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# Study of the Uniform Corrosion Effects on Mechanical Properties of Tensile Plates by Experimental Tests and Scanning Electron Microscope (SEM)

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**Abstract:** The incidents due to the weakness of corroded steel members of structures, involves economic and human costs, to avoid the mentioned costs, an accurate estimation of the residual bearing capacity of corroded steel members is required. In this experimental study, uniform corrosion was applied on steel of types ST37, ST52 and Iracore with thicknesses of 4, 5, 6 and 8 mm by using salt spray machine. Two specimens from each thickness were tested by tensile test after times of 48, 96, 144 and 192 h and one specimen was also considered for corrosion penetration test. The reduction percentage of Ultimate Tensile Strength (UTS) obtained from force-displacement curve was compared to the expected reduction percentage of Ultimate Tensile Strength ($EUTS_c$). The results showed that in various specimens, the ultimate tensile strength obtained from exact measurement of the thickness of corroded steel plate could have a difference of 3-8% with the ultimate tensile strength obtained from the tensile test. Based on dimensional and weighted investigations and the Scanning Electron Microscopy (SEM) it was concluded that this difference is because of the creation of small-scale cavity corrosions despite applying uniform corrosion and also penetrating the corrosion in the depth of the plate. It seems that despite the direct relation that is considered between thickness parameter and tensile load in the calculations, applying a reduction factor for accurate estimation of the residual tensile strength capacity of corroded steel is required. It was shown that corrosion is not affected by the steel ductility and the speed of corrosion penetration in the Iracore specimens had a different process than the other specimens.

**Key words:** Steel plates, uniform corrosion, ultimate tensile strength, ductility, Scanning Electron Microscopy (SEM)

## INTRODUCTION

By definition, the corrosion phenomenon is a chemical or electrochemical reaction between material, usually a metal and its surrounding environment. One of the major causes of losses and damages on steel structures in the past decades is recognized to be the corrosion. The results of damage caused by corrosion may vary from the gradual degradation of structural components during a long time to its sudden collapse. Due to the different parameters influencing the corrosion penetration in steel structures, each type of steel shows a different behavior against corrosion. Due to the heavy damages been exerted, significant researches are done about corrosion, its early identification and its effects and will go on (Ebrahimkhanlou *et al*., 2015, 2016a, b). Steel corrosion imposes huge costs on governments, annually which a part of it spending on the maintenance of steel to prevent its progress and part of it is for inspection, repair and replacement of deteriorated members or the entire structure. This study has been done in the Products Laboratory of Mobarakeh Steel Company and the Center for Advanced Materials of Islamic Azad University of Najafabad in the period of February to September 2015. In this study, the tensile behavior against uniform load and the corrosion mechanism including the speed and intensity of the corrosion in steel with normal strength (ST37), steel with high strength (ST52) and Iracore steel are investigated. It was being questioned that the direct relation between the residual capacities of the tensile strength of corroded steel is only with the remained thickness of the plate after corrosion and the possibility of the impact of factors causing corrosion on its tensile behavior and ductility due to penetration or changing its nature is also studied.

**The empirical literature:** Cabezas and Celentano (2004) conducted their experimental and numerical studies on

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tensile steel plates. They have used SAE1045 steel in this research. The results showed that the steel had a better strength due to having more Manganese in it (Ranji and Zakeri, 2011). Paik *et al.* (2004) have done their studies about the ultimate shear strength of steel plate with pitting corrosion. Results showed that corrosion could lead to large reduction of the ultimate strength and the most reduction in strength occurs when the cavity diameters are small and their number is high (Appuhamy *et al.*, 2012). Nakai *et al.* (2004) have done their research on the influence of corrosion on the strength. They have resulted that the tensile strength of corroded member reduces gradually and the specimens elongation caused by corrosion strongly decreases with increase in cavity diameter.

In the worst case, the reduction of nominal tensile strength of specimens in cavity corrosion is 2.5 times the corrosion in uniform condition (Nakai *et al.*, 2006). Results of the work done by Nakai *et al.* (2006) showed that in the corroded plate with cavity, the ultimate supportable compressive load and bending moment is less than uniformly corroded plate with equal average loosed thickness, and in the prediction of ultimate strength, considering the average loosed thickness in the minimum cross section will be very conservative. Reduction in compressive load and bending moment is less than reduction in the tensile strength of with vacuolar corroded plate with equal thickness (Dolat Abadi, 2013). The results of the study by Mobesher and Sumi indicated that the material properties have no influence on the results. The way and the type of pitting corrosions have an obvious influence on the results and the triaxial strain factor of corrosion can be estimated by axial strain (Rabiul Islam Sumi, 2011). It was specified from the research by Ranji and Zakeri (2011) that the weight reduction caused by corrosion is similar for both sheets of steel until 144 h, thereafter the weight reduction of high strength material is more. It was also showed that manganese leads to reduce the speed of corrosion. The mechanical changes are similar in both steels and the ultimate strength is reduced which must be considered in the design of structures in the limit state design (also known as load and resistance factor design). The results from the study Appuhamy *et al.* (2012) showed that the location of large cavities can influence the tensile strength up to 15%. The research conducted by Rabiul Islam and Sumi (2011) showed that the reduction in bending strength due to semi-elliptical cavities is more than the reduction of compressive, tensile and shear strengths. Finally, an empirical formula is presented for the reduction of bending strength due to the semi-elliptical cavities created by corrosion which is a useful tool in the evaluation of old marine structures.

**Hypotheses:**

- The corrosion of steel affects the steel's nature and it can make the steel becoming ceramic and change its nature in the thickness.
- Corrosion can penetrate the steel thickness and affect its mechanical properties and equations.
- The Iracore type of steel shows a better and different performance against corrosion
- The work stages

## MATERIALS AND METHODS

**Checking the chemical composition of used steel:** To ensure about used steel type and investigate the possibility of effects of the percentage of alloys on the test results, quantometer test has been done using quantometer device. The chemical composition of used steels has been identified with quantometer test in the laboratory which the results along with standard values (Based on standards DIN 17100 and MSC) is shown in Table 1. It can be obtained from the following table that the selected steels all are in the standard range.

### Production of specimens

#### Tensile test specimen

**The used standard:** The tensile test was conducted by using Zwick-Roel machine made by Germany which is owned by the Products Laboratory of Mobarakeh Steel Complex. Because in the present study the purpose is to compare the forces, the force-displacement curve was used as the device output. In order to obtain the accurate amount of ultimate tensile strength, the device software was used (Nakai *et al.*, 2004). The produced specimens for the tensile test are producing based on ISO 6892-1 (2009) and ASIRI10272 standards which are the standards for tensile test in the environment temperature (Nakai *et al.*, 2004; Ahmmad and Sumi, 2010). Standards ISO 3785 (2006) and ISIRI 12694 of the Institute of Standards and Industrial Research of Iran are also considered in manufacturing specimens to identify the specimens. All the specimens are produced in such a way that the length of the specimen being perpendicular to the direction of rolling the steel that is the long length of it. The importance of this subject is because the mechanical properties of the steel plate can have a significant different together. The tests were performed at the standard speed of 15 Mpa $sec^{-1}$ and environment temperature of 25°C. As there was this guess that in the

Table 1: Standard range and chemical composition of used steel plates

| Chemical composition (%) | St37-2 (DIN 17100) Standard | S14 | St52-3 (DIN 17100) S16 | Standard | Iracor(MSC) S25 | Standard | S38 |
|---|---|---|---|---|---|---|---|
| C | <0.17 | 0.0150 | 0.0140 | <0.2 | 0.1670 | <0.12 | 0.110 |
| Si | | 0.3000 | 0.2500 | | 0.2100 | <0.3 | 0.231 |
| Mn | | 0.4870 | 0.5100 | | 0.9900 | <1 | 0.817 |
| P | <0.05 | 0.0300 | 0.0250 | <0.04 | 0.0100 | <0.12, >0.08 | 0.083 |
| S | <0.05 | 0.0230 | 0.0190 | <0.04 | 0.0120 | <0.03 | 0.010 |
| Cr | | 0.0130 | 0.0120 | | 0.0110 | - | 0.008 |
| Mo | | 0.0300 | 0.0250 | | 0.0120 | | 0.042 |
| Ni | <0.09 | 0.0220 | 0.0200 | | 0.0230 | <0.4 | 0.231 |
| Al | | 0.0380 | 0.0380 | | 0.0340 | | 0.051 |
| Co | | 0.0080 | 0.0070 | | 0.0035 | | 0.004 |
| Cu | | 0.0400 | 0.0500 | | 0.0130 | <0.5, >0.25 | 0.360 |
| Nb | | 0.0040 | 0.0030 | | 0.0030 | <0.06 | 0.040 |
| Ti | | 0.0010 | 0.0010 | | 0.0020 | | 0.006 |
| V | | 0.0020 | 0.0010 | | 0.0050 | | 0.014 |
| W | | 0.0050 | 0.0040 | | 0.0070 | | 0.044 |
| Pb | | 0.0010 | 0.0010 | | 0.0020 | | 0.002 |
| Sn | | 0.0150 | 0.0140 | | 0.0010 | | 0.007 |
| As | | 0.0010 | 0.0010 | | 0.0010 | | 0.005 |
| Ca | | 0.0000 | 0.0010 | | 0.0001 | | 0.001 |
| B | | 0.0001 | 0.0001 | | 0.0010 | | 0.001 |
| Zn | | 0.0030 | 0.0030 | | 0.0050 | | 0.030 |
| Fe | | 98.960 | 99.0000 | | 98.4800 | | 97.900 |

Table 2: Specimens manufactured for tensile test according to standard ASO 6892

| Specimen | t (mm) | W0 (mm) | W1 (mm) | R (mm) | Lj (mm) | Lt (mm) | L0 (mm) |
|---|---|---|---|---|---|---|---|
| SS14 | 4 | 20 | 30 | 12 | 80 | 68 | 50 |
| SS16 | 6 | 20 | 30 | 12 | 80 | 84 | 60 |
| SS25 | 5 | 20 | 30 | 12 | 80 | 76 | 55 |
| SS38 | 8 | 20 | 30 | 12 | 80 | 97 | 70 |

case of any discrepancy between expected and measured ultimate tensile strength from tensile test, this difference can be small, it was tried that all the steps of test especially the tensile test, be performed with an accurate and calibrated device. In order to the most avoid of human and machine errors, a great sensitivity was considered with implementing the standards.

**Manufacturing procedure:** After preparing the plates used in the experiment and quantometer test and ensuring their compliance with relevant standards, in order to minimize the effects of external factors (such as temperature) on the mechanical properties and also increasing the accuracy in the manufacture of specimens in accordance with standards, the specimens were manufactured with waterjet device according to the dimensions in Table 2 and Fig. 1.

**Numbering and piercing of the specimens:** Concerning the steel type, thickness and the time exposed to corrosion, the specimens were numbered by swab. The specimens were needed to be suspended in the salt spray

Table 3: Numbering of the specimens of corrosion rate test

| Specimens | t (mm) | L (mm) | 0 |
|---|---|---|---|
| CS14 | 4 | 150 | 100 |
| CS16 | 6 | 150 | 100 |
| CS25 | 5 | 150 | 100 |
| CS38 | 8 | 150 | 100 |

machine to have a uniform effect of the environment of the machine on the specimens, this was performed by creating a small hole on the specimens.

**Manufacturing the specimens of measuring the corrosion rate:** Separate specimens were built to measure the corrosion rate of various steels according to standards and penetration depth method, and to determine the performance of them.

**The used standard:** The used standard for manufacturing the specimens of measuring corrosion rate is ASTMG50 which rectangular specimens with 15×10 cm of dimensions were produced based on it according to Table 3.

**Production of specimens:** The specimens are cut by cutter device and were pierced and numbered.

**Actions before putting the samples in the salt spray machine:** The specimens were prepared based on standard ISO 9227 before putting in the salt spray machine and were washed by detergents To be without any contamination that may have a negative effect on the process of the experiment (Cabezas and Celentano, 2004). Thereafter, the specimen's weight and dimensions were measured accurately. In order to eliminate differenced and

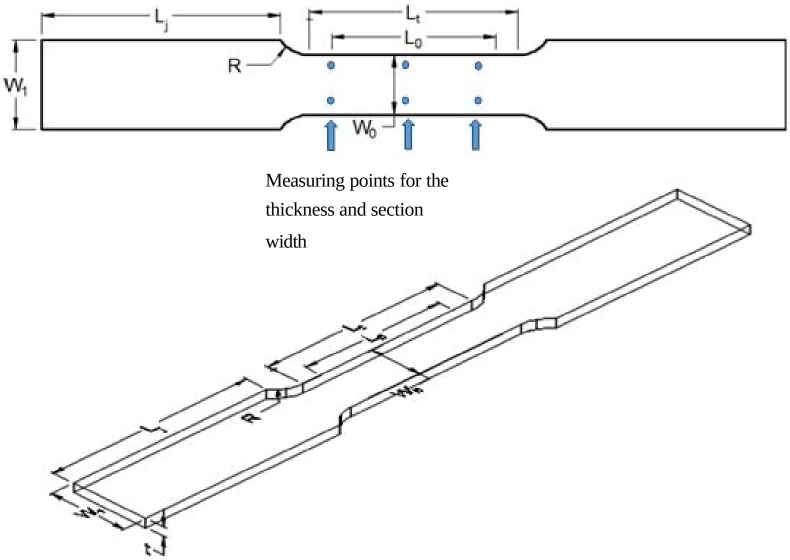


Fig. 1: Specimens used in tensile test; t: thickness, $W_1$: jaw width, $L_j$: jaw length, $W_0$: width, R: shear radius, $L_t$: milling length, $L_0$: the basis length

obtaining correct numbers, measurement were done in different points of specimens and the average was considered for calculation.

**Salt spray machine**

**Preparing the specimens to put them in the salt spray machine:** Specimens were prepared by closing plastic rope and hooks for hanging in the machine. An additional numbering was performed by plastic sheets that was attached to the hooks to ensure that specimens will be recognized if the swabed numbers are corroded.

**The work stages in salt spray machine:** According to standard ISO 9227, sodium chloride solution 5% with a PH range of 5.6-2.7 was prepared in separate containers by preparing the correct ratio for salt and distilled water and was poured in solution's reservoirs (Cabezas and Celentano, 2004). Then, the time, pressure and temperature were adjusted in accordance with standards and after placing the specimens the container was isolated by pouring water into its door groove and closing it during the test. According to the scheme for doing the work, two specimens of tensile test and one specimen of corrosion rate test for each steel type were brought out from the machine at time periods of 48, 96, 144 and 192 h and their appearance were evaluated and after washing and wiping the rust according to instructions, they were prepared for weighing, measuring dimensions and tensile test.

## RESULTS AND DISCUSSION

**Appearance observations:** The produced and observable changes regarding corroded surface grow with time during the test and the thickness of produced rust is increased during the test time. Although, these changes are a little different from each other. Meanwhile, corrosion products formed on steel SS38 and SS52 demonstrated a thicker orange color. The corroded specimens are shown in Fig. 2 and 3.

**Investigation the weighted and dimensional results of specimens of tensile test:** As it can be seen from Table 4 and 5 the specimen's weight and cross section are reduced with an increase in the number of days of corrosion, although, the decline is different for each type of steel. Nevertheless, the interesting point is the difference of 2-6% between the percentages of weight loss and cross section reduction. However, it seems that due to the applying uniform corrosion, the reduction of these two parameters should be performed by the same percentage.

It can be concluded that the difference between the percentages of the weight loss and cross section reduction increases by increasing the days of corrosion. This happens because of becoming to cavity corrosion. It should be noted that the large difference between the percentages of the weight loss and cross section reduction of different types of steel is due to the different between the initial thickness and weight of tested

Fig. 2: Corroded plates in salt spray machine

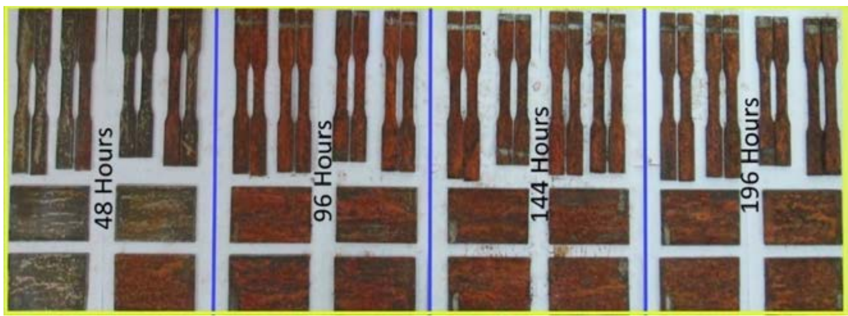


Fig. 3: Plates exposed to corrosion in the time duration of 48 h

Table 4: Average percentage of weight loss for steels SS14, SS16, SS25 and SS38

| | Percentage | | | |
|---|---|---|---|---|
| Specimen | 48 (h) | 96 (h) | 144 (h) | 192 (h) |
| SS14 | 3.94 | 9.26 | 19.75 | 29.70 |
| SS16 | 3.57 | 6.57 | 15.67 | 21.00 |
| SS25 | 3.56 | 9.63 | 18.72 | 24.56 |
| SS38 | 3.33 | 9.45 | 14.93 | 17.00 |

Table 5: Average percentage of cross section reduction for steels SS14, SS16, SS25 and SS38

| | Percentage | | | |
|---|---|---|---|---|
| Specimen | 48 (h) | 96 (h) | 144 (h) | 192 (h) |
| SS14 | 3.28 | 7.72 | 16.12 | 23.76 |
| SS16 | 2.80 | 5.36 | 12.29 | 16.80 |
| SS25 | 2.74 | 7.41 | 14.40 | 18.89 |
| SS38 | 2.61 | 7.41 | 11.94 | 13.60 |

specimens. For instance, the percentage of the cross section for steel SS14 is equal to 23.76 for 192 h of applying corrosion that is obtained from the ratio of reduced cross section with the initial cross section of the plate with 4 mm of thickness. While this value is obtained equals to 13.6% for steel of type SS38 with a difference that this value is for a plate with 8 mm of thickness (2 times the previous one).

Despite the fact that the percentage of weight loss and cross section reduction should be equal, a difference has been observed between them. By detailed investigating the corroded surface and seeing its pores, as is shown in Fig. 4 it seems that in the process of applying uniform corrosion, pitting corrosion also reveals in small scale that cannot be determined when measuring the thickness, this is the reason for the difference. As it was determined from the results of weight loss and cross section reduction, applying the uniform corrosion can result in reducing the thickness uniformly and producing some holes in the plate. These holes are similar to the vacuolar corroded specimen.

**The results of tensile test and comparing them with ultimate tensile strength:** In this step, to undestand if measuring the thickness (and consequently measuring the cross section of corroded steel) gives a correct estimation of the residual tensile strength of steel, a detailed investigation and comparison will be performed between the expected residual strength (theoretical) and the residual strength obtained from the tensile test of corroded steel (residual strength is the tensile strength of specimens after applying corrosion). The tensile strength of specimens before corrosion is obtained from equation 1 and according to the obtained stress from a tensile test of non-corroded specimens (coupon test). Then the expected obtained strength will be compared with the ultimate tensile strength from the test:

$$S = \frac{T_e}{A_1} \tag{1}$$

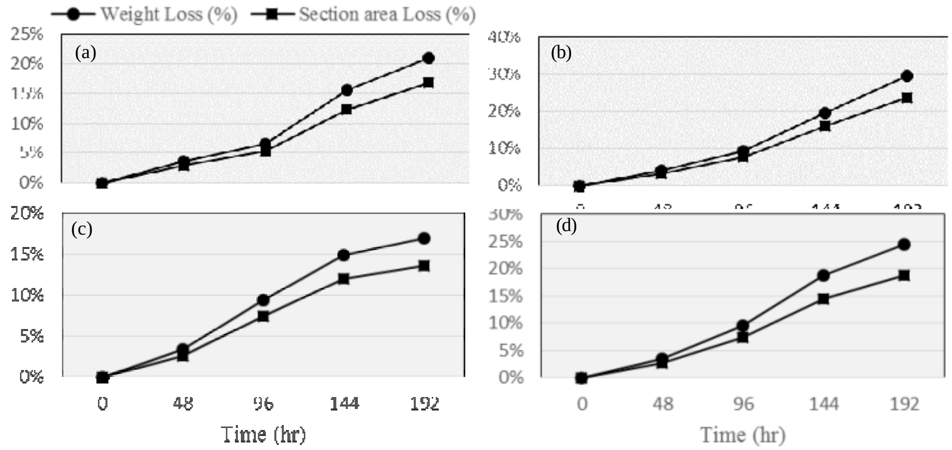


Fig. 4: Comparison between the percentage of weight loss and thickness reduction for steel of types: a) SS16, b) SS14, c) SS38 and d) SS25

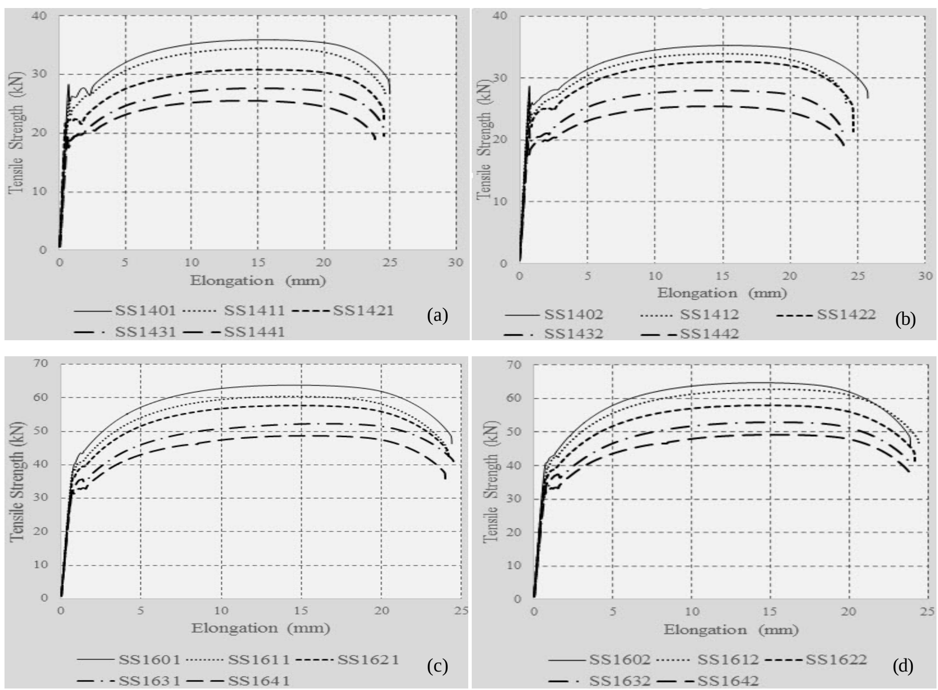


Fig. 5: Comparison of the load-elongation: a) SS14 specimens with number one, b) SS14 specimens with number two, c) SS16 specimens with number one and d) SS16 specimens with number two

where, S is the average obtained stress from a tensile test of the specimen without applying corrosion for each type of steel (the obtained stresses are presented in Table 6), $T_e$ is the expected tensile load after corrosion, and $A_1$ is the corroded cross section of each specimen.

251659264251660288 According to the obtained stresses from Eq. 1, the expected tensile strength (theoretical) is calculated and presented in Table 6. The average tensile strength (theoretical) and the tensile strength from the test, obtained from load-displacement curves (Fig. 5 and 6) are given in Table 7-10 for comparison.

As is shown in above tables the difference between expected tensile strength and the tensile strength obtained from tests is evident. The reduction trend is so that the difference between mentioned strengths increases with increase in the days of the corrosion process. This procedure is a little different for steel SS38

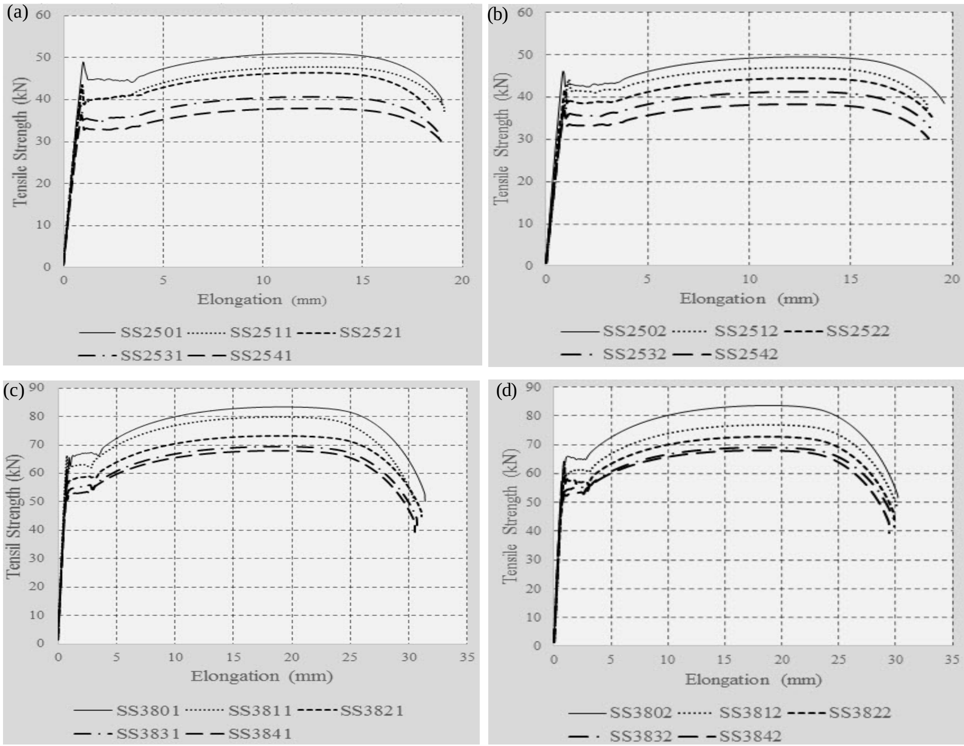


Fig. 6: Comparison of the load-elongation: a) SS25 specimens with number one, b) SS25 specimens with number two, c) SS38 specimens with number one and d) SS38 specimens with number two

Table 6: The average ultimate tensile stress of non-corroded specimens (coupon test) for steels SS14, SS16, SS25 and SS38

| Steel | UTS (Mpa) | Steel | UTS (Mpa) | Steel | UTS (Mpa) | Steel | UTS (Mpa) |
|---|---|---|---|---|---|---|---|
| SS14 | 420.93 | SS16 | 473.74 | SS25 | 515.31 | SS38 | 513.05 |

Table 7: Average expected tensile strength and the tensile strength obtained from tests for steel of type SS14

| Specimens | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Time (h) | 48 | 96 | 144 | 192 |
| EUTSC (N) | 34732 | 31392 | 28454 | 27001 |
| UTS (N) | 33924 | 29502 | 25992 | 24079 |

Table 8: Average expected tensile strength and the tensile strength obtained from tests for steel of type SS16

| Specimens | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Time (h) | 48 | 96 | 144 | 192 |
| EUTSC (N) | 62701 | 60925 | 56276 | 53825 |
| UTS (N) | 61731 | 58015 | 51321 | 48741 |

Table 9: Average expected tensile strength and the tensile strength obtained from tests for steel of type SS25

| Specimens | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Time (h) | 48 | 96 | 144 | 192 |
| EUTSC (N) | 47614 | 46252 | 42615 | 40036 |
| UTS (N) | 46207 | 46252 | 42615 | 40036 |

and it seems that in this type of steel, the difference goes toward stability and loses its desire to an upward trend. Producing cavities due to the corrosion (pitting corrosion) can be of the reasons of such a difference which is led to reducing the tolerable load in the specimens. The increasing trend of this difference is also because of the tendency of steel to pitting corrosion which leads to more reduction in the residual tensile strength of the steel plates.

Table 10: Average expected tensile strength and the tensile strength obtained from tests for steel of type SS38

| Specimens | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Time (h) | 48 | 96 | 144 | 192 |
| EUTSC (N) | 79834 | 76352 | 72006 | 70899 |
| UTS (N) | 76993 | 71237 | 67764 | 66817 |

To have a more perceptible comparison between the expected tensile strength and the tensile strength obtained from the test and to be able to define a reduction factor from the result to apply in the cross section or to theoretically estimated load (strength), following tables are useful. These strengths need to be presented by reduction percentages compared to the ultimate tensile strengths of non-corroded case of each specimen. The above-mentioned percentages and their difference which can be used for defining reduction factor, are presented in Table 11-14. The reduction percent of loads (strengths) are defined from Eq. 2 and 3:

Table 11: The difference between the reduction percentages of expected ultimate tensile strength and the ultimate tensile strength from tensile test of steel SS14

| Specimens | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Time (h) | 48 | 96 | 144 | 192 |
| EUTSC loss (%) | 3 | 8 | 16 | 24 |
| UTS loss (%) | 6 | 13 | 23 | 32 |
| Difference (%) | 3 | 5 | 7 | 8 |

Table 12: The difference between the reduction percentages of expected ultimate tensile strength and the ultimate tensile strength from tensile test of steel SS16

| Specimens | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Time (h) | 48 | 96 | 144 | 192 |
| EUTSC loss (%) | 3 | 5 | 12 | 17 |
| UTS loss (%) | 4 | 10 | 20 | 24 |
| Difference (%) | 1 | 5 | 8 | 7 |

Table 13: The difference between the reduction percentages of expected ultimate tensile strength and the ultimate tensile strength from tensile test of steel SS25

| Specimens | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Time (h) | 48 | 96 | 144 | 192 |
| EUTSC loss (%) | 3 | 7 | 14 | 19 |
| UTS loss (%) | 6 | 13 | 21 | 26 |
| Difference (%) | 3 | 6 | 7 | 7 |

Table 14: The difference between the reduction percentages of expected ultimate tensile strength and the ultimate tensile strength from tensile test of steel SS38

| Specimens | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Time (h) | 48 | 96 | 144 | 192 |
| EUTSC loss (%) | 3 | 7 | 12 | 14 |
| UTS loss (%) | 6 | 14 | 17 | 19 |
| Difference (%) | 3 | 7 | 5 | 5 |

$$LEUTS_c = \frac{(EUTS)-(EUTSC)}{(EUTS)} \times 100 \quad (2)$$

$$L_{UTS} = \frac{(EUTS)-(UTS)}{(EUTS)} \times 100 \quad (3)$$

where, $L_{EUTSc}$ is the reduction of expected tensile load in term of percentage and is the reduction of tensile load obtained from the tensile test regarding percentage.

Because the effects of corrosion have not a particular pattern and depends on the steel type and each steel molding in each production turn, the type of corrosion and its effect on strength reduction is different and finding a special pattern is difficult. However, the difference between mentioned values indicates that it can increase from 1-8% by increasing the time duration. An increasing trend is seen in the steel of types SS14, SS16 and SS25 but for steel SS38 it was found that after increasing from 3-7% the trend constantly remains in 5%.

**Ductility:** In this study, the ductility of specimens will be studied according to the curves of tensile test to obtain the possibility effects of corrosion on the ductility. Base on the definition, ductility is equal to the ratio of failure strain to yielding strain which is expressed in Eq. 4:

Table 15: The ductility of steel SS14

| Time (h) | 0 | 48 | 96 | 144 | 192 |
|---|---|---|---|---|---|
| Specimen 1 | 38.46 | 37.40 | 37.39 | 38.43 | 36.71 |
| Specimen 2 | 38.43 | 35.45 | 36.81 | 37.32 | 36.56 |
| Average | 38.44 | 36.43 | 37.10 | 37.88 | 36.64 |

Table 16: The ductility of steel SS16

| Time (h) | 0 | 48 | 96 | 144 | 192 |
|---|---|---|---|---|---|
| Specimen 1 | 34.85 | 32.52 | 33.17 | 34.56 | 34.31 |
| Specimen 2 | 31.44 | 33.41 | 33.61 | 33.66 | 33.83 |
| Average | 33.15 | 32.96 | 33.39 | 34.11 | 34.07 |

Table 17: The ductility of steel SS25

| Time (h) | 0 | 48 | 96 | 144 | 192 |
|---|---|---|---|---|---|
| Specimen 1 | 24.64 | 25.23 | 27.3 | 26.88 | 25.29 |
| Specimen 2 | 26.86 | 26.08 | 26.81 | 27.02 | 25.08 |
| Average | 25.75 | 25.65 | 27.05 | 26.95 | 25.18 |

Table 18: The ductility of steel SS38

| Time (h) | 0 | 48 | 96 | 144 | 192 |
|---|---|---|---|---|---|
| Specimen 1 | 28.53 | 26.87 | 26.7 | 27.66 | 27.7 |
| Specimen 2 | 27.12 | 26.93 | 27.5 | 26.94 | 28.03 |
| Average | 27.83 | 26.90 | 27.1 | 27.3 | 27.87 |

$$\mu = \frac{\varepsilon_u}{\varepsilon_y} \quad (4)$$

Where:

$\mu$ = The steel ductility

$E_u$ = The strain in the failure momen

$E_y$ = The yielding strain

According to the performed measurements and load-displacement curves from tensile test, the ductility of specimens is presented in Table 15-18.

The values in above tables indicating this subject that corrosion is not affected the ductility of specimens and this can be another reason for the fact that the applying corrosion doesn't affect the nature of steel and the strength reduction should be studied seeking for other reasons.

**Investigating the specimens with SEM microscope specimen preparation:** A corroded specimen and a non-corroded one from steel of type SS14 have been created with dimensions of 2.5×3 cm.

**Placing specimens in the microscope:** The specimens were gold-plated in Scouter Coater device to have better conductivity. Then, the prepared specimens first were placed on the surface in the device and after creating required vacuum which is a prerequisite for the work, photographs were taken of the surface at different magnifications.

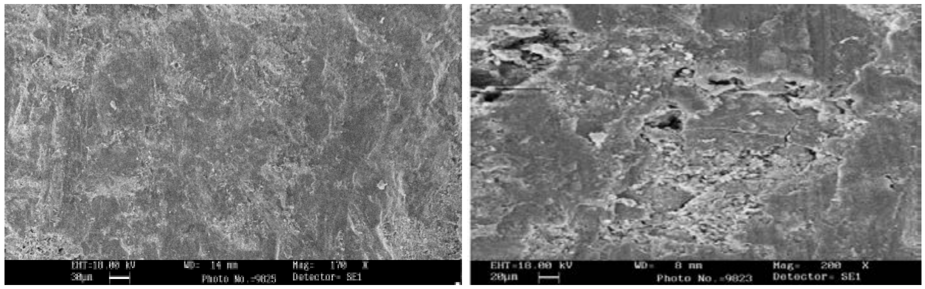

Fig. 7: Photos of the specimen surface taken by scanning electron microscope: a) before corrosion and b) after corrosion

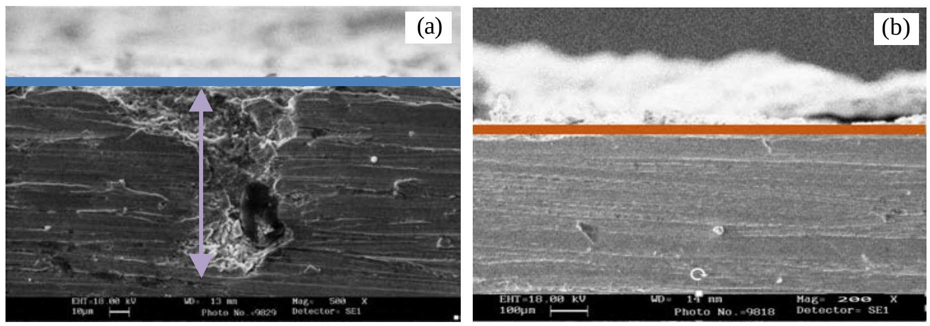


Fig. 8: Photos of the specimen cross section taken by scanning electron microscope: a) the specimen cross section before corrosion and b) after corrosion

**Analysis of photos taken:** Figure 7 presents two photos from specimen's surface. The photo (b) is the surface of the corroded specimen. As it can be seen, the surface has very small pores (small-penetrated corrosion). Tiny cracks of microscopic scale are also observable in the photos which can be the cause of a microscopic penetration of corrosion in the cross section and thereby reduction in the bearable tensile strength of steel. The cut of cross section of the specimen after applying corrosion is presented in Fig. 8a. As it can be observed, the corrosion is penetrated in depth. This can be another cause of weakness of the strength of corroded steel. Although, it is noteworthy that because this penetration can be completely random and scattered, it is impossible to obtain a general rule for it. Thus, the differences obtained from the test results may be a suitable solution to define a reduction factor which the cause of mentioned penetration is also included in it. Finally, it seems that the reduction in tensile strength as the result of corrosion is because of three reasons:

- Uniform thickness reduction due to uniform corrosion, which is of less important because it is considered in the estimation of tensile capacity with parameters thickness and cross section area
- The presence of pitting corrosion and the impossibility of measuring it properly despite the accurate common measurement which leads to a mistake in estimation
- The corrosion can penetrate microscopically which this issue is not considered in measurements and affects our estimation of residual tensile capacity

**Determining the corrosion penetration rate:** In the current study, corrosion penetration rate is used for reporting the amount of corrosion speed and also performing a comparison between corrosion behaviors of tested steels. This quantity actually expresses the amount of corrosion penetration in the unit time. This value is calculating from the amount of weight reduction of specimen in a given moment and is based on the following relation (Table 19-22):

$$mpy\frac{\Delta W\times 3.45\times 10^{6}}{D\times A\times T} \qquad (4)$$

Where:

mpy = The speed of corrosion penetration in milli inch per year
$\Delta W$ = Weight reduction due to corrosion (g)
D = The specimen density (gr/$m^3$)
T = The time of being exposed to corrosion (h)
A = The specimen's area exposed to corrosion ($cm^2$)

The calculations of each specimen are presented in Table 19-22. As is shown in Fig. 9, the corrosion penetration rate in steel types SS14 and SS16 follow a

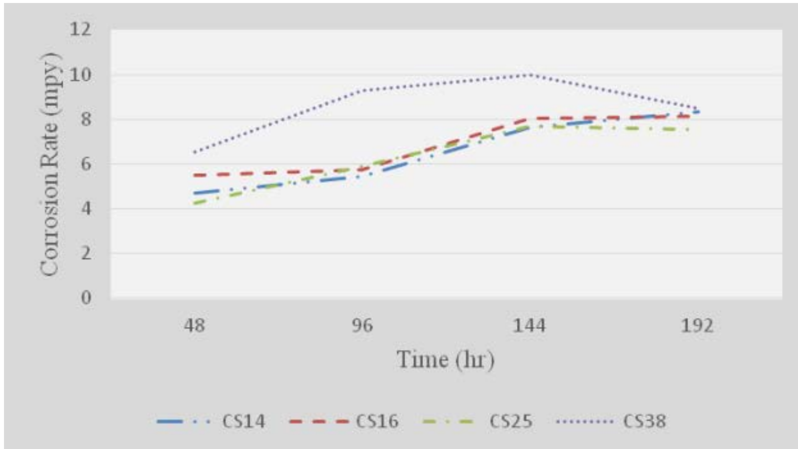


Fig. 9: Comparison of the average corrosion rate of specimens

Table 19: The calculation of corrosion rate of steel CS14

| Specimen | Weight loss (g) | Time (h) | Area (mm$^2$) | mpy |
|---|---|---|---|---|
| CS141 | 16.54 | 48 | 32228.16 | 4.70 |
| CS142 | 38.82 | 96 | 32545.22 | 5.46 |
| CS143 | 81.74 | 144 | 32750.20 | 7.62 |
| CS144 | 117.12 | 192 | 32242.45 | 8.32 |

Table 20: The calculation of corrosion rate of steel CS16

| Specimen | Weight loss (g) | Time (h) | Area (mm$^2$) | mpy |
|---|---|---|---|---|
| CS161 | 20.13 | 48 | 33464.63 | 5.51 |
| CS162 | 41.88 | 96 | 33378.96 | 5.74 |
| CS163 | 87.52 | 144 | 33162.67 | 8.05 |
| CS164 | 117.83 | 192 | 33093.87 | 8.15 |

Table 21: The calculation of corrosion rate of steel CS25

| Specimen | Weight loss (g) | Time (h) | Area (mm$^2$) | mpy |
|---|---|---|---|---|
| CS251 | 15.15 | 48 | 32588.74 | 4.26 |
| CS252 | 42.94 | 96 | 33344.57 | 5.90 |
| CS253 | 83.32 | 144 | 33125.68 | 7.68 |
| CS254 | 108.96 | 192 | 33105.05 | 7.53 |

Table 22: The calculation of corrosion rate of steel CS38

| Specimen | Weight loss (g) | Time (h) | Area (mm$^2$) | mpy |
|---|---|---|---|---|
| CS381 | 24.43 | 48 | 34230.53 | 6.53 |
| CS382 | 69.56 | 96 | 34250.92 | 9.30 |
| CS383 | 111.53 | 144 | 34132.98 | 9.97 |
| CS384 | 127.86 | 192 | 34411.79 | 8.51 |

similar trend such that the corrosion penetration rate has a gentle gradient until 96 h. They keep their upward trends until the end of the test. However, steel of the type SS25 first starts with the lowest rate of corrosion and will continue until 144 h thereafter, its corrosion trend remains constant. The corrosion rate in steel type SS38 shows a completely different trend. This steel first begins to corrode with the maximum rate and continues with an upward gradient until time 144 h. Finally, after 144 h, the corrosion rate decreases quickly until the end. The reason for this difference between corrosion rates is the way to forming a protective (oxide) layer that differs in various steels. In steel SS38, it changes from active mode to passive. In the steel SS38, this protective layer (coating) which is a stainless steel, forms faster and it seems that the way to protecting corrosion is this fast formation of the oxide layer.

## CONCLUSION

The findings are summarized herein: applying uniform corrosion even in salt spray machine despite its identical atmospheric conditions at all the surface can cause pitting corrosion in any case which is because of the non-uniformity of steel chemical elements and its effect on the non-uniform corrosion rate in different regions of the surface. The weight loss and the cross section reduction of specimens is different from each other due to the possibility of pitting corrosion. The difference in the percentage of cross section reduction and weight reduction was observed up to 6 percent, which increases with increase in time due to the steel tendency to pitting corrosion or cavity.

The various thicknesses used of steel of type ST37 did not affect the mechanical properties and corrosion rate of specimens, significantly. By investigating the corroded and non-corroded cross section, it was observed that the corrosion is capable of penetrating in the steel depth at the microscopic scale which leads to infirmity in corroded steel, itself. The ultimate tensile load (strength) obtained from tensile test curve with expected ultimate tensile load differs in steel types ST37 and ST52 up to about 8%. This value is about 5% for Iracore steel. This difference is due to the simultaneous effect of pitting corrosion and penetrating of it which leads to reducing the tensile load capacity. Applied corrosion had not affected the ductility of specimens. According to the superposition of load-displacement curves, it was observed that the corrosion has not a significant effect on the gradient of the elastic region (modulus of elasticity).

The corrosion penetration rate in steel of type ST37, trends upward, however, this trend in ST52 has a constant gradient at the end of the test while Iracore steel despite the increasing corrosion rate until 144 h, it shows a steep reducing gradient at time 192 h. This can be because of the existence of more copper in Iracore steel and ST52.

## SUGGESTIONS

**Pragmatic suggestions:** Defining a reduction factor called "corrosion reduction factor" is efficient in the correct estimation of the residual tensile capacity of steel structures. This factor can be 90% for conventional steels and 95% for corrosion-resistant steels.

## RECOMMENDATIONS

- It is recommended that by applying other types of loading (shear, bending, etc.) on the corroded specimens, mechanical changes be performed
- Studying of creating different atmospheric conditions in salt spray machine and investigating the effects
- Providing conditions for applying other types of corrosion in salt spray machine including stress corrosion, pitting corrosion, furrow corrosion and studying the mechanical properties and corrosion behavior of the specimens
- Increasing the time of applying corrosion in the salt spray machine to study the mechanical properties and corrosion behavior of the specimens in a longer period
- It is recommended to use other types of structural steels and various types of plate beam and rolled beams and studying the corrosion effects in them
- It is recommended to study the effects of corrosion on steel members with actual dimensions such as shear walls, etc

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