BIMETALLIC CORROSION FAILURE OF A LADDER CHASSIS FRAME EXPOSED TO HUMID ENVIRONMENT AND THE JUSTIFICATION OF CATHODIC PROTECTION METHODS BY NUMERICAL ANALYSIS

S. Chowdhury[1], R. K. Das[2*] and M. A. M. Hossain[2]

[1]Assistant Engineer, Bangladesh Steel Rerolling Mills Ltd, Chittagong, Bangladesh
[2]Department of Mechanical Engineering, Chittagong University of Engineering and Technology, Chittagong-4349, Bangladesh

Abstract: Bimetallic corrosion or galvanic corrosion occurs when two different metals come in contact with each other through an electrolyte medium. The metal with higher equilibrium potential acts as anode and the metal with lower equilibrium potential acts as cathode. A ladder chassis frame could be subjected to corrosion failure if it is exposed to corrosive environment without any protection. Galvanic corrosion could occur on a chassis frame if the fasteners or bolts and screws used are non-passive or electrochemically active. A numerical analysis has been performed in this study to examine the failure of the structural steel chassis frame due to atmospheric bimetallic corrosion when the stainless steel fasteners are in active state. The study is further extended to discuss two cathodic protection techniques for the chassis frame with the justification of using coating worldwide as a common corrosion prevention technique. The electrochemical study has been performed by numerical analysis in COMSOL Multiphysics. SOLIDWORKS has been used to draw Ram chassis frame for the numerical analysis. Numerical study confirms that the high relative humidity of about 85%-89% and lower salt density in the atmospheric salt humid air is more likely to cause electrochemical bi-metallic corrosion of the metal steel chassis frame. The study also depicts that the galvanized or coated steel frame provides more compact prevention from the corrosion failure than the sacrificial anodic protection when the fastener becomes electrochemically active.

Keywords: *Ram Chassis Frame, Stainless Steel Bolt, Galvanic Corrosion, Cathodic Protection, Coating.*

1. INTRODUCTION

Chassis frame refers to the main building block of a vehicle. The stability of a vehicle entirely depends on its chassis frame as all other components are mounted on it. A ladder chassis frame could be subjected to many failures which can appear in the form of cracks, buckling or bending (yielding), erosion of chassis material and cavities on the frame surface. Erosion of chassis material mainly results from the electrochemical corrosion on the frame surface. Electrochemical corrosion occurs mainly when the chassis frame is exposed to a corrosive medium such as atmospheric air with high humidity. In present most of the chassis frames are coated with anti-corrosion paintings before assembling as a vehicle. This painting is comparatively cheaper than metal coating and it also adds no extra weight on the chassis

frame, unlikely if a portion of the coating gets damaged the metal frame surface will be exposed to the corrosive environment as the undamaged coating is unable to give protection from electrochemical corrosion especially when the corrosion is bimetallic. Thus, a suitable cathodic protection method is needed along with painting to tackle corrosion for a longer period of time. The failure due to corrosion also depends on the chassis frame material. Structural steel or carbon steel and aluminum are the common materials generally used for chassis manufacturing. Aluminum is generally corrosion resistant due to the presence of aluminum oxide layer on its surface which is totally corrosion and thermal resistant. While the structural steel it is totally different from the aluminum as there is no oxide layer forms on its surface. When the steel frame is exposed to atmospheric air the surface area is attacked by the atmospheric oxygen and a

resistive film forms on the metal surface which prevents further corrosion of the surface. But the resistive film itself is a form of failure as the metal surface deteriorates with the increase of temperature. The resistive film formation which is termed as general attack corrosion is usually a safe form of corrosion, because this type of corrosion is predictable, manageable and often preventable. While in most cases electrochemical corrosion failure of the chassis frame is credited by the galvanic corrosion between the structural steel frame and the stainless steel bolt in the presence of atmospheric humid air. The rate of this corrosion is much higher than any kind of corrosion as the anode which is structural steel chassis frame corrodes and deteriorates faster than it would alone, while the cathode which is stainless steel bolt in the chassis frame deteriorates more slowly than it would otherwise.

Many research and studies have been carried out for years on the corrosion failure of the metal structures. Some researchers carried out experiments and reasonable studies on the fatigue failure of the chassis frame due to corrosion. C. M. Sonsino *et al.* [1] found that the fatigue strength of aluminium chassis frame components, submitted to spectrum loading and salt corrosion, diminishes significantly less than under constant amplitude loading and salt corrosion. Hagele *et al.* [2] introduced a tension support on the aluminium chassis frame and analyzed the effect of salt corrosion loading on the fatigue strength of the chassis frame. Kurdi *et al.* [3] performed finite element analysis of a corroded truck chassis frame and found that the equivalent stress increases due to the corrosion. But the impact of bimetallic corrosion and crevice corrosion on the chassis frame, as these two types of corrosion are mainly responsible for the chassis frame failure, was not described properly. Moreover, no suitable corrosion protection techniques were described to determine the impact of corrosion on the chassis frame with the change of environment. The current study focuses on the impact of bimetallic corrosion on the chassis frame in the presence of atmospheric salt humid air (marine environment) with two suitable cathodic protection methods. .

Atmospheric corrosion depends on many factors including relative humidity, salt contents or aerosols, pollutants, temperature, sulphur contents etc. R. G. Kelly *et al.* [4] described the effect of relative humidity and NaCl particles on atmospheric corrosion and laid down an analytical expression of calculating electrolyte conductivity which is a function of relative humidity with the electrolyte thin film thickness depends on deposited NaCl particles and relative humidity. The analytical expressions are used in this study to calculate the electrolyte conductivity and thickness. D. Mizuno and R. G. Kelly [5–6] proposed a method to calculate galvanic current density on a bimetallic couple of Aluminum AA5083-H131 alloy and AISI4340 steel by defining a limiting current density on the cathode surface because according to them oxygen reduction reaction on the cathode surface is slower due to the solubility of oxygen through the thin electrolyte film. D. Mizuno *et al.* [7] revealed that the electrolyte film thickness should not be less than 0.1 mm as the numerical analysis will not converge below this value. Researchers also found that the corrosion rate of carbon steel increases with the chloride ion and Sulphur contents deposition rates in the atmospheric air (marine environment) [8–11]. In this study the effect of relative humidity and deposition of NaCl particles will be discussed on atmospheric galvanic corrosion of chassis frame with along cathodic protection techniques. The corresponding data and parameters of this study are derived from the research papers of D. Mizuno and R. G. Kelly [4–7] and also from the Comsol Multiphysics material library and electrochemical values of the corresponding alloys defined in corrosion modules of the software.

Due to the robustness of the study and time shortage no experimental analysis has been carried out in this study and moreover the effect of changing values of salt density and relative humidity on the atmospheric corrosion is difficult to sort out experimentally. So numerical analysis is best suited to predict the failure and possible solution to the corrosion failure of the chassis frame as it saves precious time and money. The results are defined graphically so an exact intermediate value could be derived from the plots which can be useful before designing the corrosion prevention techniques for variable environments.

2. METHODOLOGY

A suitable chassis frame CAD model has been made in SOLIDWORKS 2012 (Fig. 1) which is a replica of a Dodge Ram chassis frame.

Fig. 1 Chassis frame (Dodge Ram) CAD model.

As the study is restricted to only numerical analysis so a small portion of the chassis frame is curved out for the analysis to minimize the computational time.

2.1 CAD Model
The models used in the analysis are described below:

(i) Corrosion in Salt Humid Air (without Protection)
The model used in this analysis (Fig. 2(a)) consists of a half portion of the rear-right side chassis frame with a stainless steel (active) bolt is coupled with it which tightens a mounting bracket to the beam. For proper simplicity of the model and to reduce the computational hours the mounting bracket and the horizontal bars are not included explicitly.
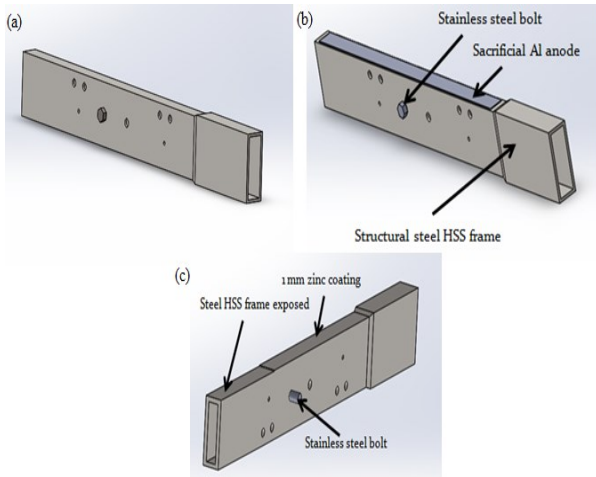
Fig. 2 3D Model geometry used in numerical analysis: (a) without any protection, (b) sacrificial anodic protection and (c) coating protection.

(ii) Sacrificial Anode Protection

The model shown in the Fig. 2(b) has two 1 mm Al sheet coupled on upper and lower side of the HSS steel frame which are used as sacrificial anode.

(iii) Galvanizing or Coating Protection

The model shown in the Fig. 2(c) is a galvanized steel frame. Zinc (anode grade zinc) is used as the galvanizing or coating metal here and the coated thickness is 1 mm.

For need of the analysis it is assumed that a portion of the coating is damaged on both sides (up and down) by variable means and the steel surface on there is exposed to the corrosive environment. The stainless steel bolt is non-passive and will act as cathode in this case study.

2.2 Numerical Method and Physics

Newton-Raphson Method and the electrochemical studies has been used in this study is listed in the table 1.

Table 1 Physics and studies used in numerical analysis on Comsol Multiphysics

Problems	Physics	Study (seconds)
Corrosion of chassis frame without any protection	Corrosion Secondary	Time study (0,10,50)
Sacrificial Anodic protection	Corrosion Secondary	Time study (0,10,50)
Coating Protection	Secondary Current Distribution	Stationary study

2.3 Electrolyte Description

Thin films of liquid water about 0.5 mm (assumed) thickness, formed on metal surfaces in contact with humidified air (Fig. 3), act as electrolyte in this study. The conductivity of the film depends on the relative humidity of the surrounding air with thin salt crystals assumed to be present on the chassis surface due to the high salinity of the environment.
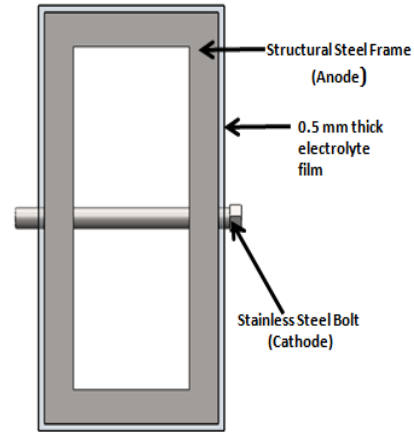

Fig. 3 Assumed electrolyte (thin film of water) distribution on the chassis frame surface.

2.4 Mesh Description

A satisfactory mesh (Fig. 4) has been constructed for this model involving triangular mesh and tetrahedron mesh. All fillets are avoided in the analysis model to prevent zero mesh or inverted mesh for smooth iteration. The finer grain size is selected for better meshing of the corners in order to improve the accuracy of the study.
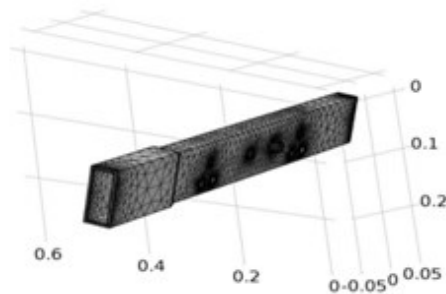

Fig. 4 Meshing of the analysis model.

2.5 Governing Equations

* Electrolyte Conductivity [4]

Electrolyte conductivity depends on relative humidity, mathematically articulated as:

$$K = 48250.20 - 287264.66RH + 683394.19RH^2 - 811693.63RH^3 + 481365.72RH^4 - 114051.78RH^5 \qquad (1)$$

* Electrolyte Film Thickness [4]

Electrolyte film thickness depends on NaCl concentration and relative humidity of the surrounding air.

$$WL=DD*(24.90+14.80RH-22.58RH^2)/(5811.94+23909.82RH -3291.21RH^2-57990.86RH^3+31576.8RH^4) \qquad (2)$$

Where WL, DD and RH represent the Film thickness, Salt concentration, and Relative Humidity respectively.

*Secondary Corrosion (*COMSOL Multiphysics-Corrosion Module)

$$\nabla.i_1 = Q_1, \; i1 = -\sigma_1\nabla\emptyset_1 \qquad (3)$$
$$\nabla. \; is = Q_s, \;\; is = - \; \sigma_s \nabla\emptyset_s$$
$$\emptyset_1 = phil, \; \emptyset_s = phis$$

where, phil is the electrolyte potential and phis is electric potential.

*Butler Volmer equation (*COMSOL Multiphysics-Corrosion Module)

The most general equation to describe the rate of this reaction as it proceeds at an electrode surface is the Butler–Volmer electro-analytical equation, can be expressed as:

$$i_{loc} = k_0 F(c_{Ox}exp(\alpha_a F_\eta/RT) - c_{Ox}exp(-\alpha_c F_\eta/RT)) \qquad (4)$$

where, k_0 is the heterogeneous rate constant (m/s) and α_c is the (cathodic) transfer coefficient (dimensionless).

$$C_{Red} = C_{Ox}exp (-FE_{eq} / RT)$$

This converts the above equation into the Butler–Volmer equation written in terms of an exchange current density i_0 (A/m^2):

$$i_{loc} = i_0(exp(\alpha_a F_\eta/RT) - exp(-\alpha_c F_\eta/RT)) \qquad (5)$$

The exchange current density i_0 is then related to the heterogeneous rate constant as

$$i_0 = k_0 F_C$$

*Tafel equation (*COMSOL Multiphysics-Corrosion Module)

$$\eta = Aln(i/i_0) \qquad (6)$$

where, η is the overpotential,

A is the so called "Tafel slope", V

i is the current density, A/m^2 and

i_0 is the so called "exchange current density", A/m^2

2.6 Iteration Parameters

A parametric sweep is defined for the whole numerical analysis to predict the effect of change in relative humidity and salt density on corrosion rate. The salt density and relative humidity taken for the analysis are included below:

- Salt Density (kg/m^2)-LD: 5*10^-4, 0.0015, 0.002, 0.003, 0.005, 0.008
- Relative Humidity (%)-RH: 0.62:0.09:0.98

3. CASE STUDIES AND CONDITIONS

Three case studies are discussed in the analysis. These are included below:

1. Bimetallic atmospheric corrosion of Ram chassis frame with active stainless-steel bolt.
2. Sacrificial anodic protection of the Ram chassis frame with active stainless-steel bolt.
3. Cathodic protection of the Ram chassis frame by coating or galvanizing with active stainless-steel bolt.

3.1 Boundary Conditions [6]

In this study the boundary condition on the anode is defined by the following equation:

$$i = i_{Anode}.exp[\{E_{Anode}-(V_m-V)\}/\beta_{Anode-A}] + [\{i_{AnodeLim}.i_{Anode}.exp[\{E_{Anode}-(V_m-V)\}/\beta_{Anode-C}]\}/\{i_{AnodeLim}+i_{Anode}exp[\{E_{Anode}-(V_m-V)\}/\beta_{Anode-C}]\}] \qquad (7)$$

where, i_{Anode} and E_{Anode} are the corrosion current density (A/m^2) and corrosion potential (V_{SCE}) for anode, respectively. The limiting current density for the cathodic reaction on the anode is represented by $i_{AnodeLim}$ and $\beta_{Anode-A}$ and $\beta_{Anode-C}$ are the Tafel slopes (V/decade) in the charge-transfer region for the anodic

and cathodic reactions on the anode surface respectively. Here, V_m (= 0) and V are the potential of the metal and solution (V_{SCE}), respectively.

For the cathode surface, the following equation was used as the boundary condition:

$$i = i_{Cathode}.i_{CathodeLim}.exp[\{E_{Cathode}-(V_m-V)\}/\beta_{Cathode-C}]/[\{i_{CathodeLim}+i_{Cathode}.exp[\{E_{Cathode}-(V_m-V)\}/\beta_{Cathode-C}]\} \qquad (8)$$

Where, $i_{Cathode}$ and $E_{Cathode}$ are the corrosion current density (A/m^2) and corrosion potential (V_{SCE}) for cathode. The limiting current density for the oxygen reaction on the cathode is represented by $i_{CathodeLim}$, and $\beta_{Cathode-C}$ is the Tafel slope (V/decade) in the charge-transfer region for cathode.

3.3 Electrochemical Reactions

(*COMSOL Multiphysics-Corrosion Module-Cathodic Protection) [6]

The less noble structural steel frame will be oxidized in the cell, with the electrode reaction kinetics described by a Butler-Volmer expression. On the stainless steel surface, oxygen reduction will occur. The oxygen reduction reaction is limited by oxygen transport through the film.

The limiting current density, $i_{lim,O2}$, depends on the film thickness, the oxygen solubility and the oxygen diffusivity according to:[6]

$$i_{lim,O2} = (4FDc_{sol})/d_{film} \qquad (9)$$

where F (96485 C/mol) is Faraday's constant, D (m^2/s) is the diffusivity of oxygen in the film, c_{sol} (mol/m^3) is the solubility of oxygen, and d_{film} (m) is the film thickness.

By assuming a first order dependency of the oxygen reduction kinetics on the local current density of the oxygen concentration, the following expression for the current density, $i_{lim,O2}$ (A/m^2), can be derived:

$$i_{loc,O2} = (i_{lim,O2}i_{expr})/i_{lim,O2}+|i_{expr}| \qquad (10)$$

$$i_{expr} = i_{Electrode}.exp[\{E_{Electrode}-(V_m-V)\}/\beta_{ElecTafel}]$$

where i_{expr} is the local current density of the electrode reaction in absence of mass transport limitations. In this model a cathode Tafel expression is used for i_{expr}.

3.3 Electrochemical Parameters of the Alloys

The electrochemical parameters of the corresponding steel frame, stainless steel bolt and aluminium and zinc anodes are included in the Table 2, Table 3, Table 4 and Table 5, respectively. Selection of the parameters of the alloys for different electrolyte conditions was very challenging in this study. The values of structural steel frame, stainless steel bolt and aluminium anode is for atmospheric humid air but the value of zinc anode owes to naval AgCl electrolyte solution.

Table 2 Parameters for structural steel frame [7]

Description	Value
Equilibrium potential	-0.535V
Kinetics expression type	Butler - Volmer
Exchange current density	0.056 A/m^2
Anodic Tafel slope (>0)	0.41V

Table 3 Parameters for aluminum anode [6-7]

Description	Value
Equilibrium potential	-0.7723V
Kinetics expression type	Butler - Volmer
Exchange current density	9.57e-4 A/m^2
Anodic transfer coefficient	2.5
Cathodic transfer coefficient	1.5
Anodic Tafel slope (>0)	0.12V

Table 4 Parameters for stainless steel bolt (Comsol Multiphysics-Corrosion Module).

Description	Value
Equilibrium potential	-0.29V
Kinetics expression type	Tafel
Exchange current density	0.012 A/m^2
Cathodic Tafel slope (<0)	-0.011153 V

Table 5 Parameters for anode grade zinc (naval material) for AgCl Solution (Comsol Multiphysics-Corrosion Module)

Description	Value
Equilibrium potential	-0.99V
Kinetics expression type	Butler - Volmer
Exchange current density	0.1 A/m^2
Anodic transfer coefficient	1.85
Cathodic transfer coefficient	0.78

3.4 Initial Conditions

- The study is performed with an assumption that no hydrogen evolution is taking place on the cathode surface.
- The anode and cathode metal alloys are free from thin oxide layer.
- Ohmic resistivity of the electrolyte is negligible.

4. RESULTS AND DISCUSSION

The results are displayed in both 3D and 2D plots. The results from the three different case studies are showed and discussed below:

(i) Corrosion of Ram Chassis Frame

Fig. 5a shows the current density on the corroded chassis frame and stainless steel bolt. The current density is negative on the bolt surface (blue color region) indicating high cathodic activity on the bolt surface. The positive current density on the chassis frame is uniform except near the bolt where the current density is maximum (red circular contours) indicating that the chassis frame will corrode faster in that region. The overall chassis frame will corrode at a slower rate except near the bolt region.

Fig. 5b shows the effect of corrosion on the frame surface by current density plot. The high current density contours near the fastener show that the chassis frame will gradually decay from that region.

Fig. 6 also shows the dependence of current density on salt density and relative humidity of the corrosive environment. It is found that the maximum current density occurs at the both anode

and cathode when relative humidity is 89% and salt density is smaller.

The maximum current density at anode and cathode indicates that the rate of corrosion of frame will be maximum near the bolt for 89% relative humidity and lower salt density load.
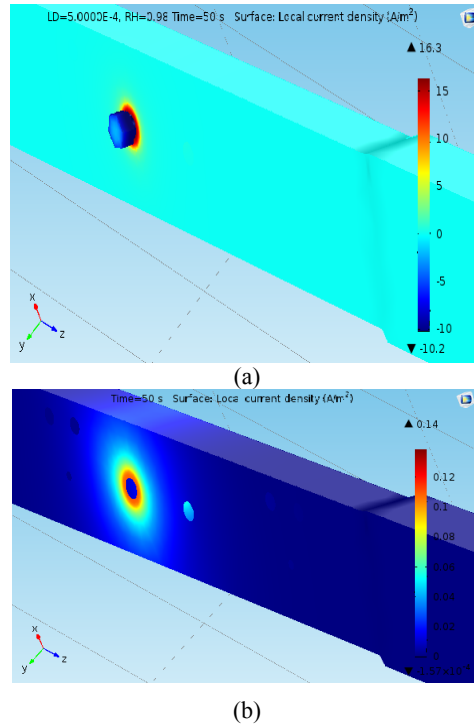

(a)

(b)

Fig. 5 Current Density on the corroded chassis frame: (a) with stainless steel bolt and (b) without stainless steel bolt.
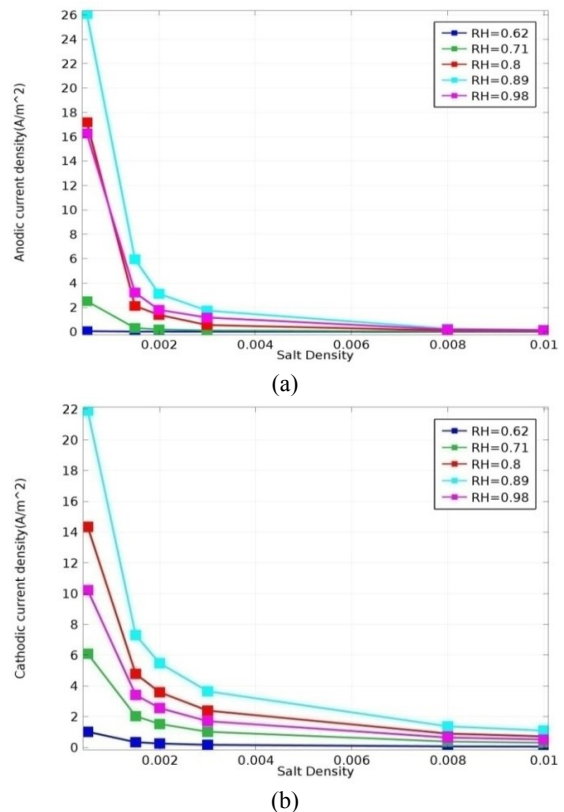

(a)

(b)

Fig. 6 Effect of Salt Density and Relative Humidity on Current Density: (a) corroding frame and (b) stainless steel bolt.

Fig. 7 reiterates the total corrosion rate of the whole chassis frame. It is found that the whole chassis frame will corrode faster at 89% relative humidity and lower salt density.
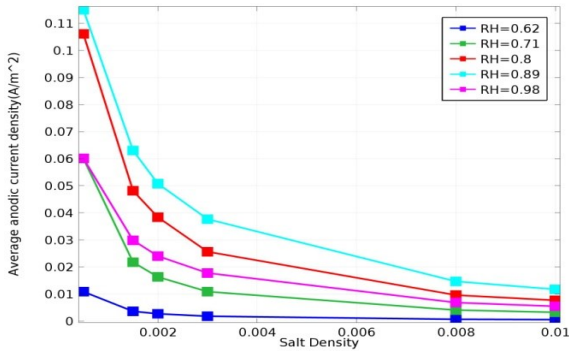

Fig. 7 Average current density on the corroded chassis frame.

The over potential plot shown in Fig. 8 also supports the combination of relative humidity and salt density behind the increasing corrosion rate of the chassis frame. The anodic over potential is maximum at 89% RH and lower LD indicating that the anodic reaction is faster for this combination. The cathodic over potential is maximum at 62% RH and higher salt density which means that the bolt will be in passive state in this condition and the galvanic corrosion rate is negligible. The over potential is smaller at 89% RH and lower LD on cathode surface making it electrochemically more active than other combinations resulting in high corrosion of the frame.
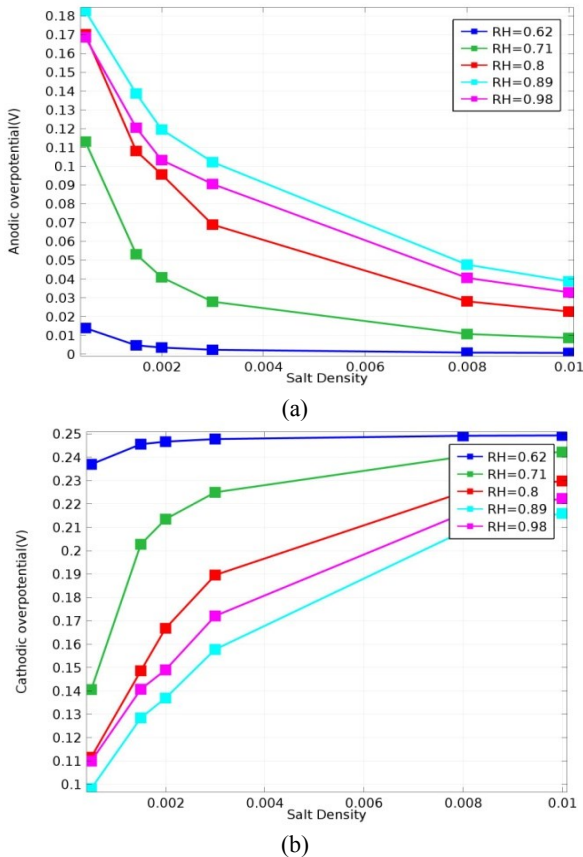

(a)

(b)

Fig. 8 Effect of Salt Density and Relative Humidity on over potential: (a) corroding frame and (b) stainless steel bolt.

(ii) Sacrificial Anode Protection of Chassis Frame

Fig. 9 shows the current density on the protected chassis frame. The current density ranges from 0 to -0.8 A/m² indicating ongoing cathodic activity on the frame surface. The surface region closes to the bolt and the front of the chassis frame experiences current density about 0 A/m² (red color contours) and is susceptible to corrosion if the sacrificial anode decays or erodes away. The result also shows that the 1 mm of aluminum sacrificial anode is not sufficient to give long term protection.
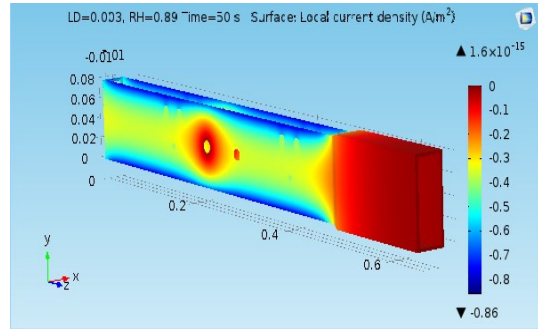

Fig. 9 Current Density on protected chassis frame by sacrificial Al anodic protection.

Fig. 10 represents a 2D plot of current density versus salt density and relative humidity for the structural steel frame and stainless steel bolt protected by sacrificial aluminum anode.
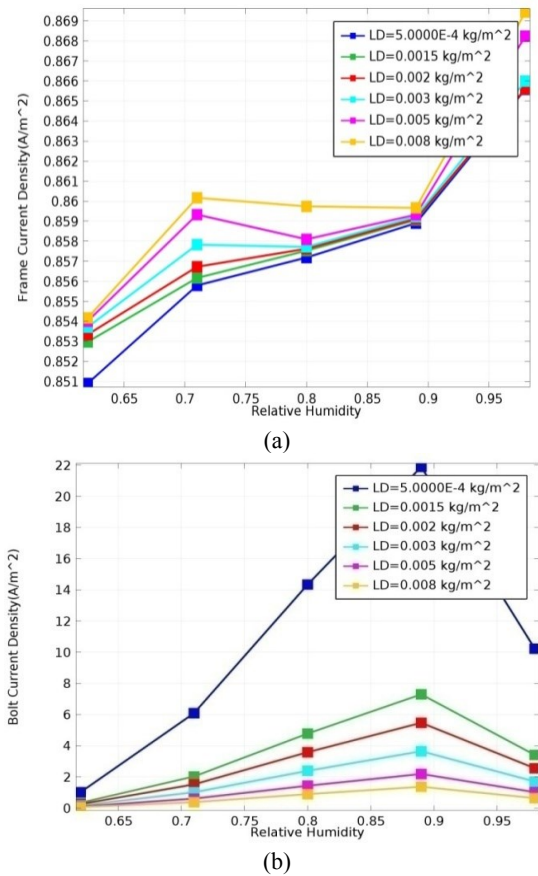

(a)

(b)

Fig. 10 Current density on the chassis frame protected by sacrificial Al anode: (a) chassis frame and (b) stainless steel bolt.
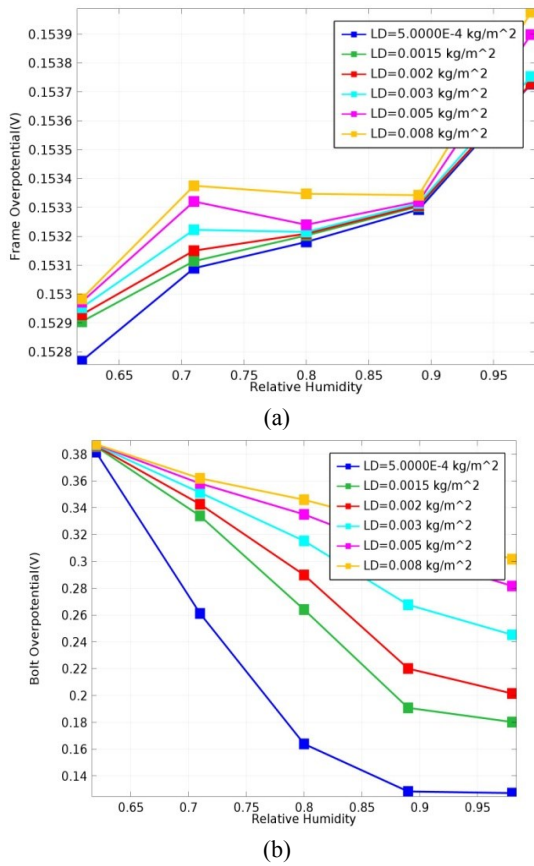
(a)

(b)

Fig. 11 Over potential change on the chassis frame protected by sacrificial Al anode: (a) chassis frame and (b) stainless steel bolt.

The maximum frame current density is below unity for all combinations of relative humidity and salt density which indicates that the aluminum anode sheet can protect the frame from any environmental change but the protection will not be longer as the current density is below one. The frame and bolt current density is maximum at 98% humidity and at higher salt density. The bolt current density is closer to limiting current density described earlier due to oxygen transfer through the electrolyte medium.
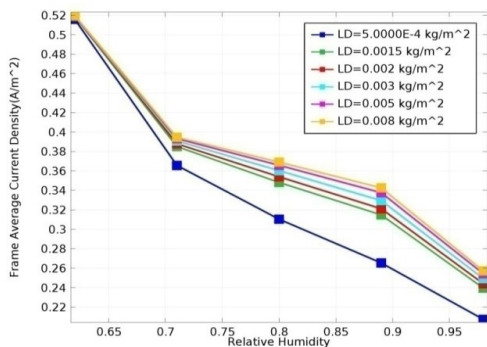

Fig. 12 Average current density on the chassis frame.

From Fig. 11 it is found that the frame and bolt over potential (negative) decreases with the decrease of salt density and is minimum for 0.008 kg/m² salt density. The over potential on bolt surface is minimum for 90%-98% relative humidity but in case of frame minimum occurs at 62% relative humidity.

Thus, it can be conclude that the frame will be susceptible to corrosion even at a lower relative humidity if the sacrificial anode fails to give protection due to other reasons.

Fig. 12 demonstrates the frame average current density with respect to various combinations of salt density and relative humidity. The result shows that for lower salt density and higher relative humidity (98%) the frame current density (negative) falls rapidly (towards positive) which can be described by the severe decay of the sacrificial anode and some corrosion could occur at the bimetallic intersection.

(iii) Coating Protection of Chassis Frame

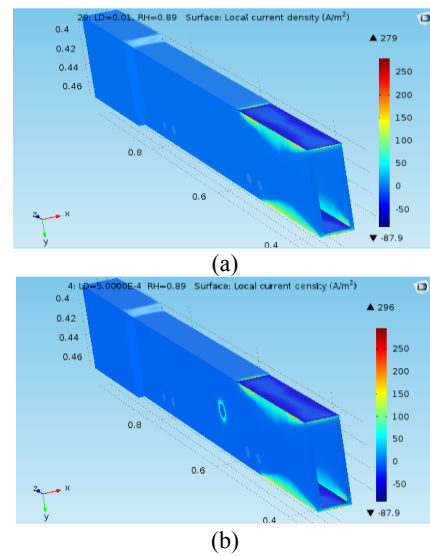Fig. 13 shows the current density of the coated steel frame.

(a)

(b)

Fig. 13 Current density on the Zn coated or galvanized steel frame for 89% relative humidity: (a) salt density- 0.01kg/m² and (b) salt density- $5*10^{-4}$ kg/m².

The exposed steel surface experiences negative current density of magnitude from -50 to -87.9 A/m², which indicates that the exposed surface will be well protected from the corrosive environment. The current density on all over the 1 mm Zn coated surface is uniform except near the exposed steel surface where the current density is maximum for all combinations of salt density and relative humidity indicating the coated surface will corrode heavily near the exposed steel surface. Additionally, for lower salt density and 89% relative humidity the coated surface adjoining the bolt experiences high current density (shown in the second picture) indicates that the surface will decay faster if the relative humidity varies from 85%-89%.

Fig. 14 shows that the current density on the exposed steel surface increases at same rate for all combinations of salt density and relative humidity. The current density is maximum at 98% humidity for all salt densities indicating that the decay of coated Zn surface surrounding the exposed steel frame is higher at this humidity condition. The current density of the stainless steel bolt is close to limiting current density and is maximum at 89% relative humidity. The coated Zn surface near bolt will corrode at a high rate for this relative humidity.
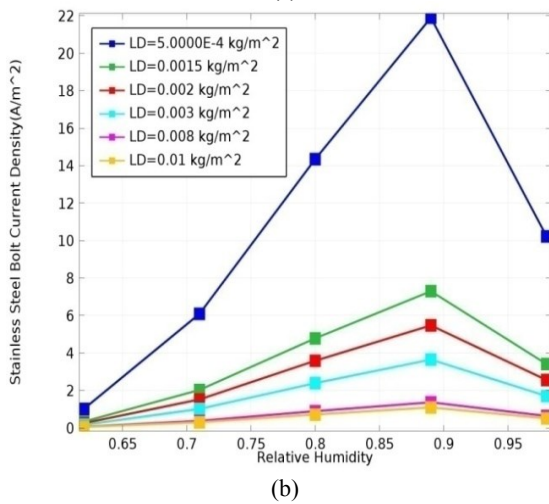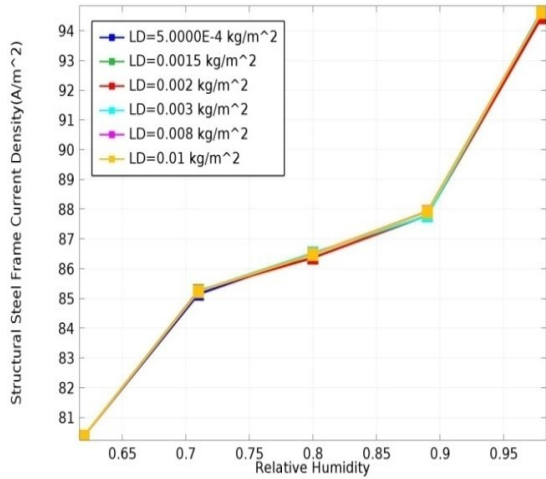
(a)

(b)

Fig. 14 Current density on the Zn coated or galvanized chassis frame: (a) chassis frame and (b) stainless steel bolt.

Fig. 15 represent that the cathode (bolt) over potential is minimum at 89% relative humidity, indicates that the decay of the zinc coating will be faster for this humidity (whatever the salt density is). The frame over potential curve is just like that of current density curve and it is maintaining similar trend for all combinations of relative humidity and salt density.
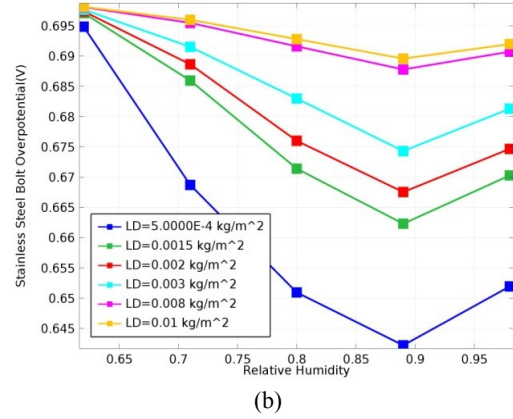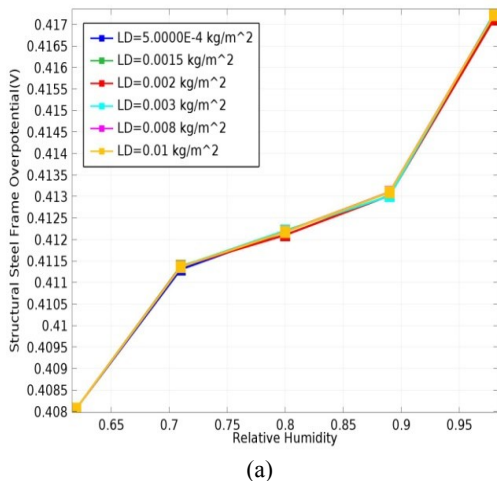

(a)

(b)

Fig. 15 Over potential on the Zn coated or galvanized chassis frame: (a) chassis frame and (b) stainless steel bolt.

5. CONCLUSIONS

The results obtained from the analysis show that the atmospheric corrosion is maximum when the relative humidity is 85%-89% and the salt density is lower. During cathodic protection the sacrificial anode and zinc coating corrode faster at this relative humidity due to maximum current density in cathode (bolt). The main findings from this study are included below:

- Bimetallic corrosion between structural steel and stainless steel bolt is not as severe in the humid environment as the maximum current density experienced on the frame is just 26 A/m^2. The passive bolt can protect the whole structure from bimetallic corrosion.

- Sacrificial anode protection is not efficient for chassis frame as it could fail if the electrolyte resistivity increases and difficult to implement because to protect a entire ladder chassis frame many anode sheets are required due to the geometrical complexity of the chassis and relocating them in different position needs great effort.

- Galvanizing or coating is the best choice as it is capable of protecting the steel frame from any environmental condition because the current density on the exposed steel surface is highly negative and higher electrolyte resistivity has no impact on the system.

REFERENCES

[1] C. M. Sonsino, C. Morgenstern, M. Streicher, H. Oppermann and A. M. Schmid, "Corrosion fatigue of welded aluminium vehicle structures under constant and variable amplitude loadings", Welding in the world, Vol. 56, 2012.

[2] N. Hagele and C. M. Sonsino, "Structural durability of forged automotive aluminium chassis components submitted to spectrum loading and salt-corrosion by the example of a tension strut", Procedia Engineering, Vol. 10, pp. 330–339, 2011.

[3]   O. Kurdi, R. A. Rahman and M. N. Tamin, "Finite element analysis of corroded truck chassis using sub modeling technique", Applied Mechanics and Materials, Vols. 110–116, pp 2411–2415, 2012.

[4]   Z. Y. Chen, F. Cui and R. G. Kelly, "Calculations of the cathodic current delivery capacity and stability of crevice corrosion under atmospheric environments", Journal of The Electrochemical Society, Vol. 155 (7) pp. C360–C368, 2008.

[5]   D. Mizuno and R.G. Kelly, "Galvanically induced intergranular corrosion of AA5083-H131 under atmospheric exposure conditions: Part 1 - Modeling of the damage distribution", Corrosion, Vol. 69, No. 6, pp. 580–592, 2013.

[6]   D. Mizuno and R.G. Kelly, "Galvanically induced intergranular corrosion of AA5083-H131 under atmospheric exposure conditions: Part 2 - Modeling of the damage distribution", Corrosion, Vol. 69, No. 7, pp. 681–692, 2013.

[7]   D. Mizuno, Y. Shi and R. Kelly, "Modeling of galvanic interactions between AA5083 and steel under atmospheric condition" Presented at the 2011 COMSOL Conference in Boston.

[8]   M. Carlos Hangarter and S. A. Policastro, "Electrochemical characterization of galvanic couples under saline droplets in a simulated atmospheric environment", Corrosion, Vol. 73, No. 3, pp. 268–280, 2016.

[9]   A. R. Mendoza and F. Corvo, "Outdoor and indoor atmospheric corrosion of carbon steel", Corrosion Science, Vol. 41, Issue 1, pp. 75–86, 1999.

[10]   Y. Ma, Y. Li and F. Wang, "Corrosion of low carbon steel in atmospheric environments of different chloride content", Corrosion Science, Vol. 51, pp. 997–1006, 2009.

[11]   Y. Ma, Y. Li and F. Wang, "The atmospheric corrosion kinetics of low carbon steel in a tropical marine environment", Corrosion Science, Vol. 52, pp. 1796–1800, 2010.