed in Abaqus 6.13 (Riveros *et al.*, 2016) and forcing the structure to deteriorate at a particular rate generates numerical data. The corrosion rates for very polluted fresh water (sewage, industrial affluent, etc.) in the zone of high attack (splash zone) ranging from 60 to 170 μm/year (0.0024-0.0066 in./year) (€223,433, American Galvanize Association) were used for the modeling considering that similar corrosion rates have been observed in the field (Riveros *et al.*, 2014). The description for each corrosion condition state is presented in Plate 1.

Because of the lack of condition states of SHS information available, a numerical simulation was formulated and performed on the basis of the condition rating system developed by Sauser and Riveros (2009). Through the use of a detailed 3D miter gate numerical model (Figures 1 and 2), different levels of corrosion were simulated in selected areas of the horizontal plate girders aligned with the splash zone of a miter gate. The objective was to document that the stress level increases in the selected area as the gate experienced degradation. Corrosion was simulated by introducing a specific amount of section loss for each level of deterioration.

Model overview and simulation

The numerical model is a representation of a typical gate on US waterways. It is a horizontally framed gate with 16 horizontal girders with a leaf of 83.60-feet high and 61.67-feet wide (Figure 1).

The main structural elements (skin plate, horizontal girders, vertical diaphragms and tapered end section) were developed as an individual part. In addition, the pintle, pintle bolts, quoin and miter blocks and the pintle ball were also constructed as individual parts (Figure 1) and were connected to the main gate by the used-on interface elements. The finite element model consisted of 3D deformable shell elements; 3D solid continuous elements at the pintle assembly and rigid elements in the pintle.

Parts properties and materials module

The materials have a modulus of elasticity 30,000 (ksi) with a Poisson's ratio of 0.3. The mass density for the steel is 0.00879 slug/in.^{3}, and the coefficient of thermal expansion is 6.5 E-006.

Plate 1.
Condition states of corrosion for HSS

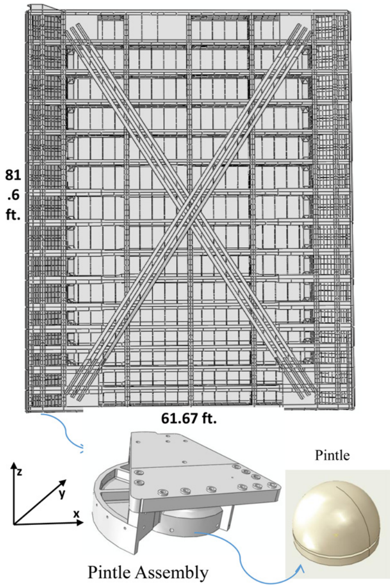

Figure 1. Leaf dimensions of a downstream view of the 3D numerical model in Abaqus

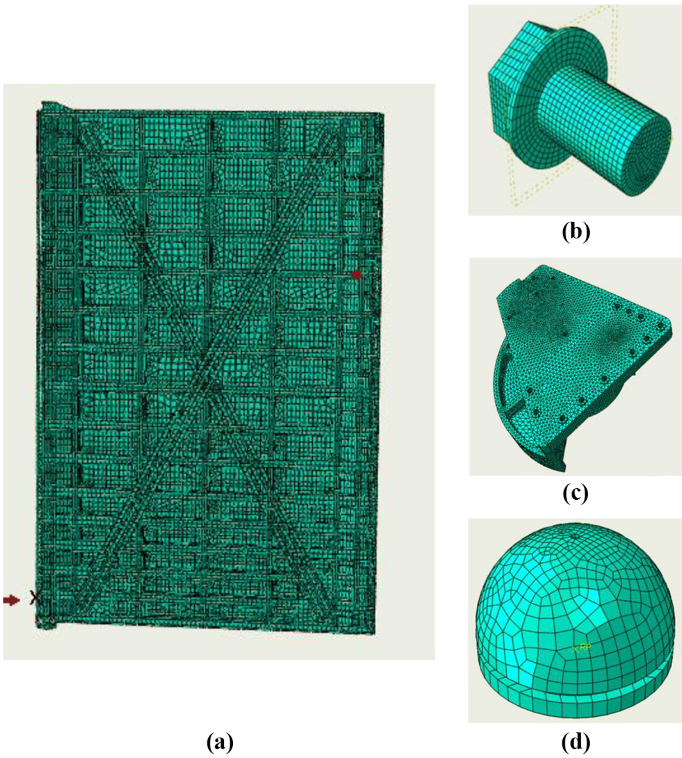

Figure 2. (a) Mesh for the 3D shell elements of the gate; (b) and (c) mesh of the 3D solid continuous elements in the bolts and pintle socket; and (d) mesh of the rigid elements in the pintle ball

Mesh

Several meshing techniques were created due to the different element types. Figures 2 shows the mesh of all the parts of the gate. The model has 608,836 elements (shells, 3D solids and tetrahedral), 790,119 nodes and approximately 4.0 million degrees of freedom.

Numerical simulation

Displacement boundary conditions

Displacement boundary conditions were applied to the miter block, quoin block, gudgeon pin and pintle. The miter block, quoin block and gudgeon pin were restricted of movement in the *x*- and *y*-directions. The pintle ball was restricted of movement in the *x*-, *y*- and *z*-directions and no rotations were allowed. Interface elements were used to connect the pintle ball with the pintle and a combination of tie constraints and interface elements was used to connect the pintle, bolts and gate bottom girder web.

Load boundary conditions

The load boundary condition consisted of the structure's self-weight, additional dead load induced by mud or ice, hydrostatic pressure induced by the upstream and downstream water levels, diagonal pre-stressing and bolt pre-stressing.

The general analysis procedure consisted of different steps to reach the final solution. In the initial step, displacements and loads and boundary conditions are applied and the predefined field (diagonal pre-stressing) is also defined. Second, the gravity force on the gate and bolt pre-stressing is applied. From this step, the maximum hydrostatic elevation is reduced until hydraulic equilibrium is reached and then the hydrostatic load is raised to its original position. This process provides a full loading cycle that is essential for any fatigue evaluation.

Validation of the computational model

Verification and validation efforts were focused on the overall model methodology and analytical validation. The analyses were carried out as a quasi-static analysis. The numerical methodology used in this study was verified through a benchmark problem such as the miter gates at Lock and Dam 27, which were modeled using the same techniques and have been validated with experimental data and are described in Riveros *et al.*'s study (2016). In addition, the analysis discussed in this paper was analytically validated against the bending stresses at the girders (Figure 3).

A series of numerical experiments were carried out using the 3D finite element model of a miter gate shown in Plate 1 and Figure 1. In everyday practice, notable levels of corrosion in miter gates have been observed on what is called the "splash" zone; the area in which the interface, atmospheric pressure and free water surface usually meet (Figure 4). To fully capture the effect that corrosion has in the gate's critical members, the center section of the miter gate (Girder 15) was selected as an ideal area to deteriorate.

Plate 2 shows the complete 3D geometry of Girder 15, and the section of the girder selected for "corrosion," respectively; 36 per cent of the girder's area was selected, which is similar to the one shown in Plate 2. The simulation consisted of a series of steps in which the gate was subjected both to gravity and different levels of hydrostatic loading. The initial miter gate step was assigned full hydrostatic pressure (design load); water depth was then lowered by 10 per cent in each of the subsequent steps until hydrostatic equilibrium was reached.

Figures 5, 6 and 7 illustrate the principal tension and compression stresses registered in the corroded area over a determined time period. As expected, the stress

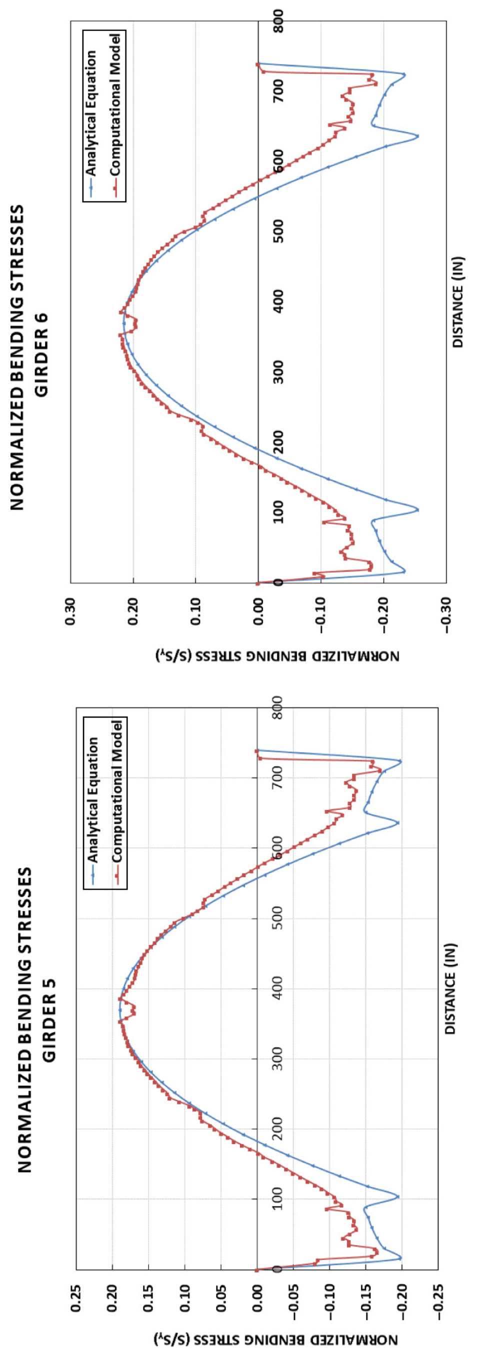

Figure 3.
Analytical validation of the numerical model

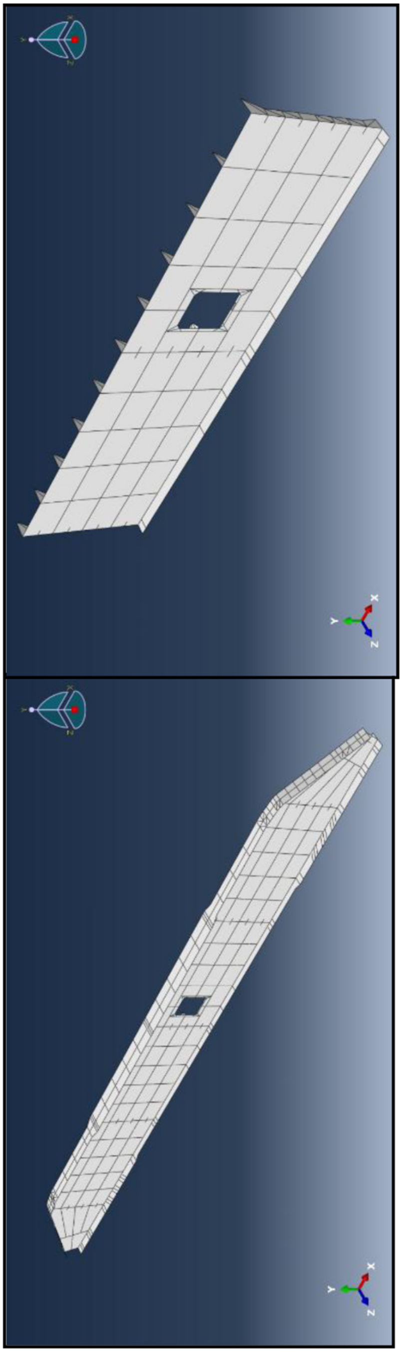

Figure 4.
Girder 15

Plate 2. Corroded area of Girder 15 (area = 33,162.81 in.^{2})

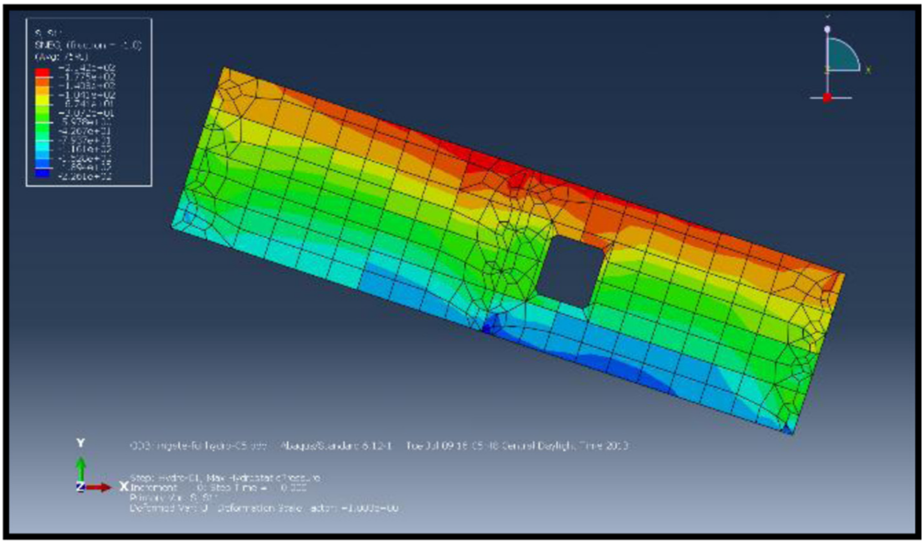

Figure 5. Principal stress distribution of reduced sectional area (Girder 15)

demand increases with a decrease in sectional area (section loss). It is also noted that a minimum effect of section loss occurs between 0 and 10 per cent of deterioration. However, once the deterioration exceeds 10 per cent, the system experiences a larger increase in stresses.

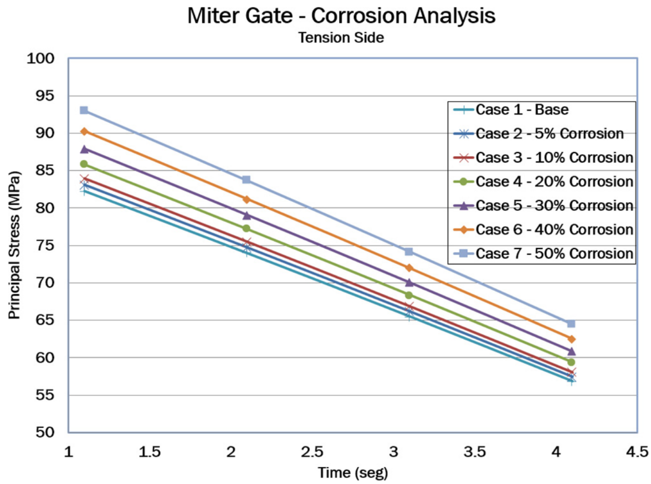

Figure 6.
Miter gate corrosion analysis; web G15, tension side

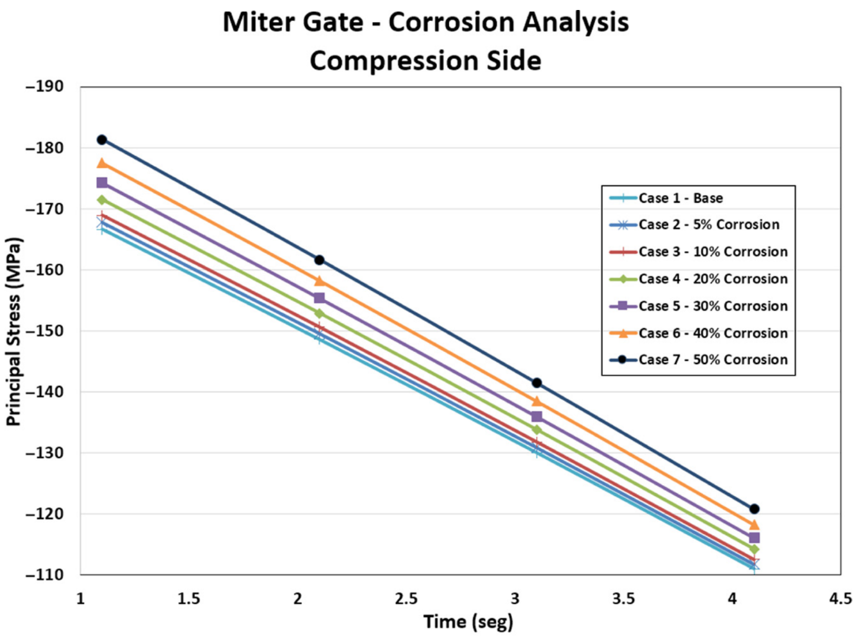

Figure 7.
Miter gate corrosion analysis; web G15, compression side

As structures experience significant amounts of section loss, their capacities decrease. Therefore, a calculation of the loss of flexural strength in Girder 15 was performed because girders in miter gates have stiffeners both in the longitudinal and transverse direction, as well as an effective width on the skin plate (b_e), which are part of the section (Figure 8). According to AISC guidelines, the flexural strength of such members could be calculated as:

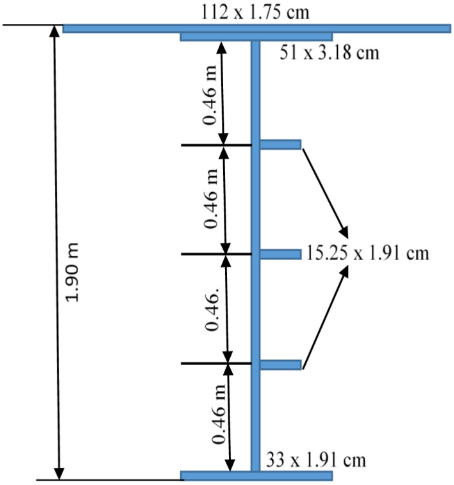

Figure 8. Typical section of G15; dimensions taken from construction plans

$$M_p = F_y Z \qquad (1)$$

Where M_p, F_y and Z are the plastic moment of the section, the material's yield strength (assumed to be 36 ksi) and the plastic section modulus (I/c), respectively. Table II shows the change in section properties caused by corrosion; and Figure 9 shows a plot of capacity loss as a function of corrosion; nearly a 13 per cent flexural capacity loss was calculated from no-corrosion to 50 per cent corrosion. Figure 10 shows the stress demand increase as section loss is experienced (greater degradation). Nearly 12 per cent of the stress increase was numerically obtained by comparing the "base" case with the "50 per cent corrosion" case. These percentages indicate that the rate of loss of flexural strength in the section is slightly greater than the rate of stress demand in the section.

Markov chain deterioration model

The literature revealed that Markov models are extensively used for infrastructure deterioration (Madanat *et al.*, 1995; Micevski *et al.*, 2002; DeStefano and Grivas, 1998) with bridges being a frequent candidate (Agrawal *et al.*, 2008; Bocchini *et al.*, 2013; Casas, 2013; Strauss *et al.*, 2016) followed by pavements (Ortiz-Garcia *et al.*, 2006) and sewer pipes (Micevski *et al.*, 2002; Baik *et al.*, 2006). The Markov chain prediction model is a stochastic process that is discrete in time, has a finite state space and establishes that future state of the

Corrosion (%)	c (in.)	I_y (in.^{4})	I_z (in.^{4})	Z_y (in.^{3})	Z_z (in.^{3})
0	23.67	6,021.41	85,371.21	254.42	3,607.17
5	23.16	6,006.30	82,498.15	259.37	3,562.52
10	22.62	5,991.22	79,553.19	264.9	3,517.48
20	21.43	5,961.08	73,423.39	278.15	3,425.95
30	20.09	5,931.00	66,921.20	295.27	3,331.66
40	18.55	5,900.96	59,969.51	318.14	3,233.12
50	16.78	5,870.96	52,468.63	349.98	3,127.72

Table II. Girder's change section properties by corrosion

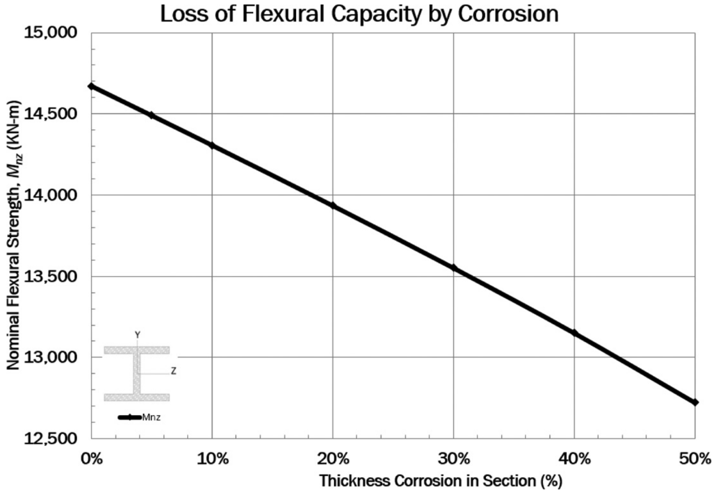

Figure 9.
Loss of flexural strength by corrosion

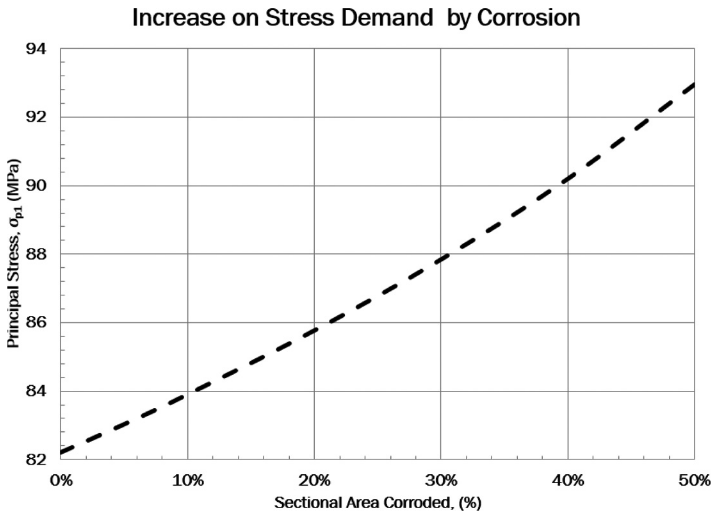

Figure 10.
Stress demand increase by corrosion

process depends only on its present state. Riveros and Arredondo (2010a, 2010b, 2011, 2014) proposed the use of the Markov chain model as a way to obtain a better prediction of the deterioration of navigation SHSs.

The Markov process can be expressed as follows:

$$P(X_{t+1} = j | X_t = i_t, X_{t-1} = i_{t-1}, \cdots, X_1 = i_1, X_0 = i_0) = P(X_{t+1} = i_{t+1} | X_t = i_t,) \qquad (2)$$

where P is a function of X, representing the probability to change from state i to state j at time $t+1$.

For all deterioration states $i_0, i_1, etc., i_{t+1}, i_t, i_{t+1}$ and all $t \geq 0$.

The Markov process assumes that the conditional probability does not change over time. Therefore, for all states, i and j and all t:

$$P(X_{t+1} = j | X_t = i) = p_{i,j} \tag{3}$$

are independent of t where $P_{i,j}$ is the probability, given the system is in state i at time t, it will be in state j at time $t+1$.

The transition probabilities are expressed by an $m \times m$ matrix called the transition probability matrix. The transition probability is defined as:

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,m} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{m,1} & p_{m,2} & \cdots & p_{m,m} \end{bmatrix} \tag{4}$$

When the process is used to simulate deterioration, the following condition applies:

$$p_{ij} = 0 \text{ for } i > j \tag{5}$$

This is because the condition of a deteriorating element will not improve by itself. When an element reaches its worst state, the following condition applies:

$$p_{mm} = 1 \tag{6}$$

This is because the condition of deteriorating an element will not change after it reaches its worst state. Consequently, the general form of the transition probability matrix for deteriorating elements is defined as:

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & p_{1,3} & \cdots & p_{1,m} \\ 0 & p_{2,2} & p_{2,3} & \cdots & p_{2,m} \\ 0 & 0 & p_{3,3} & \cdots & p_{3,m} \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{7}$$

A further restriction allowing the condition to deteriorate by no more than one state in one rating cycle is commonly used in deterioration modeling. The transition probability matrix is defined as:

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & 0 & \cdots & 0 \\ 0 & p_{2,2} & p_{2,3} & \cdots & 0 \\ 0 & 0 & p_{3,3} & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{8}$$

Discussion

Establishing the number of years the structural member is at a certain condition state (Table III), the transition probability matrix can be formulated using the results obtained from the numerical analysis. These values assume that at an inspection period of n years, the structural member was rated to go from state i to state j (i.e. duration of condition ratings). In addition, the condition state limits are defined by a predetermined level of corrosion (i.e. each condition state limit has an associated level of corrosion to it).

The probability of the member to change from one condition to the next was calculated on the basis of the number of years the structural member was in condition i. The probability of change is calculated as the inverse of the number of years in the current condition. The resulting transition probability matrix is illustrated in equation (9):

$$P = \begin{bmatrix} 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0.933 & 0.067 & 0 & 0 \\ 0 & 0 & 0.9 & 0.1 & 0 \\ 0 & 0 & 0 & 0.9 & 0.1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

By analyzing the worst case scenarios for each level of corrosion (maximum hydrostatic pressure, p_{max}) in the 3D finite element analyses (FEM), the maximun principal stess σ_1 was extracted (Figure 10). Hence, each condition state limit is directly associated with a determined stress level. Figure 11 shows that the combination of the Markovian solution and the stress demand increases; both as functions of time. According to the Markov chain prediction model, Girder 15 is expected to have a condition state of approximately 4.6 at a period of 74 years. At 65 years (50 per cent corrosion), the numerical model predicted the member to have a stress demand of approximately 36 per cent of its yield strength (considering the modeling constraints mentioned in section no. 4), which according to the deterioration model, corresponds to a condition state of 4.4. Debate has been formulated by Riveros and Arredondo (2011, 2014) on when is the optimum time to perform repairs if the Markov chain prediction model is used. Figure 9 shows that at the intersection between the demand and the Markovian solution, the system has a condition state of 3.6 and that the demand starts increasing rapidly.

Conclusions

By combining numerical (FEM) and probabilistic methods (Markov chain), the possibility of predicting the future condition state of the structure at a particular period, as well as having the capability of associating that state with a corresponding

Table III. Established rate of deterioration and corrosion level for each condition state

Time (years)	Corrosion (%)	Stress (psi)	State
0	0	11,928.2	1
20	10	12,176	2
35	20	12,447.2	3
45	30	12,748.6	4
55	40	13,090.6	5
65	50	13,491.2	5

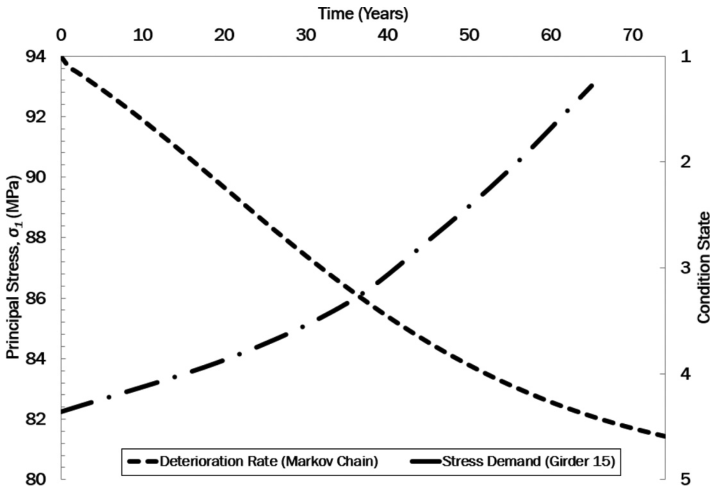

Figure 11. Deterioration rate vs stress demand increase

level of stress allows us to determine whether a critical structural member could experience significant stress levels such that material yielding, crack propagation or any other phenomena could occur at a predetermined number of years. The prior example illustrates the applicability of both these methods to accurately predict the condition state of a structure or structural member, as well as the states of stress associated with it. It is up to the engineers in charge of maintenace and repair prioritization to determine whether the predicted stress levels are sufficiently large enough to take proactive rather than reactive maintenance action. This significant tool could potentially save millions of dollars and most importantly human life.

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