ASEAN Engineering Journal

Full Paper

CORROSION OF GALVANISED AND UNGALVANISED COLD-FORMED STEEL IN CHLORIDE AND SULPHATE SOLUTIONS

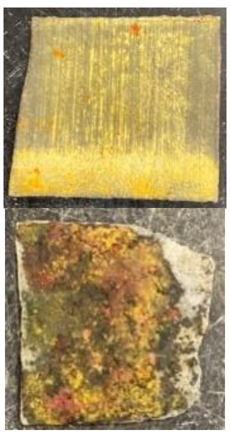
Brandon Yi Yang Ling[a], Yeong Huei Lee[a], Shahrin Mohammad[b], Cher Siang Tan[b*]

[a]Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
[b]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
21 April 2022
Received in revised form
26 July 2022
Accepted
07 August 2022
Published online
28 February 2023

*Corresponding author
tcsiang@utm.my

Graphical abstract



Abstract

The light steel framing is widely use around the world to replace the conventional construction method. However, there are some factors that affect the corrosion rate of the steel framing structures. The factors are oxygen, humidity, sulphate, chloride and copper sulphate which highly contain in seawater regions or specifically coastal area. Hence, all these factors that influence the corrosion rate of the steel framing shall be study to determine the service life and the maintenance required throughout their service life. This paper studies the effect of the chloride, sulphate and the rainwater to the light steel framing structure and the corrosion resistance that provided by the zinc coating on the surface of the steel. The galvanized steel and ungalvanized steel are immersed in different concentration of sodium chloride and copper sulphate solutions for 28 days. The corrosion rate is obtained by measured the weight loss of the steel coupons in the interval 7-days of the immersion time. Other than that, the corrosion rate in seawater is analysed by the result of 0.5 Mol of NaCl and 0.016 Mol of $CuSO_4$. The corrosion rate for the NaCl and $CuSO_4$ is much higher than the corrosion rate in the rainwater. The corrosion resistance that provided by the zinc coating is extremely higher compared to the steel that without the protection. Prediction equation of metal loss from experimental study is proposed for a reliable light steel structure in a function of time.

Keywords: corrosion, durability, light steel frame, cold-formed steel, strength reduction

© 2023 Penerbit UTM Press. All rights reserved

1.0 INTRODUCTION

As one of the alternatives of conventional construction, dry construction with light steel frames provides a fast and clean construction solution which is more preferable [1]. The construction time could be shortened 50% using light steel framing [2]. There were 15% market share of housing construction with light steel frames annually in Australia [3]. The benefits of light steel framing include high strength to weight ratio, high degree of prefabrication, better site waste management, shorter construction period, environmental-friendly and etc. The strength these cold-formed steel as structural members under ultimate limit state have been investigated and proved their loading carrying characteristics with massive of previous studies [4–7].

Corrosion is one of the hazards of durability for steel structures which may progressively weaken structural members due to strength reduction [8]. Zinc coating of cold-formed steel serves as a physical barrier between steel and corrosive environment. The rate of zinc loss or steel corrosion should be determined for further strength reduction analysis. Corrosion studies have been conducted for cold-formed steel [9-10] and corroded structural members [11-12]. As compared to hot-rolled steel, cold-rolled steel has higher corrosion rate when exposed to an aggressive solution of 16.9 vol% $H{=}SO_4$ + 0.35 vol% HCl at 60°C and pH 0.3 [13]. Other study also investigated the electrochemical properties in an acid chloride solution [14]. Corrosion of galvanized steel and cooper also have been studied in sea environment [15]. Most of the corrosion studies were conducted for material properties study and rarely relating to structural member analysis in building construction.

In tropics, relative high humidity may accelerate steel corrosion in hot and humid weather condition. The study of durability of light steel frames in tropics are rarely found in current research trend. Therefore, this paper investigates the corrosion rate of galvanized and ungalvanised cold-formed steel coupons with different concentrations of chloride and sulphate solutions. Rainwater in tropic, specifically Miri, Malaysia is also collected locally and used as a comparison with those in solutions. Metal losses are calculated for further corrosion analysis.

2.0 METHODOLOGY

Experimental speed corrosion tests are conducted, modified from ASTM G31. The weight of the specimens is determined for strength loss prediction. The specimens are immersed into desired concentration of solutions for a time period and remove the rust for obtaining the remaining weight of the specimens.

Specimens Preparation

The coupon size is 100 × 50 mm from a 3 mm channel section of cold-formed steel. The cold-formed sections were cut into desired size using grinder. The tested cold-formed sections from previous beam flexural experiments were used, as shown in Figure 1. Galvanised or ungalvanised steel coupons were prepared for the immersion tests in chemical solutions.

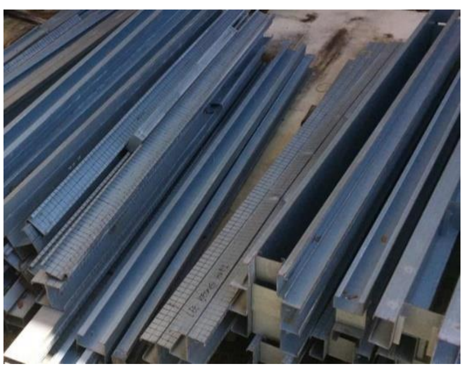


Figure 1 Used channel cold-formed steel section for corrosion tests

Chemicals and Solutions

For speed corrosion tests, there are two different chemicals, namely chloride and sulphate solutions, which they are accelerating the rusting process. NaCl and $CuSO_4$ powder are utilized to prepared different concentration solutions. Five concentrations of each chemicals have been prepared for steel coupons immersion tests. The information of the solutions is tabulated in Table 1. The natural rainwater also was collected from Miri, Sarawak, Malaysia for the immersion tests for comparison with the stated solutions.

Table 1 Details of The Solutions for Speed Corrosion Tests

Amount of Powder, g	Amount of Distilled Water, mL	Concentration, Mol
NaCl		
5.84	200	0.5
11.69	200	1
23.38	200	2
35.06	200	3
46.75	200	4
$CuSO_4$		
0.51	200	0.016
1.60	200	0.05
3.19	200	0.1
9.58	200	0.3
15.96	200	0.5
31.92	200	1

Test Procedures

The solutions were prepared, and the steel coupons were immersed in. Before immersion tests, the steel coupons were weighted. The coupons were immersed for one, two, three and four weeks respectively. Upon reaching the desired time frame, the specimen was dried, the rusts on the specimen were removed and weighted. Figure 2 shows the specimens that immersed in the different concentration of $CuSO_4$ solutions.

Figure 2 Immersion tests in $CuSO_4$ solutions

Corrosion Rate Analysis

The metal loss is determined with the measured coupon's weights for the corrosion rate analysis. The rates between galvanised and ungalvanised were determined and compared with the corrosion rate in natural rainwater. Different solution concentrations and time periods are the variables in the following discussions. Eq. 1 shows the chemical reaction to produce rust (iron oxide) when exposed to oxygen.

$$2Fe + O_2 + 4H^+ \rightarrow 2Fe^{2+} + 2H_2O \quad \text{(Eq.1)}$$

3.0 RESULTS AND DISCUSSION

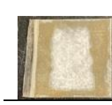
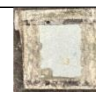
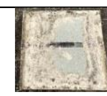
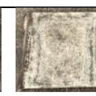
Chloride Solutions

The corroded specimens can be visualized from Table 2. The corroded coupons revealed that there were no rusts (ferum oxide) found on the galvanized surfaces of the cold-formed steel coupons. Contrary, the rusts were observed in all surfaces. Figures 3 and 4 show the corrosion rate of immersed steel coupons in different concentration of NaCl. Due to an exceedingly small difference of metal loss, removing of the corroded iron oxide may cause the fluctuation of the data in the graph illustrations. Generally, the corrosion rate increased with the increment of solution concentration and time frame for both galvanized and ungalvanised cold-formed steel coupons. According to [16], zinc is corroded as steel while exposed to the atmosphere, however, the corrosion rate of zinc is approximately 1/30 of steel.

From previous study, a passive film of iron oxide is formed at the initial stage with more aggressive reaction [17] and the reaction is slowed down as the impermeable layer of the oxide preventing further chemical reaction with oxygen. This fact can be revealed on Figure 4 where higher rate at initial stage and lower rate at later stage for ungalvanised cold-formed steel coupons. As the immersion time increased, the formation of passive film is become more adherent and compact and decreased the diffusion and absorption of oxygen in the NaCl solution [18]. However, higher metal loss rate can be found in Figure 3 at later stage for galvanized cold-formed steel coupons. This is due to the zinc coating is consumed and exposed the steel to the corrosive environment and corrosion reaction is accelerated in later stage.

While the corrosion reaction occurred, the zinc coating on the galvanized steel transferred the electrons to the environment enabling the formation of dissolved species (Zn^{2+}) form the zinc coating in the solution. Besides that, with the presence of dissolved NaCl, the NaCl solution is break down into sodium ions (Na^{+}) and chloride ions (Cl^{-}) which help to transfer the electron during the corrosion reaction. Hence, the higher the concentration of NaCl, more ion involve in the corrosion reaction and resulting in increased of corrosion rate.
The highest corrosion rate for 7 days of immersion of un-galvanized steel was 0.5 Mol NaCl which is 0.07 g and the lowest corrosion rate was 4.0M NaCl which was only 0.02 g of metal loss. This can be clearly stated that the corrosion rate is decreased when the concentration of NaCl increased due to the formation of the ferrous hydroxide, Fe (OH_2) which is insoluble in water is act as a barrier layer to isolate the steel from the environment. As the concentration of the NaCl solution increased, the barrier layer is converted to a thicker layer of ferrous hydroxide, Fe (OH_3) and therefore decreased the corrosion rate of the steel.

Table 2 Corrosion Behaviour of Immersed Steel Coupons in NaCl

Steel Coupon	Mol	Week 1 (7 Days)	Week 2 (14 Days)	Week 3 (21Days)	Week 4 (28 Days)
Galvanized	0.5				
Ungalvanized					
Galvanized	1.0				
Ungalvanized					
Galvanized	2.0				
Ungalvanized					
Galvanized	3.0				
Ungalvanized					
Galvanized	4.0				
Ungalvanized					

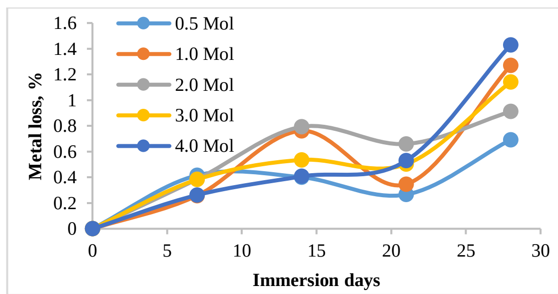


Figure 3 Corrosion rate for galvanised cold-formed steel coupons in NaCl

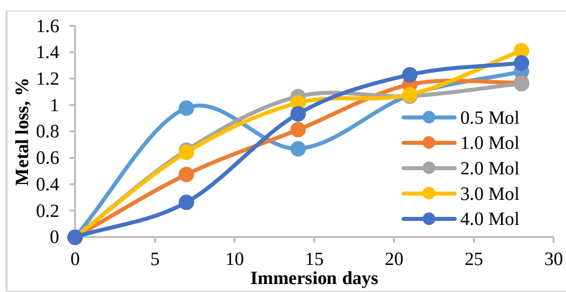


Figure 4 Corrosion rate for ungalvanised cold-formed steel coupons in NaCl

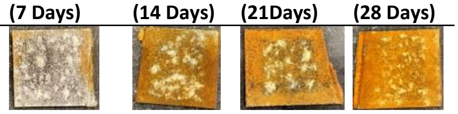
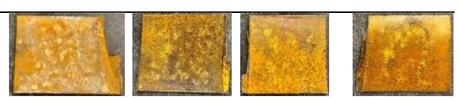
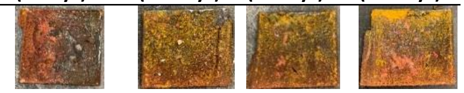
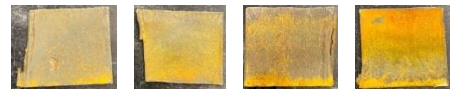
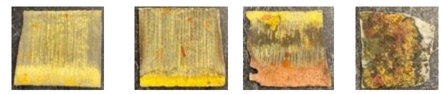
Sulphate Solutions

Table 3 shows the corroded specimens of galvanized and un-galvanized cold-formed steel coupons in $CuSO_4$ solutions. Unlike in NaCl solutions, the zinc coating only can be found in the lowest solution concentration in $CuSO_4$ in 7-days immersion. Corrosion rates of ungalvanised cold-formed steel coupons were obviously greater than those galvanised steel coupons. Figures 5 and 6 show the corrosion rates of galvanised and ungalvanised steel coupons in different concentration of $CuSO_4$ solutions.

The highest weight loss was discovered at the initial stage due to the redox reactions that occurred between the zinc coating surface and the copper ion in the $CuSO_4$ solution. The copper ion oxidized the zinc coating on the surface of the specimens. When the immersion time of the galvanized steel in the $CuSO_4$ solution increased, the corrosion rate of the galvanized steel increased. This is due to the decay of the zinc coating by oxidation process for a longer period of time which known as corrosion. Simultaneously, the copper ions that present in the solution are reduced to form copper metal that caused the $CuSO_4$ to become colourless [19]. The yellow rust can be shown on the surface of the galvanized steel. It shows that the longer the immersion time, the thicker the formation of the yellow rust on the surface of galvanized steel.

The weight loss of the galvanized steel is extremely lower than the un-galvanized steel whether in longer immersion time or higher concentration of the $CuSO_4$ solution. This has proved that the zinc coating is sufficient to reduce the corrosion rate of the steel. Zinc coating prevent the corrosive elements direct reaching to the steel that underneath as it acts as a sacrificial metal. Zinc is more easily to oxidize compare to steel. It consists lower reduction potential and resulting to be more active metal. Hence, the zinc shall be oxidized prior to the steel even the zinc coating has been scratched.

Table 3 Corrosion Behaviour of Immersed Steel Coupons in $CuSO_4$

Steel Coupons	Mol	Week 1 (7 Days)	Week 2 (14 Days)	Week 3 (21Days)	Week 4 (28 Days)
Galvanized					
Ungalvanized	0.016				
Galvanized					
Ungalvanized	0.05				
Galvanized					
Ungalvanized	0.1				
Galvanized					
Ungalvanized	0.3				
Galvanized					
Ungalvanized	0.5				
Galvanized					
Ungalvanized	1.0				

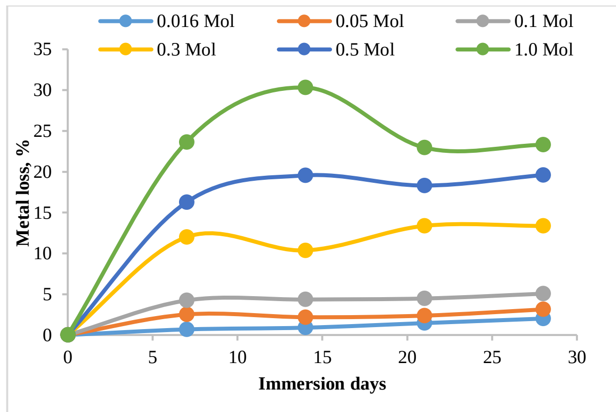


Figure 5 Corrosion rate for galvanised cold-formed steel coupons in $CuSO_4$

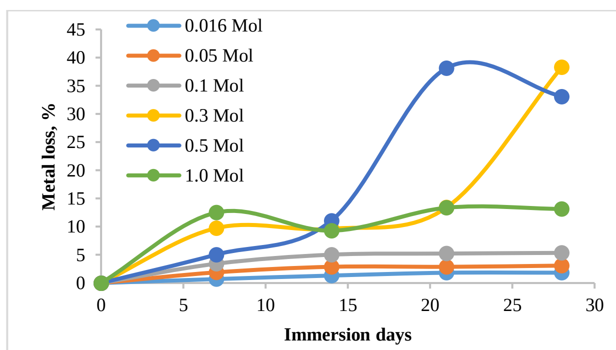


Figure 6 Corrosion rate for ungalvanised cold-formed steel coupons in $CuSO_4$

Rainwater

Table 4 shows the corroded specimens of galvanized and un-galvanized cold-formed steel coupons in rainwater. The rainwater was obtained at Miri, Sarawak. Previous findings found that the range of the rain pH value in Miri, Sarawak is 4.8 to 5.6 which considered least moderate acidic [20]. However, while the rainwater is falling through the atmosphere, the oxygen gas from the atmosphere is absorbed and dissolved in the rainwater which increased the corrosion rate.

Figure 7 shows the corrosion rates for both galvanized and ungalvanised cold-formed steel in the collected natural rainwater. In the immersion period of 7-days, there was no metal loss found for galvanized steel coupons. The overall corrosion rates were lower than those immersed in chloride and sulphate solutions.

Previous research revealed that the corrosion rate of the galvanized steel is high initially due to the amount of reactants between the galvanized steel and the rainwater is high [15, 21]. However, the amount of reactants decreased following by the immersion time of the galvanized steel and therefore resulting in decreased of the corrosion rate. Besides that, the corrosion rate reduced following the immersion time is due to the protective film that formed on the surfaced of the galvanized steel [21]. The protective film is known as zinc carbonate. This protective film reduced the corrosion rate of the galvanized steel by avoid the rainwater dissolved and contact the zinc coating surface easily. However, the formation of the protective film has assisted the galvanized steel became superior corrosion resistance for long time exposure of the galvanized steel.

The corrosion rate by the rainwater also is affected by the component such as pollutant concentration level of Sulphur dioxide (SO_2), Nitrate (NO_3), Chloride (Cl^-) and the rain pH level. Therefore, the corrosion rate of the galvanized steel by the rainwater should be always measured accordance to the latest pollutant rate of the environment to ensure the durability of the galvanized steel for their service life.

Table 4 Corrosion Behaviour of Immersed Steel Coupons in rainwater

Steel Coupon	Solution	Week 1 (7 Days)	Week 2 (14 Days)	Week 3 (21Days)	Week 4 (28 Days)
Galvanized					
Ungalvanized	rain water				

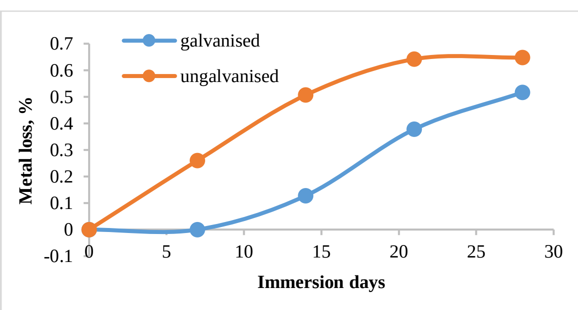


Figure 7 Corrosion for cold-formed steel coupons in natural rainwater

Durability of Corroded Cold-Formed Steel in Chloride Condition

Light steel framing structure is widely use in the seawater. Therefore, the durability of the light steel framing shall be known. In this study, the durability of the galvanized steel for service life in sea water is analysed to ensure that the steel framing structure is still qualified for service and provide maintenance when it is required. Seawater is the water obtained from the sea or ocean. On average, the salinity of the sea water in the world's ocean is approximate 3.5%. This means that it consists 35 grams of salts in every 1 litre of sea water. This salt not entire but mostly is the sodium chloride. This can be expressed as approximately 0.5 Mol of NaCl which is the lowest molarity of immersion test that utilized in this study

The weight loss is increased following the immersion time increased. This means that the corrosion rate is increased following the service life of the steel framing. However, the corrosion rate of the galvanized steel is decreased following the immersion time in the solution due to the dramatic patina that formed on the surface of the galvanized steel, but it might undergo corrosion throughout their service life. Therefore, it is significant to determine the durability of the steel framing during their service life to ensure they are still sufficient to provide services. The trendline of the 0.5 Mol NaCl in this study remain unclear with lower R^2 value and further justification is needed, as shown in Figure 8.

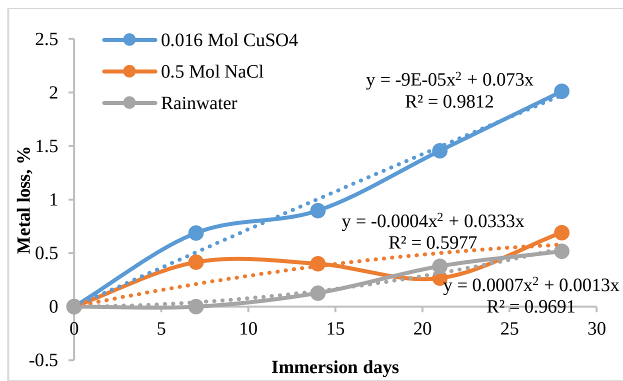


Figure 8 Metal loss prediction for galvanized cold-formed steel in 0.016 Mol $CuSO_4$, 0.5 Mol NaCl and rainwater

Durability of Corroded Cold-Formed Steel in Sulphate Condition

Seawater contains the abundant ions which is the sulphate. This salt content is indicated by salinity in seawater. Therefore, it is significant to study the corrosion rate of the present of sulphate in the seawater to ensure the durability of the steel framing structure. It is defined by the amount of salt in grams (g) that can dissolve in one kilogram (kg) of seawater. The sulphate can dissolve approximately 2.68 g/kg of seawater which mean that it approximately 0.016 moles of concentration in the seawater. Therefore, in the study, Copper Sulphate is utilized for my corrosion test to represent the Sulphate in the seawater and 0.016 Mol of concentration is set as a lowest concentration of $CuSO_4$ immersion test in this study.

Figure 8 shows the weight losses per m^2 of the galvanized steel specimens against the immersion time in the 0.016 Mol concentration of $CuSO_4$ solution. It can be shows that the weight losses are increased while the immersion time increased. It means that the corrosion rate is increased following by their service time. Hence, it is important to study their durability throughout their service life to avoid failure of the structure occurred. Eq. 2 can be obtained from the graph and used to predict the metal loss.

$$\text{Metal loss in } \% = -0.00009 \times exposure\ time + 0.073 \times exposure\ time \qquad \text{(Eq.2)}$$

Strength Prediction with Weight Loss

Strength reduction due to corrosion is assessed in automobile industry and also been conducted when applying as a construction material. As in previous research [22], the weight loss was 36.46% and the ultimate stress ratio was 0.679 for normal strength steel after 192 hours of corrosion exposure for 20% NaCl of 1200 mL pure water. Although the weight loss was high in previous study, however, due to impermeable layer of metal oxide of initial stage corrosion, it is suspected that the corrosion rate will remain constant after oxide is formed on the steel surface.

4.0 CONCLUSION

The benefits of light steel framing in dry construction have been discovered earlier, however, its durability towards corrosive environments yet to be studied. In this investigation, metal loss of cold-formed steel with galvanised and ungalvanised specimens were measured after immersion test in chloride and sulphate solutions in a week interval time frame until reaching a month. Several conclusions can be drawn from this study.

i. The corrosion rates of the steel coupons were decreased following by the immersion period and the concentration of the NaCl and $CuSO_4$ solutions increased.

ii. The oxidation rate was greater when the concentration is higher and reduced following the immersion time.

iii. The corrosion rate of the galvanized steel in rainwater is lower than the specimens in NaCl and $CuSO_4$ solutions.

iv. The galvanized steel has extremely lower corrosion rate compared to the un-galvanized steel. The zinc coating has provided excellent corrosion resistance.

v. Metal loss can be used to predict the durability of light steel framing with the new proposed empirical equation.

Acknowledgement

This work was supported by the Ministry of Higher Education under Fundamental Research Grant Scheme (FRGS/1/2020/TK0/UTM/01/7), Universiti Teknologi Malaysia (UTM-FR 21H68) and Curtin University Malaysia.

References

[1] L. Yeong-Huei, T. Cher-Siang, L. Yee-Ling, A.M. Muhd Zaimi, 2013 Dry Wall Construction in Light Steel Framing, in: M. Soutsos, C. Goodier, T. Le Trung, T. Nguyen Van (Eds.), Sustain. Built Environ. 461–466. Now Futur., Construction Publishing House, Hanoi, Vietnam

[2] R.M. Lawson, P. Grubb, J. Prewer, P.J. Trebilcock, 1999. Modular Construction using Light Steel Framing: An Architect 's Guide, Steel Construction Institute. SCI Publication P272, The Steel Construction Institute.https://www.steelconstruction.info/images/f/fd/SCI_P272.pdf

[3] R.M. Lawson, S.O. Popo-Ola, A.G. Way, T. Heatley, R. Pedreschi, 2010. Durability of light steel framing in residential applications, Proceedings of the Institution of Civil Engineers. Construction Materials. 163(2):109-121. https://doi.org/10.1680/coma.2010.163.2.109.

[4] Y.H. Lee, Y.L. Lee, C.S. Tan, 2012. Experimental investigation on cold-formed steel beams under pure bending, Jurnal. Teknologi. (Sciences Engineering). 58(1):13-20 https://doi.org/10.11113/jt.v58.1257.

[5] Y.H. Lee, C.S. Tan, S. Mohammad, 2017 In-plane sway behaviour of slender cold-formed steel bolted frames, Thin-Walled Structures. 114:11-21. https://doi.org/10.1016/j.tws.2017.01.024.

[6] C.S. Tan, Y.H. Lee, Y.L. Lee, S. Mohammad, A. Sulaiman, M. Md Tahir, P.N. Shek, 2013. Numerical simulation of cold-formed steel top-seat flange cleat connection, Jurnal Teknologi (Sciences Engineering). 61(3):63-71. https://doi.org/10.11113/jt.v61.1769.

[7] Y.H. Lee, C.S. Tan, S. Mohammad, J.B.P. Lim, R. Johnston, 2015. Numerical study of joint behaviour for top-seat flange cleat connection in cold-formed steel structures. Sci. Iran. 22(4):1554-1566

[8] J.M.R.S. Appuhamy, M. Ohga, T. Kaita, R. Dissanayake, 2011. Reduction of Ultimate Strength due to Corrosion-A Finite Element Computational Method, *International Journal of Engineering* 5(2):194-207

[9] A. Britner, C. Dieu, R. Podleschny. 2021. Corrosion protection for cold-formed structural steel elements. *Steel Construction,* 14(4):250-257 https://doi.org/10.1002/stco.202100002

[10] S. Xu, Z. Zhang, R. Li, H. Wang. 2019. Effect of cleaned corrosion surface topography on mechanical properties of cold-formed thin-walled steel. *Construction and Building Materials*, 222:1-14. https://doi.org/10.1016/j.conbuildmat.2019.06.130

[11] B. Nie, S. Xu, Z. Zhang, R. Gu. Experimental investigation on corroded cold-formed steel beam-columns under compression and major axis bending. *Journal of Constructional Steel Research*, 169:106026. https://doi.org/10.1016/j.jcsr.2020.106026

[12] M. Xia, S. Xu, Y. Wang, H. Li, B. Zhao. 2022 Experimental study on bearing capacity of corroded Q345 H-shaped steel column under axial compression load. *Journal of Building Engineering*, 52: 104354. https://doi.org/10.1016/j.jobe.2022.104354

[13] S.A. Park, J.G. Kim, Y.S. He, K.S. Shin, J.B. Yoon, Comparative study on the corrosion behavior of the cold rolled and hot rolled low-alloy steels containing copper and antimony in flue gas desulfurization environment, T*he Physics of Metals and Metallography* 115:1285-1294 (2014). https://doi.org/10.1134/S0031918X14130201

[14] N.D. Nam, M.J. Kim, Y.W. Jang, J.G. Kim, Effect of tin on the corrosion behavior of low-alloy steel in an acid chloride solution, *Corrosion Science*. 52(1):14-20 (2010). https://doi.org/10.1016/j.corsci.2009.08.036

[15] M. Moniruzzaman, M.M.A. Bepari, M.M. Haque, S.A. Limon, 2014 Corrosion of Galvanized Steel and Copper in Aqueous Environments, *Journal of Mechanical Engineering.* 43(2):63-67. https://doi.org/10.3329/jme.v43i2.17828

[16] A.G. Association, 2010. Performance of Hot-Dip Galvanized Steel Products in the atmosphere, soil, water, concrete and more, North Am.

[17] K. Zhang, R. Song, Y. Gao, 2019 Corrosion behavior of hot-dip galvanized advanced high strength steel sheet in a simulated marine

atmospheric environment, *International Journal of Electrochemical Science* 14:1488-1499 https://doi.org/10.20964/2019.02.13

[18] T. Ahn, H. Jung, X. He, O. Pensado, 2008. Understanding long-term corrosion of Alloy 22 container in the potential Yucca Mountain repository for high-level nuclear waste disposal, *Journal of Nuclear Materials* 379(1-3):33-41 https://doi.org/10.1016/j.jnucmat.2008.06.031

[19] T. Hirato, 2013 Thermodynamics of Aqueous Phases, in: Treatise Process Metall., Process Fundamentals, 1: 641-652, Elsevier. https://doi.org/10.1016/B978-0-08-096986-2.00036-9

[20] M.Z. Omar, M. Rindam, 2011 The impact of acid rain on historical buildings in Kuala Lumpur, Malaysia, *Design Principles & Practices*. 5(6):175-191. https://doi.org/10.18848/1833-1874/cgp/v05i06/38233

[21] M. Merajul Haque, S.A. Limon, M. Moniruzzaman, M. Mohar Ali Bepari, 2014 Corrosion comparison of galvanized steel and aluminum in aqueous environments, *International Journal of Automotive and Mechanical Engineering* 9:1758-1767. https://doi.org/10.15282/ijame.9.2013.24.0146

[22] R.A. Rahbar, S.A.H. Zakeri, 2011. Mechanical properties and corrosion resistance of normal strength and high strength steels in chloride solution, *Journal of Naval Architecture and Marine Engineering*. 7(2): 94-100. https://doi.org/10.3329/jname.v7i2.5309