Because of the destructive and unpredictable nature of MIC, both above and below water inspection procedures should be put into place immediately if MIC is suspected at a given site. It is essential that inspection personnel be well versed in identification and remediation techniques. With rapid identification and quickly ensuing rehabilitation efforts, the lifespan of any steel marine structure can be extended well beyond the length that it would have otherwise had.

Relative Material Loss - A Methodology for Approximating Material Loss on Structural Plating Separating Dissimilar Marine Environments

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ABSTRACT

The use of non-destructive testing techniques such as ultrasonic pulse echo is typical for measuring remaining member thickness on structural plating for determination of remaining service life. However, ultrasonic methods are limited and can only determine *total* material loss across the structural member - it cannot distinguish the degree of material loss on each side of the member – especially when the marine environments are dissimilar. This paper presents a new maintenance inspection methodology called *relative material loss* (RML) for approximating material loss on each side of structural plating separating two or more dissimilar marine environments. The RML methodology leverages actual "at sea" environmental and operational conditions and the relationships between each to solve for material loss contribution on each plate side. The technique can determine the effectiveness of the structure's preservation and coating system in its real word operational and marine environments. Byproducts of RML include (1) reduction in precision error and (2) location of structural anomalies inside inaccessible structures such as sealed ballast tanks. The paper presents a case study on a sixty five year old "at-sea" structure; a dry dock caisson gate to demonstrate the RML methodology.

INTRODUCTION

The August 2007 I35W bridge collapse renewed public concern over the condition of the U.S. aging infrastructure. In 2009, the American Society of Civil Engineers (ASCE) set the overall grade point average to a "D" and reported a staggering $2.2 trillion over a five-year period is required to raise the letter grade to a "B". This figure is up from $1.6 trillion reported in the 2005 ASCE report (ASCE 2009). Compounding this problem, economic and political pressures in the private and public sectors are placing new demands to extend service lives on aging facilities. The service lives of aging infrastructure is being pressed to, and more frequently expected to, perform beyond original design lives (Melchers 2001). As available capital for replacement facilities dwindle, service life extension projects (SLEP) are becoming more commonplace. This trend is placing new challenges on engineers and maintenance managers to do more with less and is resulting in a paradigmatic shift towards development of new and innovative maintenance inspection methodologies (Frangopol et al. 2004; Melchers 2001). This paper presents a new maintenance inspection methodology called *relative material loss* (RML) that can be used to approximate material loss and coating system effectiveness on structural plating subjected to dissimilar marine environments. The benefits of RML is wide reaching and can be applied in industries that include waterfront structures, shipbuilding, offshore oil, nuclear power and urban systems (i.e. underground piping).

MARINE CORROSION

The modern age of marine corrosion research pursued shortly after World War II (Southwell et al. 1976). In the quest to understand corrosion in marine environments, researchers subjected various ferrous metal test coupons in various marine environments and measured the amount of material loss over time. However, the *Erika* sinking off the French Brittany coast in 1999 and the *Prestige* sinking off the Spanish Galician coast in 2003 caused a paradigm shift in research direction (Paik et al. 2006; Tscheliesnig 2006). With a heightened focus on structural reliability, the maritime industry placed new demands on better understanding and predicting marine corrosion on hull structure of tankers and cargo vessels under operational and "at sea" conditions. More recent ship reliability and life expectancy models combine corrosion mechanisms with various modes of hull loading conditions to predict corrosion behavior from a structural limit state perspective (Paik and Thayamballi 2003).

Today's corrosion models depend on determining *total* remaining plate thickness and stop short of differentiating the amount (or contribution) of material loss occurring on each side of the structural member. Understanding the material loss contribution on each plate side would be of value to (1) maintenance engineers who are interested in optimizing overhaul and paint schedules, (2) material engineers who are interested in measuring the performance of various preservation and coating systems, or (3) corrosion researchers who interests lay in better understanding the mechanics of corrosion and pitting processes.

RELATIVE MATERIAL LOSS

The immersion of a ferrous plate in a particular environment, such as seawater, produces two-sided corrosion on each side of the plate. The solution to determine the material loss contribution on each plate side is straightforward when the corrosion environment is homogeneous and equivalent on both sides of the plate. The calculation simply involves dividing the total material loss by two. However, ultrasonic test devices used for measuring plate thickness wastage can only determine *total* material loss across hull shell plating; the tool cannot distinguish the amount of material loss contribution on each plate side. Therefore, when the environments on each plate sides are dissimilar, determining the material loss on each plate side is not so elementary. This paper introduces a new methodology called *Relative Material Loss* (RML) that provides a useful tool for solving this problem.

The RML methodology leverages actual "at sea" environmental and operational conditions and the relationships between them to solve for material loss contribution of each plate side of shell plating separating two dissimilar corrosion environments. In much the same fashion as a structural engineer isolates joints on a truss and solves free body diagram equations to determine member forces, relative loss (RL) equations are defined across various environmental boundaries (i.e. shell plating) and solved simultaneously to suggest solutions (or material loss contributions). A unique byproduct of RML is precision error, the error that occurs naturally due to variation in the environment, is reduced. The next section presents the RML theory using a theoretical example.

THEORETICAL EXAMPLE

A single Steel Plate A (Figure 1) with original plate thickness d_{oA} creates a boundary between two dissimilar marine environments $\mathbf{E}_1$ and $\mathbf{E}_2$, where $\mathbf{E}_1 \neq \mathbf{E}_2$. Environments $\mathbf{E}_1$ and $\mathbf{E}_2$ contribute to material loss $c_1(t)$ and $c_2(t)$, respectively, such that over time t, $c_1(t) \neq c_2(t)$. Corrosion protection systems such as coatings and cathodic protection $\mathbf{P}_1$ and $\mathbf{P}_2$ resist the effects of material loss $c_1(t)$ and $c_2(t)$, respectively. Where **E** and **P** are vectors of parameters that influence material loss. Through ultrasonic or caliper measurement, a thickness reading of Steel Plate A at time t is taken to determine remaining plate thickness $d(t)_A$.

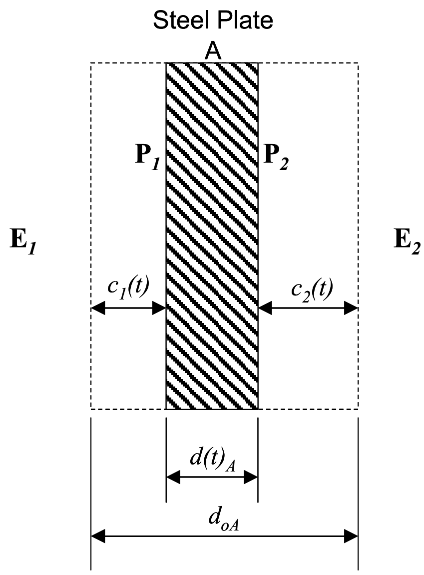

Figure 1. Single plate separating two dissimilar environments

The definition of total material loss (or wastage) W_A across Steel Plate A is:

$$W_A(t) = c_1(t) + c_2(t) \tag{1}$$

Note: For clarity purposes, parameter vectors **E** and **P** are temporarily omitted. To account for the real world variability, precision error, $\varepsilon_A(t)$, and bias error, $b_A(t)$, are added (Melchers 2003):

$$W_A(t) = b_A(t) \cdot [c_1(t) + c_2(t)] + \varepsilon_A(t) \tag{2}$$

Precision error will occur from the natural variation of the environment and bias error can occur from improperly calibrated test equipment, test methods or inexperienced surveyors (Figliola and Beasley 2001). Solving for $c_1(t)$, a relative loss (RL) equation in terms $c_2(t)$ is defined:

$$c_1(t) = \frac{W_A(t)}{b_A(t)} - c_2(t) - \frac{\varepsilon_A(t)}{b_A(t)} \tag{3}$$

If the test equipment is carefully calibrated and sound sampling methods are used, bias can be assumed to be unity (Melchers 2003). The RL equation above reduces:

$$c_1(t) = W_A(t) - c_2(t) - \varepsilon_A(t) \tag{4}$$

Where $c_1(t)$ is the material loss contribution of Steel Plate A, on side 1 in terms $c_2(t)$. The parametric vectors **P** and **E** omitted earlier for clarity reasons are added back:

$$c_1(t, \mathbf{P}_1, \mathbf{E}_1) = W_A(t) - c_2(t, \mathbf{P}_2, \mathbf{E}_2) - \varepsilon_A(t) \tag{5}$$

$W_A(t)$ is obtained from direct field measurement (i.e. ultrasonic measuring device). However, the solution remains indeterminate. Since $c_2(t)$ is unknown, it must be determined either by assumption or modeled probabilistically. Note that the scalar value of the error term $\varepsilon_A(t)$ did not change. The important RML characteristic of precision error reduction becomes apparent in the next section as a third environment and a second RL equation are introduced.

A second steel plate (Figure 2) with original plate thickness d_{oB} shares environment $\mathbf{E}_2$ and provides a boundary between a third dissimilar marine environment, $\mathbf{E}_3$, where $\mathbf{E}_1 \neq \mathbf{E}_2 \neq \mathbf{E}_3$. Since all three environments are assumed to be homogeneous, the assumption $c_2(t)_{PLATE\ A} = c_2(t)_{PLATE\ B}$ is made.

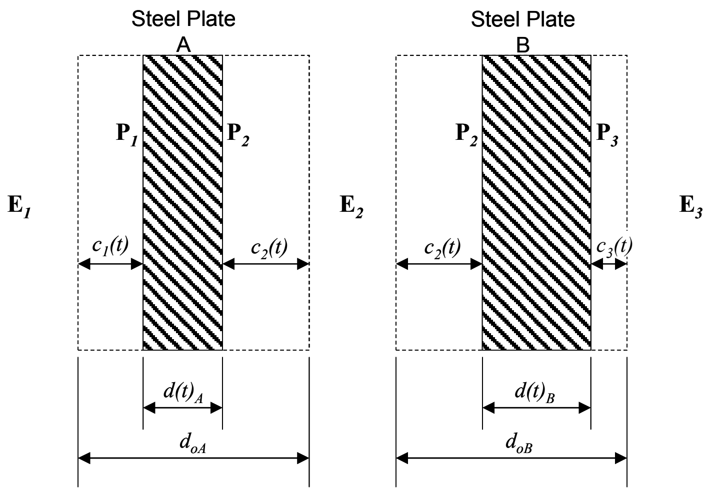

Figure 2. Two plates separating three dissimilar environments

The definition of total material loss of the steel plate, W_B across steel plate B is:

$$W_B(t) = c_2(t) + c_3(t) \tag{6}$$

The bias error, $b_B(t)$ and precision, $\varepsilon_B(t)$ are added:

$$W_B(t) = b_B(t) \cdot [c_2(t) + c_3(t)] + \varepsilon_B(t) \tag{7}$$

Solving for $c_2(t)$, a second RL equation is defined:

$$b_B(t) \cdot c_2(t) = W_B(t) - b_B(t) \cdot c_3(t) - \varepsilon_B(t) \tag{8}$$

Combining the two RL equations (3) and (8) and solving simultaneously, the RL equation in terms of $c_1(t)$ is defined as a function of $c_3(t)$:

$$c_1(t) = c_3(t) + \left[\frac{W_A(t) - \varepsilon_A(t)}{b_A(t)}\right] - \left[\frac{W_B(t) - \varepsilon_B(t)}{b_B(t)}\right] \tag{9}$$

Rewriting the RL equation to isolate the two error terms:

$$c_1(t) = c_3(t) + \frac{W_A(t)}{b_A(t)} - \frac{W_B(t)}{b_B(t)} + \frac{\varepsilon_B(t)}{b_B(t)} - \frac{\varepsilon_A(t)}{b_A(t)} \tag{10}$$

Assuming the test equipment is carefully calibrated and sound sampling methodologies are used, bias is unity; the RL equation reduces to:

$$c_1(t) = c_3(t) + W_A(t) - W_B(t) + \varepsilon_B(t) - \varepsilon_A(t) \tag{11}$$

Precision error reduction. From a deterministic perspective, under conditions where $\varepsilon_A(t) \approx \varepsilon_B(t)$, an argument is made that the composite precision error term in equation (11) approaches zero and can be neglected under special conditions. This state is said to occur when the manufacturing, maintenance and measurement processes are consistently applied throughout (the structure). For example, if procedures for surface preparation and coating application are standardized and controlled, then the precision error for the dry film thickness (DFT) is assumed equivalent across all shell plate coverage, supporting the argument that $\varepsilon_A(t) \approx \varepsilon_B(t)$. If $\varepsilon_A(t)$ and $\varepsilon_B(t)$ are treated as random variables and second moment algebra is applied, this the precision error reduction theory does not hold.

The parametric vectors **P** and **E** omitted earlier are added back to define a "zero error" RL equation $c_1(t)$ as a function of $c_3(t)$, $W_A(t)$ and $W_B(t)$:

$$c_1(t, \mathbf{P}_1, \mathbf{E}_1) = c_3(t, \mathbf{P}_3, \mathbf{E}_3) + W_A(t) - W_B(t) \tag{12}$$

Although the equation is still indeterminate, additional information in terms of $W_A(t)$ and $W_B(t)$ are known. If $c_3(t)$ is known or can be reasonable assumed, an approximation of $c_1(t)$ is made using equation (12). Knowing $c_1(t)$ or $c_3(t)$, $c_2(t)$ can be directly calculated using Eqs. (1) or (6), respectively.

A CASE STUDY – THE DRY DOCK CAISSON GATE

The case study involves a 65-year-old dry dock caisson gate located at Northrop Grumman Shipbuilding in Newport News, Virginia. Because of their passiveness, caisson gates are unique marine laboratories that are ideal for researching marine corrosion (Ernsting et al. 2009). The dry dock caisson gate (identified as "D") is a floatable steel vessel positioned and submerged on the sill of the open end of the dry dock to serve as a barrier between the free water and the dry dock interior (Figure 3)

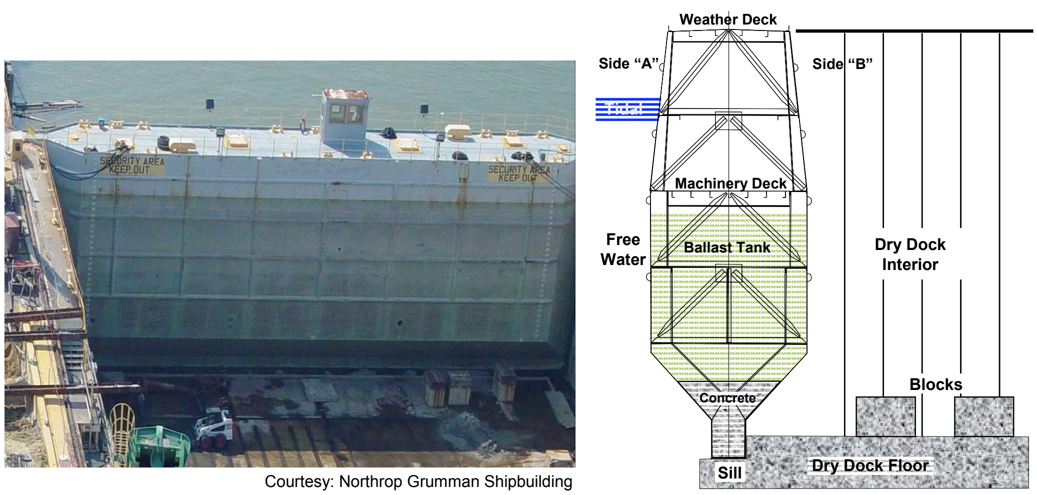

Figure 3. Dry Dock Caisson Gate "D" and Section View

Once the caisson gate is in place and the ship aligned over prearranged blocks, the dry dock is dewatered and the ship is safely lowered onto the blocks. As the water level of the dry dock lowers, hydrostatic forces from the free-water side of the gate increase and cause a natural water seal, forcing the caisson gate rubber seal to press into the concrete abutments around the bottom and two sides of the gate. Upon completion of dry dock dewatering and the ship safely seated on the blocks, ship maintenance and repair operations can safely be conducted on the ship hull, waterborne structures, and mechanical systems otherwise exposed to the sea.

Unique marine environments. Caisson Gate "D" main ballast tank shell plating is exposed to five marine environments: ballast tank atmospheric (E_1), marine atmospheric (E_2), ballast tank immersed (E_3), river water (E_4), and concrete ballast (E_5). Ten (10) relative loss (RL) equations are defined incorporating variables that identify these environments at Levels A, B, C, D and K and on Sides "A" and "B" (Figure 4). Where $W_{D\text{-}smSP}$ is the total wastage measured on side s, level m and R_{em} is the relative loss contribution influenced by environment e, at level m. For example, $W_{D\text{-}AASP}$ is the total wastage along Side "A" at Level A. R_{1a} is the relative loss contribution from E_1 at Level A.

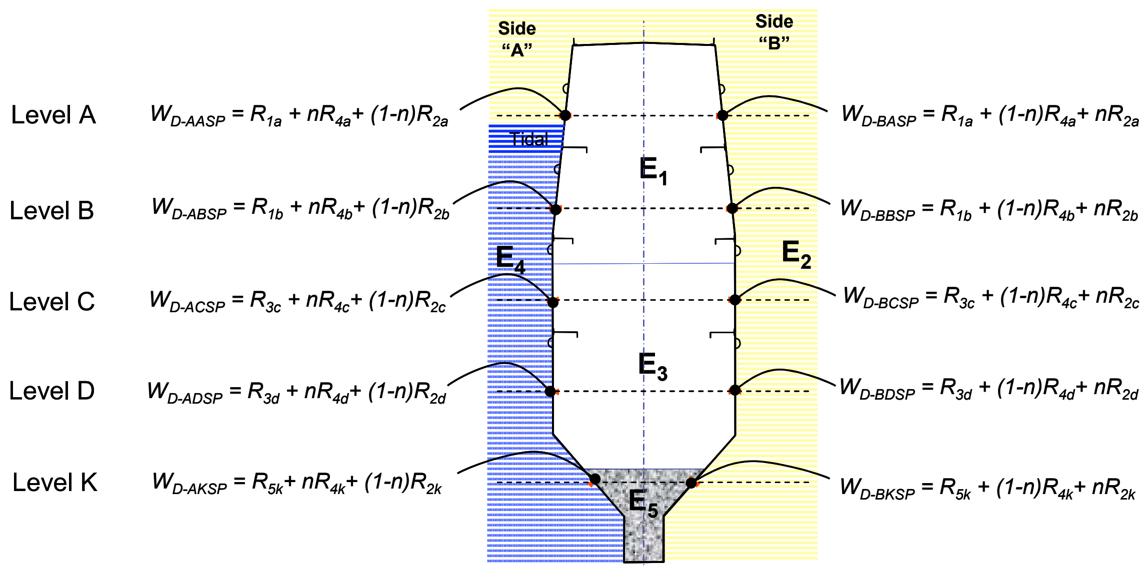

Figure 4. Relative Loss Equations across Shell Plating on Caisson Gate "D"

Caisson Gate "D" is reversible and is often rotated end for end to extend coating life and prevent permanent deflection from occurring due to hydrostatic pressure. To account for gate rotation, an operational parameter, n, is included, where n is the percentage of time Side "A" has been exposed to $\mathbf{E}_4$ (or conversely, $n - 1$ exposure to $\mathbf{E}_2$). For Caisson Gate "D", $n = .84$ (Ernsting 2009).

Assumptions. However, the solution in Figure 4 is indeterminate (10 equations, 15 unknown variables). To solve for the unknown variables, more information is required. It is reasonable to assume that when a side is exposed to the marine atmospheric environment, E_2, material loss is relatively small compared to the other environments and material loss contribution is near zero. Additionally, is it reasonable to assume that the marine atmospheric environment is equivalent at all caisson gate levels. Therefore, for caisson gate "D", the following assumption is reasonable:

$$R_{2a} = R_{2b} = R_{2c} = R_{2d} = R_{2k} \approx 0 \tag{13}$$

Negative Wastage. During data analysis, many of the measured ultrasonic readings produced negative values, giving an interesting perception that the shell plating thickness was actually *increasing* (or negative wastage). A finding from the study suggests that this phenomenon is likely caused when the original plate thickness is assumed nominal and the allowable mill tolerance for the plate is ignored. The allowable overage of the shell plating is 1.78mm (ASTM 2007) and found to be close to the needed value to zero out the measurements. Therefore, 1.78mm is added to each value of $W_{D\text{-}nmSP}$ to account for "negative wastage" and calibrate the RL equations (Ernsting 2009).

Relative loss variable R_{em} solutions. The ten RL equations in Figure 4 are combined with the five assumptions made in Eq. (13) to produce 15 equations and 15 unknowns (relative loss variables, R_{em}). The solutions to R_{em} are solved using a system of linear, simultaneous algebraic equations such that:

$$\mathbf{R}_x = \mathbf{A}^{-1}\mathbf{W}_x \tag{14}$$

Where x = frame locations 2, 5, 8, …41 (each third frame location number starting at x = 2)

The process above is repeated for all caisson gate levels and on both caisson gate sides for each caisson gate frame location, x. For example, at frame location x = 10, a summary of the solutions is presented in Table 1.

Table 1. RML Contributions, *c(t)* (at frame location: x=10)

Thickness add = 1.78		RML Contributions, *c(t)* :			Wastage	
n = 0.84	Elev	Ballast	River	Atm	Total	
D-AASP	101.3	**1.370**	**(0.009)**	**0.000**	**1.361**	
D-ABSP	93.3	**1.031**	**0.641**	**0.000**	**1.672**	
D-ACSP	85.3	**2.681**	**1.036**	**0.000**	**3.717**	**Example**
D-ADSP	77.3	**1.497**	**0.840**	**0.000**	**2.337**	
D-AKSP	69.3	**1.037**	**1.577**	**0.000**	**2.613**	
D-BASP	101.3	**1.370**	**(0.002)**	**0.000**	**1.368**	
D-BBSP	93.3	**1.031**	**0.122**	**0.000**	**1.153**	
D-BCSP	85.3	**2.681**	**0.197**	**0.000**	**2.879**	
D-BDSP	77.3	**1.497**	**0.160**	**0.000**	**1.657**	
D-BKSP	69.3	**1.037**	**0.300**	**0.000**	**1.337**	

The Table 1 example reads as follows: At caisson gate frame location x = 10, level C, Side "A", the total material loss across the shell plating is 3.717 mm. The loss contribution due to ballast tank water conditions is 2.681 mm (72%) and loss contribution due to river water conditions is 1.036 mm (28%). The loss contribution due to marine atmospheric is assumed to be near zero and therefore, negligible. The relative material loss can be expressed as a ratio such that:

$$RML_{D-ACSP} = \frac{c(t)_{Ballast}}{c(t)_{River}} = \frac{2.681}{1.036} = 2.59 \tag{15}$$

Meaning the relative material loss on the shell plating inside due to ballast tank water at this location is 2.59 times the outside surface exposed to the river side.

RML PROFILES AND ANALYSIS

For each third frame location along the Side "A" of caisson gate, vertical profile lines (black lines) of the total wastage as measure in the field and corrected for negative wastage are plotted (Figure 5). The mean value point estimate at each level is then calculated and profile plotted (indicated by the thicker red line). The thin black lines provide an approximate confidence interval of the point estimate.

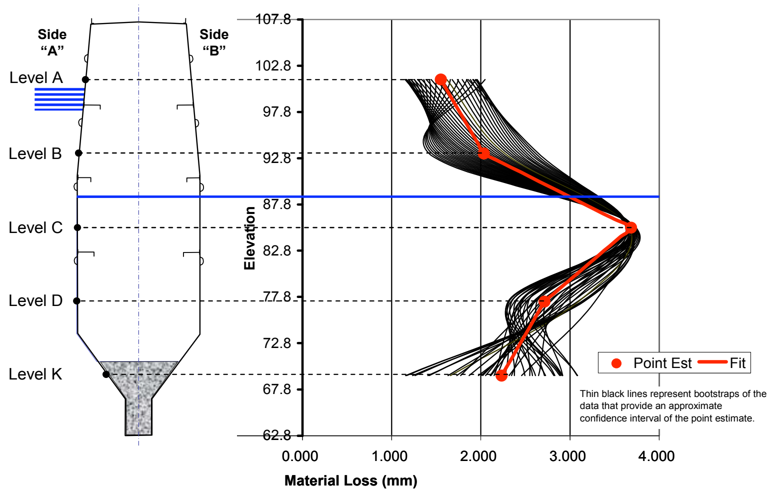

Figure 5. Caisson Gate "D", Side "A", Total Shell Plating Material Loss

The vertical profiles for the riverside contribution are plotted (Figure 6). A least squares fit is performed between the four mean value point estimates at levels B, C, D, and K and profile curve developed (adj. R^2 value = 94.5%). Note that the inflection points of the bootstrapped confidence intervals suggest locations of structural anomalies such as change in shell plating orientation (elevation 72.8), location of horizontal plate stiffeners (elevation 82.8) and top of ballast tank water level (elevation 88). Thus, the RML methodology can also serve as a means for locating structural anomalies hidden inside inaccessible areas or sealed containment.

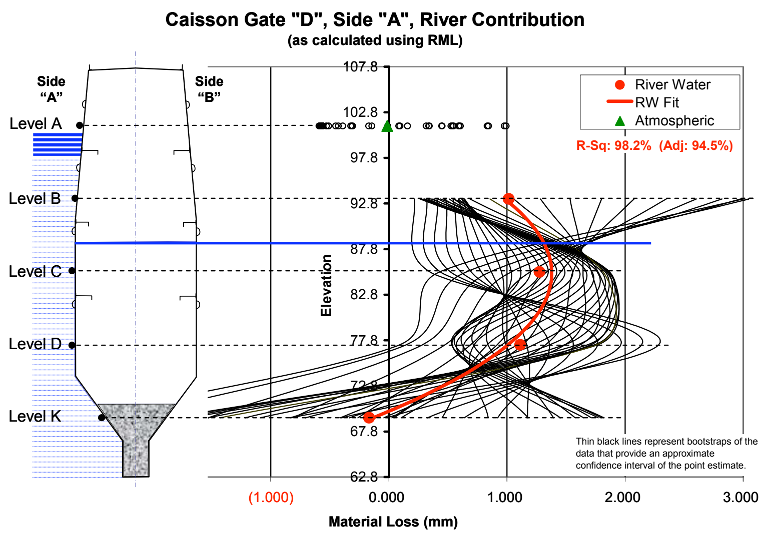

Figure 6. Caisson Gate "D", Side "A", River Side Material Loss Contribution

And lastly, vertical profiles of the material loss contribution for inside the ballast tank are plotted (Figure 7).

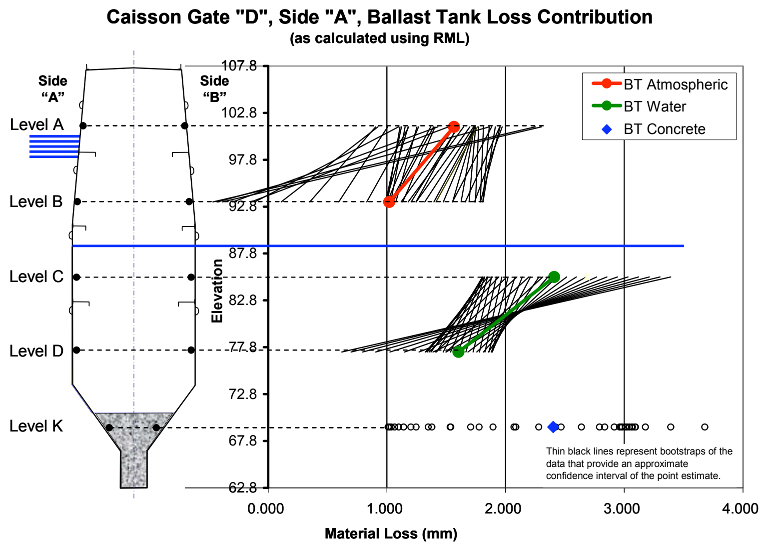

Figure 7. Caisson Gate "D", Side "A", Ballast Tank Side Material Loss Contribution

Comparing the Level K values in Figure 6 with Figure 7, the RML solution suggests that the highest rate of corrosion is occurring on the inside surface of the concrete ballast tank area. The concrete ballast was poured when the caisson gate was constructed circa 1940. Over its 65 years service, the concrete was never replaced. Therefore, it is reasonable to assume that salts from the constant contact with the saltwater ballast (directly above) likely leached through the concrete ballast over time and made its way to the inside surface of the shell plating at Level K. This RML solution has identified the Level K inside surface as a critical area for future inspection and maintenance considerations. Again, notice the inflection point near elevation 82.8 appears to correspond to the location of the horizontal plate stiffener. Again, supporting the idea that RML can also serve as a means for locating structural anomalies hidden inside inaccessible areas or sealed containment.

Validation. For validation, Pearson product correlations are performed between the material loss profiles on each plate side and the environmental factors known to influence marine corrosion; namely water temperature and dissolved oxygen content (Melchers 2005; Melchers and Jeffrey 2008). The correlations are significant and within the standard Type I error of alpha = 0.05 and supports validation of the RML methodology (Ernsting 2009).

CONCLUSION

The relative material loss methodology provides (1) a new paradigm from which marine corrosion researchers can apply their corrosion models directly using actual "at-sea" conditions as well as (2) a new maintenance inspection method that can better approximate marine material loss and coating effectiveness directly from structural shell plating thickness measurements taken from "at-sea" marine structures. The new methodology takes a deterministic approach by including actual operational and environmental conditions of the sea structure into the RML model. The new tool gives material science researchers and maintenance engineers the ability to study operational and environmental effects on shell