SINERGI Vol. 27, No. 2, June 2023: 153-162
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2023.2.002

Effect of one-year corrosion on steel bridge materials in the maintenance stage with the Charpy impact test method

Fauzri Fahimuddin[1*], Mudiono Kasmuri[1], Rikki Sofyan[1], Syarif Junaidi[2], Latha MS[3]
[1]Department of Civil Engineering, Politeknik Negeri Jakarta, Indonesia
[2]Department of Mechanical and Nuclear Engineering, College of Engineering, University of Sharjah, Uni Arab Emirates
[3]Department of Civil Engineering, Sri Venkateshwara College of Engineering, India

Abstract
Corrosion of steel bridges is a major problem because it has the potential to reduce the performance of the structure over its lifetime. One factor that should not be reduced is fracture toughness, so this should be a very important concern in the maintenance program. Existing guidelines do not specify when corrosion conditions are hazardous and when corrosion conditions are not hazardous to structural performance. This study aims to explain how long corrosion does not cause danger, and when corrosion becomes dangerous. The Charpy Impact Test was used in this study to examine the effect of corrosion with a corrosion duration of weekly up to one year on fracture toughness. The series of tests in this research program used SM-490-type specimens which are steel plates commonly used for bridge structures. Specimens with variations in corrosion duration which were the result of immersion in sulfuric acid solution to simulate corrosion growth were then subjected to crack toughness testing. The toughness of each specimen was tested with a corrosion period starting from 1 week and so on up to 1 year to determine the level of fracture toughness. The results obtained from all tests showed that there was no decrease in the toughness of the corroded specimens for up to 1 year. The data presented in this study is very helpful for the designers and maintainers to plan corrosion treatment programs with clearer and more accurate considerations in assessing the structural integrity of steel bridges affected by corrosion.

Keywords:
Bridge Fracture;
Bridge Maintenance;
Bridge Toughness;
Corrosion Period;
SM 490;
Steel Corrosion;

Article History:
Received: December 23, 2022
Revised: January 20, 2023
Accepted: January 27, 2023
Published: June 2, 2023

Corresponding Author:
Fauzri Fahimuddin
Civil Engineering Department, Politeknik Negeri Jakarta, Indonesia
Email:
fauzri.fahimuddin@sipil.pnj.ac.id

INTRODUCTION

The existence of corrosion on steel as in bridge construction is very dangerous because it has the potential to cause construction to collapse before the design life. Therefore, this is a serious hazard that must be a concern in the process of designing and maintaining a construction using steel material.

The occurrence of corrosion is an influence of the natural environment which in fact cannot be easily avoided, especially in tropical areas which are highly susceptible to corrosion. The hazards that arise can be caused by several possibilities that can reduce construction performance during the service life of the construction. This study focuses on the effect of corrosion on the possibility of decreasing fracture toughness associated with the duration of corrosion.

Wang et al. [1] have carried out experimental tests on the characteristics of naturally corroded steel strips on bridge girders. The girder has been in use for 128 years, which is a very long time exposed in nature, both day and night. Based on the results obtained from the experimental analysis, one of the conclusions they found was a decrease in fracture toughness due to corrosion.

Zhang et al. [2] said that degradation of fracture toughness occurs in structures made of steel which then experience corrosion. They have even investigated that the presence of corrosion can accelerate crack propagation. The fracture toughness of corroded steel decreases with increasing corrosion severity [3].

Ermakova et al. [4] in their study also paid attention to the behavior that appears concerning toughness, especially the degree of sensitivity shown with the fracture toughness properties that occur in corrosive environments. They also concluded that in the study there had been a decrease in the yield stress due to corrosives.

Wang et al. [5] analyzed the causes and mechanisms that affect the fracture toughness of a welded joint in steel due to the presence of corrosion. The result obtained is the formation of hydrogen cracks due to H2S corrosion causing a decrease in fracture toughness.

Guo et al. in their publication [6], said that corrosion events in the field are very scary and very dangerous to the performance of steel bridge structures, so it is very urgent to determine how to program corrosion cleaning during the period of use and the maintenance period of the steel bridge to be free from this dangerous threat.

In the construction of new bridges as well as the regeneration of several old bridges, there needs to be an effort to reduce the uncomfortable and unsafe impacts caused by environmental influences such as corrosion [7, 8, 9].

Various maintenance efforts have been made by the community and agencies with guidelines to achieve what is required to meet the health and safety standards of steel bridge construction affected by corrosion, such as cleaning to prevent corrosion, such as painting before corrosion, and important maintenance, for instance replacing girders. as stated by Han, et al. [10]. This is very closely related to inspection and maintenance, especially in steel bridge construction because the construction is openly exposed in an environment that is not protected from rain and heat. Inspection and maintenance of steel bridges must be carried out to avoid a decrease in the performance of steel bridges during service or use, therefore those who carry out inspections and maintenance need to know when, how long, and what kind of corrosion conditions start to reduce the performance of steel bridges.

Existing inspection and maintenance guidelines do not explain when it is dangerous and when conditions are not classified as dangerous in detail on steel bridges that experience corrosion, considering the impact of corrosion on performance degradation or the mechanical properties of the material [11][12]. If corrosion is already in a dangerous state, maintenance alone is no longer sufficient and repair measures must be taken [13].

Repair activities should be avoided because they will disrupt the service of the steel bridge and require high costs. This research is intended to meet these demands, so that it can be used as a guideline and to keep steel bridges always in prime condition and very feasible for operation by knowing how long the corrosion conditions occur in prime condition and not endangering the safety and comfort of bridge users [14].

Steel corrosion has been extensively studied. After all, it is a serious problem for the performance of structures, especially steel bridges, because it can result in a reduction in cross-section and a decrease in the mechanical properties of the material, such as a decrease in ductility, including a decrease in ultimate strength, and a decrease in yield strength [15][16]. Other studies conducted on steel for pipelines and bridges also concluded the same thing. These studies concluded that corrosion could reduce the service life of steel pipelines and steel bridges and make them susceptible to failure [17, 18, 19, 20].

In various cases that occur in steel construction, it simultaneously experiences stress due to loading and is also under corrosive conditions [21]. Therefore, it becomes very important to consider and measure the corrosion behavior and its impact on steel, including its fracture toughness. This is because every construction that experiences corrosion will also experience stress simultaneously, this condition is closely related to efforts to optimize the process of maintaining, repairing, and rehabilitating steel bridges during the design life of the bridge. The stress acting on the structure causes a decrease in the corrosion resistance of the steel [22, 23, 24, 25, 26].

The corrosion process of steel materials has also been studied extensively, in detail, [27, 28, 29], which shows that the formation of a passive oxide film that occurs both before as well as during corrosion gives rise to a protective layer against corrosion on steel. From the results of a study, it was also stated that the stress applied damaged the passive oxide film which resulted in increased dissolution growth that occurred on the outer layer of steel [29]. It was also found that the stress that occurs also causes deformation on the outside of the steel plate, which results in an increase in energy that occurs on the outside of the steel which results in easy corrosion and covering the outer area of the plate [25][26].

The combination of stress and corrosion can also result in a decrease in the mechanical properties of steel [27][29]. On the one hand, as previously mentioned, Stress is the main cause of the occurrence of passive oxygen film rupture and at the same time is the beginning of microplastic deformation in the microstructure of the material, starting from the grain boundaries. These things are closely related and even directly cause the initiation and can also be continued with the propagation of stress corrosion cracking [26]. On the other hand, the occurrence of the phenomenon of hydrogen embrittlement results in a more serious condition if, at the same time, the steel is also under stress [27][28]. This is because stress causes more cracks and cavities in the steel which favor diffusion and housing of hydrogen atoms [30].

In most real cases, steel is subjected to elastic stress ranging from 70% to 80% of its yield strength under service loads used in bridge design standards [31], and knowledge of the effect of elastic stress on corrosion is still a topic of research concern. Researchers showed that elastic stress is associated with an increase in surface energy, which then can also lead to an increase in the growth of corrosion in the steel material. However, other researchers found that operating elastic stress did not affect corrosion growth in steel. To examine the different views from each other, studies are still being carried out on this topic, for example by conducting comprehensive studies and tests to learn more about the effect of elastic stress on corrosion growth which is still a concern today.

In addition, these researchers have shown that steel materials subjected to overstress are hazardous to corrosion cracking due to these stresses, and thus to hydrogen embrittlement [27, 32, 33]. In addition, the combined effects of corrosion and stress on mechanical properties have been studied especially for pipe steel, high tensile stress, and corrosion-resistant steels [34, 35, 36] as well as by other researchers [37, 38, 39]. From the literature, it can be assumed that a greater number of hydrogen atoms can enter the steel when the steel is under stress, and at the same time undergo a process of corrosion. Although it is realized that corrosion is a problem, however, steel materials have been widely used, including for bridge construction [40].

Many studies on the corrosion of steel have been carried out with their respective characteristics, including research on the effect of the surface area ratio of steel to aluminum on the corrosion rate [41][42]. This study looks at the aspect between surface area and corrosion rate, where with an increase in the surface area ratio an increase in the corrosion rate occurs.

This research has carried out a comprehensive experimental program to achieve the goal of investigating what happens to non-corrosive and corrosive steel materials by conducting tests to measure the degradation of mechanical properties under a corrosive environment that increases the concentration of hydrogen which results in the corrosion of steel materials.

After going through several stages of corrosion time according to the plan on the test object, then each of these stages is also followed by an investigation of the impact on the possibility of decreasing the mechanical properties of the material, such as its toughness by carrying out an impact test. This is following the purpose of this study to explain how long corrosion does not cause danger, and when corrosion becomes dangerous.

METHODS

The type of steel used in this study is a type that is commonly used and widely applied in steel bridge construction. The simulation of the corrosion process was carried out by immersing the steel specimens in an acid solution. Loss of mass and mechanical properties of the specimens after each stage of immersion were measured.

The research has been carried out in several stages. In the early stages, a literature study was carried out including consultations and discussions with industry parties such as the PT BUKAKA team. Then preparations were made with the internal research team. Furthermore, several main stages have been carried out in this study, as explained below.

Preparation of the test object

The specimens used in this study were made of steel and specially selected from the SM-490 type. This is done because this type of steel material is a steel plate that is commonly used and widely applied to bridge construction and other steel construction everywhere.

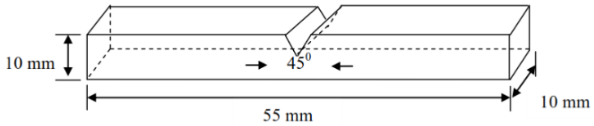

Figure 1. Charpy-impact-test object [43] ASTM E 23-18, 2018

The dimensions and shapes as well as the provisions used on all test objects are made according to international standards, in this study ASTM E23-18 was used, 2018 [43] as shown in Figure 1.

This study conducted tests on the specimens in the laboratory using the Charpy Impact Test Machine.

Making Impact Test Objects

In the process of making this impact test object, steel material with grade JIS G3106 SM-490 is used which is very much and is commonly used in bridge construction both in Indonesia and in other countries. The standard size of each test object is adjusted to ASTM E23-18 [43]. The process of making the test object itself was carried out at the Mechanical Engineering Laboratory of the Jakarta State Polytechnic using a 3-axis CNC, MORI SEIKI MV-45/40, made in Japan. Test objects that have been made according to standards are shown in Figure 2.

Figure 2. Test the object before it is corroded

The process of corroding the test object.

After making the test object, then the corrosion process is carried out using a mixture of distilled water mixed with Sulfuric Acid (H_2SO_4) ASTM G31-21. 2021 [44]. The corrosion process using Sulfuric Acid (H_2SO_4) for research has been widely used and is still frequently used today which aims to determine the rate of corrosion reactions in steel [45, 46, 47, 48, 49]. When the mixture of distilled water and H_2SO_4 is ready, the specimen is dipped into the mixture for a day. After a day of immersing the test object using a mixture of solutions with a percentage of H_2SO_4 content of 30%, 40%, and 50%, then removed from the mixed solution and placed in a room that has a room temperature of approximately 25^0 C so that the oxidation process occurs, and the test object corrodes [44]. The duration of corrosion on the specimen for the impact test in this study was carried out in five variations, namely 1 week, 2 weeks, 3 weeks, 4 weeks, and 52 weeks or one year. The implementation of immersing the test object in a mixed solution with a predetermined percentage of H_2SO_4 is shown in Figure 3, and the test object that has been corroded is shown in Figure 4. The H_2SO_4 used in this study is a product from the manufacturer Chepy Elkimy Chemindo, and the H_2SO_4 content is 98%.

Figure 3. Immersion of Test Objects

Figure 4. Test object after being corroded

Testing

This research was conducted in the Center of Excellence for Infrastructure Technology Laboratory - Jakarta State Polytechnic or PUTI - PNJ. The tool used is the Charpy Impact Test MTS-E22 Pendulum Impact Test System for Metals, Standard GB/T 229-2007 which has a maximum impact energy of 450J, made in the United States.

Impact testing for all corroded and non-corroding specimens was carried out. The first test was carried out on non-corroding specimens. Then, after all the non-corroding specimens have been tested for impact, the test is continued with the specimens which have corroded because of the immersion process in the H_2SO_4 mixed liquid according to the length of time specified for each group of test objects.

RESULTS AND DISCUSSION

The following are the results of the impact tests that have been carried out for both corroded and non-corroded specimens. Detailed test results are presented in graphical form, and summary test results for specimens without corrosion and specimens with corrosion are presented in tabulation form.

Specimens that were not corroded or in this study called 0-week corrosion were directly tested for impact. The test results are shown in Figure 5. The data obtained show that the resulting impact energy has a close tendency between one test object and another, which is around 200 Joules.

The test specimens are corroded simultaneously, then tested according to plan, namely for corrosion times of 1-week, 2-week, 3-week, 4-week, and 52-week or one year.

Following the test schedule, the specimens that have been corroded during the first 1-week are immediately impact tested. The test results are shown in Figure 6.

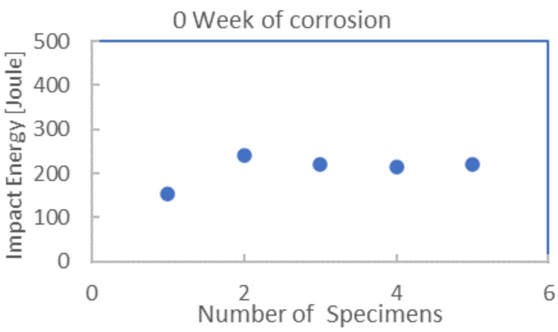

Figure 5. Impact test results with 0-week corrosion

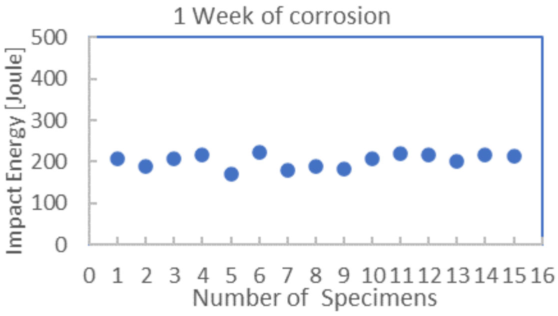

Figure 6. Impact test results with 1-week corrosion

The data obtained show that the resulting impact energy has a close tendency between one test object and another, which is around 200 Joules. This tendency is the same as that obtained from the specimen without corroding.

Subsequent tests were carried out on specimens that had been corroded for 2 weeks. The test results obtained are shown in Figure 7 below. The data obtained from all these test objects show results with impact energies that also have a close tendency between one test object and another, which is still around 200 Joules. This tendency is the same as the results obtained from testing the specimens without corroding.

Subsequent tests were carried out with specimens that had been corroded for 3-weeks. This test also shows the same test results with the tendency of the results obtained from the test object without corroding, as shown in Figure 8. The data obtained from this test object shows results with close impact energy between the test objects, which is still around 200 Joules.

The test was continued with the corroded specimen for 4-weeks. Like the previous tests, at this stage, it also showed the same test results with the tendency of the results obtained from testing the test object without corroding, as shown in Figure 9.

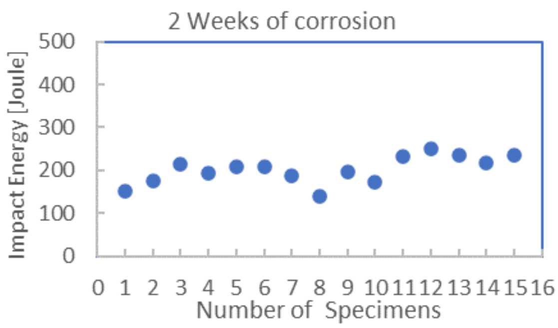

Figure 7. Impact test results with 2-week corrosion

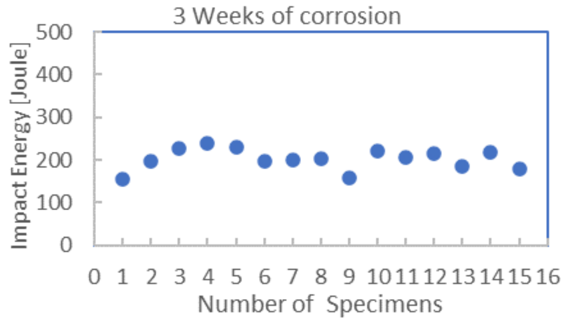

Figure 8. Impact test results with 3 weeks of corrosion

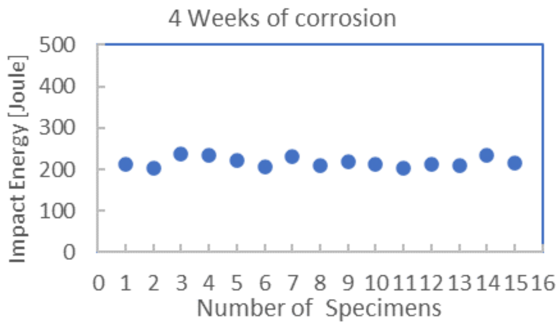

Figure 9. Impact test results with 4-week corrosion

The data obtained from this test object showed results with a close impact energy between one test object and another, which is still around 200 Joules.

Subsequent tests were carried out on specimens that had been prepared for a 52-week or one-year corrosion period. The results obtained were still the same as previous tests, namely testing of specimens without corrosion and specimens with corrosion at 1-week, 2-week, 3-week, and 4-week respectively. At this stage, it also shows the same test results, as shown in Figure 10. The data obtained from this test object also still shows results with a close impact energy between one test object and another, which is still around 200 Joules.

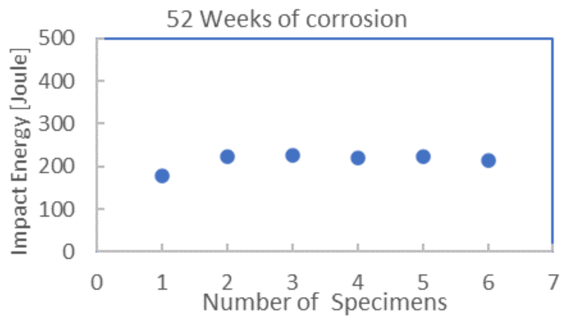

Figure 10. Impact test results with 52-week corrosion

To show the results of the fracture toughness test of the specimens without corrosion or 0-week corrosion compared to all the specimens that were corroded, the following is presented the results of the test without corrosion and the average value presented by each group of corroded specimens as shown in Table 1.

An overview of the fracture toughness from the test results, which is presented the average results confirmed by each group of test objects with a duration of corrosion with conditions between 0-week to 52 weeks shown in Figure 11.

Statistical analysis was used to compare the performance shown by the test results for each specimen condition with corrosion durations of 0 weeks, 1 week, 2 weeks, 3 weeks, 4 weeks, and 52 weeks, respectively. From the plot data shown above, the results of the T-test were obtained with a standard deviation of 6.825697 and skewness of 0.393543.

In Figure 11 it is seen that the impact of the duration of corrosion starts from the specimens with 0-week corrosion or rusting conditions to the specimens with 52-week corrosion conditions showing the same results. The test results obtained are absorbed energy or impact energy of around 200 Joules, which is a condition where there has been no change indicating a decrease in the fracture toughness of the steel material.

The actual corrosion rate is the speed of propagation or the speed of material degradation over time.

Table 1. Test Results of Non-Corroded and Average Values of Corroded Specimens

No	Non-Corroded (Joule)	Corroded (Joule)
1	153	210
2	241	203
3	221	201
4	215	202
5	220	217
6	-	214

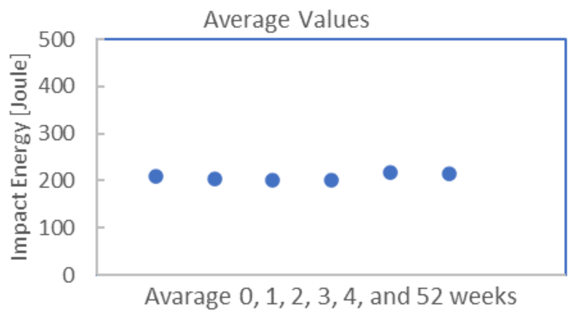

Figure 11. Average impact test results with 0-week to 52-week corrosion duration

In this study to show the trend of corrosion rate is calculated using the Loss of Weight Method. The weight loss method uses the weight loss due to corrosion to determine the corrosion rate with the formula:

$$W = W_2 - W_1 \quad (1)$$

where:
W = weight reduction (mg)
W_2 = final weight
W_1 = initial weight

Specimen weighing was carried out before and after corrosion to determine the development of corrosion on the surface of the test object. The first weighing is carried out for specimens without corrosion which is called 0-week corrosion. Then proceed with specimens that have been corroded for 1 week, 2 weeks, 3 weeks, 4 weeks, and specimens with 52 weeks corrosion. The weighing results that describe the corrosion rate are shown in Figure 12.

The test specimens as described above show that the selected corrosion time is up to 1 year and the fracture toughness that occurs has not shown a decrease in material performance. On the other hand, it is generally known and has long been common knowledge of engineers that corrosion is very dangerous and can lead to the collapse of a structure.

The results of several studies indicate that the hazard that arises can be caused by a decrease in the volume of the steel plate, a decrease in the yield stress capability, and other mechanical properties including fracture toughness. This study focuses on the effect of corrosion on fracture toughness concerning the duration of corrosion.

The mechanical properties and other properties of corroded steel material also affect the stress and conversely the stress that occurs also affects the rate of corrosion.

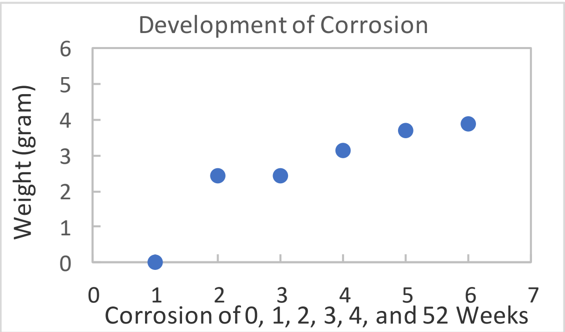

Figure 12. Development of corrosion from 0-week to 52 weeks

In fact, what is happening in the field, is the bridge steel material does not only experience corrosion as a single cause. Stress and other environmental conditions also greatly affect the performance of steel materials. Research related to this matter should be of concern to researchers and bridge managers, especially for steel bridges. Aspects related to the decrease in the performance of bridge steel materials will be carried out in further research activities and will become part of this research roadmap.

Previous research [1] conducted experimental tests on the characteristics of steel pieces that had undergone natural corrosion on bridge girders that had been used for a very long time of 128 years, proving that there had been a decrease in fracture resistance due to corrosion. Accordingly, [2] found that degradation of fracture toughness also occurred in structures made of steel and corroded. The fracture toughness of corroded steel decreases with increasing corrosion severity. Other researchers [3][4] in their research demonstrated the level of sensitivity related to the fracture toughness properties that appear in a corrosive environment, such as the decrease in yield stress due to corrosive effects. However, those studies do not specifically examine the impact of the length of time of corrosion that needs to be considered and carried out in a process of maintaining or inspecting steel bridges. Generally, only describes the process carried out between 6 months to 1 year.

The existing guidelines [11][12] require an inspection to be carried out once a year, but it is not clear what the consequences of corrosion occurring during the year on the mechanical properties of the steel material are not explained. This study explains that corrosion within a year still provides excellent performance because during such a period there has been no reduction or decrease in the performance of steel materials due to corrosion. Thus, inspection and maintenance if carried out no later than once a year will maintain conditions that can maintain the performance of the bridge steel material as it was in its initial state [50].

This research continues to carry out the corrosion process on many test objects over a longer period with variations to help designers and managers of steel bridges make inspection and maintenance plans more accurately in assessing the integrity and performance of steel bridge structures subject to corrosion.

Further research will also continue to be carried out to analyze the rate of corrosion development, examine the effect of reducing the volume of steel on the existing stress capabilities, and test fatigue performance after experiencing corrosion, including changes in the material's microstructure.

CONCLUSION

Test results from corroded specimens for one week to one year did not show any decrease in fracture toughness compared to non-corrosive specimens. Specimens that have been corroded for one year still have the same fracture toughness as specimens without corrosion. This shows that steel that is corroded with a corrosion time of up to one year still shows very good performance or is not yet dangerous for hydrogen embrittlement during the corrosion process. The strategy of routine inspection once a year can be carried out if it is accompanied by cleaning in perfect corrosion treatment, by maintaining the condition of the steel as if it is not corroded.

ACKNOWLEDGMENT

We are very grateful for the financial support from the Ministry of Education, Culture, Research, and Technology, Republic of Indonesia through the Research and Community Service Unit, Jakarta State Polytechnic in supporting the implementation of this research and publication with our deepest gratitude. We also convey high appreciation to PT. BUKAKA for supporting the provision of materials for testing as well as for valuable input in supporting this research. We hope that what we have done and are currently doing in terms of research can provide contributions and benefits to society, government, science, and technology.

REFERENCES

[1] Y. Wang, W. Wang, B. Zhang, Y. Zhao, C-Q. Li, “Fracture resistance of naturally corroded steel after service for 128 years,” *Engineering Fracture Mechanics*, vol. 265, ID: 108367, April 2022. doi: 10.1016/j.engfracmech.2022.108367.

[2] H. Zhang, S. Xu, B. Nie, Y. Wen, “Effect of corrosion on the fracture properties of steel plates,” *Construction and Building Materials*, vol. 225, pp. 1202-1213, 2019, doi: 10.1016/j.conbuildmat.2019.07.345.

[3] Y. Zhang, K. Zheng, J. Heng, J. Zhu, “Corrosion-Fatigue Evaluation of Uncoated Weathering Steel Bridges,” *Applied Sciences*, vol. 9, no. 17, 3461, 2019, doi: 10.3390/app9173461.

[4] A. Ermakova and A. Mehmanparast, “Corrosion Effects on Fracture Toughness Properties of Wire Arc Additively Manufactured Low Carbon Steel Specimens,” *Metals*, vol. 12, no. 2, pp. 238, 2022, doi: 10.3390/met12020238.

[5] X. Wang, D. Wang, C. Deng, C. Li, “Effect of H2S Corrosion on the Fracture Toughness of the X80 Pipeline Steel Welded Joint,” *Materials*, vol. 15, no. 13, pp. 4458, 2022, doi: 10.3390/ma15134458.

[6] S. Guo, R. Si, Q. Dai, Z. You, Y. Ma, J. Wang, “A critical review of corrosion development and rust removal techniques on the structural/environmental performance of corroded steel bridges,” *Journal of Cleaner Production*, vol. 233, pp. 126-146, 2019, doi: 10.1016/j.jclepro.2019.06.023.

[7] N. Ali, M. A. Fulazzaky, “The empirical prediction of weight change and corrosion rate of low-carbon steel,” *Heliyon*, vol. 6, no. 9, e05050, 2020 doi: 10.1016/j.heliyon. 2020.e05050.

[8] Y. X. Cai, Y. Z. Yu, and M. Xiaobing, “Atmospheric corrosion prediction: a review," Corrosion Reviews, vol. 38, no. 4, pp. 299-321, 2020, doi: 10.1515/corrrev-2019-0100.

[9] S. Habib, R. A. Shakoor, R. Kahraman, “A focused review on smart carriers tailored for corrosion protection: Developments, applications, and challenges,” *Progress in Organic Coatings*, vol. 154, 106218, 2021, doi: 10.1016/j.porgcoat.2021.106218.

[10] X. Han, D. Y. Yang, D. M. Frangopol, “Optimum maintenance of deteriorated steel bridges using corrosion resistant steel based on system reliability and life-cycle cost,” *Engineering Structures*, vol. 243, ID: 112633, 2021, doi: 10.1016/j.engstruct. 2021.112633.

[11] NN, Pemeriksaan Jembatan, Pedoman Bidang Jalan dan Jembatan, Direktorat jenderal Binamarga, *Kementerian Pekerjaan Umum dan Perumahan Rakyat*, No. 01/ P/ BM/ 2022, 2022.

[12] NN, Standar dan Tata Cara Perawatan Prasarana Perkeretaapian, *Peraturan Meneteri Perhubungan*, PM 32: 40-47, 2011.

[13] T. B. Balogun, et al., "Sustainability of bridge maintenance," *Proceedings of the Institution of Civil Engineers-Bridge Engineering*, 2019, vol. 172, doi: 10.1680/jbren.15.00027.

[14] J. Selejdak, M. Urbański, and M. Winiarski, “Assessment of a steel bridge corrosion degree,” *E3S Web of Conferences,* no. 49, 00098, 2018, doi: 10.1051/e3sconf/ 20184900098

[15] N. Gathimba, Y. Kitane, “Effect of surface roughness on tensile ductility of artificially corroded steel plates,” *Journal of Constructional Steel Research*, vol. 176, 106392, 2021, doi: 10.1016/j.jcsr.2020.106392.
[16] X. Sun, H. Kong, H. Wang, Z. Zhang, “Evaluation of corrosion characteristics and corrosion effects on the mechanical properties of reinforcing steel bars based on three-dimensional scanning,” *Corrosion Science*, vol. 42, pp. 284-294, 2018, doi: 10.1016/j.corsci.2018.07.030.
[17] A. H. Alamri, “Localized corrosion and mitigation approach of steel materials used in oil and gas pipelines – An overview,” *Engineering Failure Analysis*, vol. 116, 104735, 2020, doi: 10.1016/j.engfailanal.2020.104735.
[18] L. Li, M. Mahmoodian, and C. Q. Li “Structural assessment of an in-service steel viaduct using time-variant reliability analysis,” in *12th International Conference on Structural Safety and Reliability*, Technische Universität Wien, Vienna, Austria, 2017.
[19] M. Wasim, C.Q. Li, D. Robert, and M. Mahmoodian, “Fracture toughness degradation of cast iron due to corrosive mediums,” *International Journal of Pressure Vessels and Piping*, vol. 186, ID: 104151, 2020, doi: 10.1016/j.ijpvp.2020.104151.
[20] W. Wang, C.Q. Li, and W. Shi, “Degradation of mechanical property of corroded water pipes after long service,” *Urban Water Journal*, vol. 16, no. 7, pp. 494-504, 2019, doi: 10.1080/1573062X.2019.1687744.
[21] E. Ohaeri, U. Eduok, J. Szpunar,” Hydrogen related degradation in pipeline steel: A review,” International Journal of Hydrogen Energy, vol. 43, no. 31, pp. 14584-14617, 2018 doi: 10.1016/j.ijhydene.2018.06.064.
[22] G. A. Pouya, et al., ”A Review of Corrosion and Protection of Steel in Concrete,” *Arabian Journal for Science and Engineering*, vol. 43, pp. 5035–5055, 2018, doi: 10.1007/s13369-018-3303-2.
[23] A. H. Ettefagh, S. Guo, J. Raush, "Corrosion performance of additively manufactured stainless steel parts: A review," *Additive Manufacturing*, vol. 37, 101689, 2021, doi: 10.1016/j.addma.2020.101689.
[24] C. Liu, et al., “Recent Advances on the Corrosion Resistance of Low-Density Steel: A Review,” *Acta Metallurgica Sinica*, vol. 35, pp. 1055–1067, 2022, doi: 10.1007/s40195-021-01369-0.
[25] M. Rohmah, P. A. Paristiawan, T. B. Romijarso, Effect of forging load and heat treatment process on the corrosion behavior of A588-1%NI for weathering steel application in a marine environment,” *SINERGI,* vol. 26, no. 2, pp. 237-248, 2022, doi: 10.22441/sinergi.2022.2.013.
[26] L. Li, C.Q. Li, M. Mahmoodian, and W. Shi, “Corrosion induced degradation of fatigue strength of steel in service for 128 years,” *Structures*, vol. 23, pp. 415–424, 2020, doi: 10.1016/j.istruc.2019.11.013.
[27] V. Maurice, P. Marcus, “Current developments of nanoscale insight into corrosion protection by passive oxide films,” *Current Opinion in Solid State and Materials Science*, vol. 22, no. 4, pp. 156-167, 2018, doi: 10.1016/j.cossms.2018.05.004.
[28] A. Nautiyal, M. Qiao, J.E. Cook, X. Zhang, T. Huang, "High-performance polypyrrole coating for corrosion protection and biocidal applications,” *Applied Surface Science*, vol. 427, Part A, pp. 922-930, 2018, doi: 10.1016/j.apsusc.2017.08.093
[29] W. K. Green, "Steel reinforcement corrosion in concrete: An overview of some fundamentals," *Corrosion Engineering, Science and Technology,* vol. 55, no. 4, pp. 289-302, 2020, doi: 10.1080/1478422X.2020.1746039.
[30] Y. S. Kim, S. S. Kim, B. H. Choe, “The Role of Hydrogen in Hydrogen Embrittlement of Metals: The Case of Stainless Steel,” *Metals*, vol. 9, no. 4, 406. 2019, doi: 10.3390/met9040406.
[31] NN, *Design loads, Bridge design, Part 2*, Australia Standards AS 5100.2, 2017.
[32] O. S. I. Fayomi, et al., "A short view on the stress corrosion cracking and the prospect of eco-friendly inhibitors," *AIP Conference Proceedings*, vol. 2437, no. 1, 2022, doi: 10.1063/5.0092413.
[33] L. Le, M. Mahmoodian, C-Q. Li, D. Robert, “Effect of corrosion and hydrogen embrittlement on microstructure and mechanical properties of mild steel,” *Construction and Building Materials*, vol. 170, pp 78-90, 2018, doi: 10.1016/j.conbuildmat, 2018.03.023.
[34] K. P. Abhijith, and M. D. Bindu, “A Review on Microstructure Development and Mechanical Properties of Fusion Welded Duplex Stainless Steels,” *SSRN*, August 6, 2022, doi: 10.2139/ssrn.4294775.
[35] U. Kivisäkk, "Duplex Stainless Steels in Sea Water—Instructions for Good Practice and Results from Exposure of Butt-Welded

Tubes," *Marine corrosion of stainless steels*, CRC Press, 2021, pp. 130-144.
[36] W. Wu, Q. Wang, L. Yang, Z. Liu, X. Li, Y. Li," Corrosion and SCC initiation behavior of low-alloy high-strength steels micro-alloyed with Nb and Sb in a simulated polluted marine atmosphere," *Journal of Materials Research and Technology*, vol. 9, no. 6, pp. 12976-12995, 2020 doi: 10.1016/j.jmrt.2020.09.033.
[37] G. Ghosh, P. Rostron, R. Garg, and A. Panday, "Hydrogen induced cracking of pipeline and pressure vessel steels: A review," *Engineering Fracture Mechanics*, vol. 199, , pp. 609-618, 2018, doi: 10.1016/j.engfracmech.2018.06.018.
[38] E. Ohaeri, U. Eduok, J. Szpunar, "Hydrogen related degradation in pipeline steel: A review," *International Journal of Hydrogen Energy*, vol. 43, no. 31, pp. 14584-14617, 2018, doi: 10.1016/j.ijhydene.2018.06.064.
[39] H. Tian, M. Chen, F. Ge, K. Song, X. Wang, Z. Cui, "Hydrogen permeation and stress corrosion cracking of heat-affected zone of E690 steel under the combined effect of sulfur species and cathodic protection in artificial seawater," *Construction and Building Materials*, vol. 296, 123721, 2021, doi: 10.1016/j.conbuildmat.2021.123721.
[40] W. Li, R. Cao, L. Xu, L. Qiao," The role of hydrogen in the corrosion and cracking of steels: A review," *Corrosion Communications*, vol., pp. 23-32, 2021, doi: 10.1016/j.corcom.2021.10.005.
[41] I. Nakatsugawa and Y. Chino," Effect of Area Ratio on the Galvanic Corrosion of AZX611 Magnesium Alloy/A6N01 Aluminum Alloy Joint," *Materials Transactions*, vol. 62, no. 12, pp. 1764-1770, 2021, doi: 10.2320/matertrans.MT-L2021011.
[42] D. Prayitno, and M. Irsyad, "Effect of Ratio of Surface Area on The Corrosion Rate," *SINERGI,* vol. 22, no.1, pp. 7-12 2018, doi: 10.22441/sinergi.2018.1.002.
[43] NN, Standard Test, Methods for Notched Bar Impact Testing of Metallic Materials, ASTM E 23-18, *ASTM*, 2018.
[44] NN, Standard Guide for Laboratory Immersion Corrosion Testing of Metals, ASTM G31-21, ASTM, 2021.
[45] O. Sanni, A.P.I. Popoola, O.S.I Fayomi, "Enhanced corrosion resistance of stainless steel type 316 in sulphuric acid solution using an eco-friendly waste product," *Results in Physics*, vol. 9, pp. 225-230, 2018, doi: 10.1016/j.rinp.2018.02.001.
[46] A. Abdelfatah, A. M. Raslan, "Lamiaa Z. Mohamed, "Corrosion Characteristics of 304 Stainless Steel in Sodium Chloride and Sulfuric Acid Solutions," *International Journal of Electrochemical Science*, vol. 17, 220417, 2022, doi: 10.20964/2022.04.29.
[47] M. H. Sliem et al., "Corrosion inhibition of mild steel in sulfuric acid by a newly synthesized Schiff base: an electrochemical, DFT, and Monte Carlo simulation study," *Electroanalysis,* 32, pp. 3145-3158, 2020, doi: 10.1002/elan.202060461.
[48] M. Ouakki et al., "Quantum chemical and experimental evaluation of the inhibitory action of two imidazole derivatives on mild steel corrosion in sulphuric acid medium," *Heliyon*, vol. 5, no. 11, e02759, 2019, doi: 10.1016/j.heliyon.2019.e02759.
[49] X. Xu et al., "Nitrogen-doped carbon quantum dots for effective corrosion inhibition of Q235 steel in concentrated sulphuric acid solution," *Materials Today Communications*, vol. 29, 2021, 102872, doi: 10.1016/j.mtcomm.2021.102872.
[50] Y. P. Asmara," Simulation of CO2 Corrosion of Carbon Steel in High Pressure and High Temperature Environment (HPHT)," *Journal of Integrated and Advanced Engineering (JIAE)*, vol. 2, no. 1, pp. 63-70, 2022, doi: 10.51662/jiae.v2i1.41