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An Overview of Corrosion and Experimental Studies on Corroded Mild Steel Compression Members

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Abstract

The performance of steel structures are strongly influenced by the damage due to corrosion, whose control is a key aspect for design and maintenance of both new and existing important structures. This paper presents various issues related to corrosion, types of corrosion, chemical reactions and electrochemistry behind corrosion of steel structural elements, approaches to quantify corrosion and experimental studies on corroded coupons and compression members made of angle and tubular sections. The various corrosion models for structural applications are also presented, by considering the depth of corrosion along with various influencing parameters. Based on experimental studies on coupons, it is concluded that corrosion results in reduction in metal thickness followed by weight loss and reduction in mechanical strength. Galvanostatic method is adopted to corrode structural steel specimens by keeping current as constant. The thickness loss and weight loss are the main parameters measured to quantify the amount of corrosion. From the studies, it is concluded that for the corroded specimens, along with reduction in thickness, the geometric properties such as area, moment of inertia, radius of gyration, section modulus changes. As the corroded surface is highly irregular these changes may not be linear. Variation in slenderness ratio also noticed for corroded specimens. In effect the overall capacity of the section reduces due to corrosion. Identifying the intensity level of corrosion such as mild, moderate and severe along with the form and location of corrosion are the other parameters discussed. A drastic reduction in mechanical properties i.e., yield and ultimate strength are observed for severely corroded specimens.

Keywords: *steel structures, corrosion models, electrochemistry, compression member, mechanical properties*

1. Introduction

Corrosion is a natural phenomenon, and major cause of deterioration of steel structures which exists as part of our everyday life. In extreme situations catastrophic failure such as collapse occurs due to reduction in the load bearing capability of a structure. Corrosion damage can also results in life threatening situations, hence it has to be addressed for safety, environment and economic reasons. Most of the steel structures in India are facing these types of problems and it demands scientific research activities to enhance their service life. Corrosion of steel is an electrochemical process causes the degradation of material. Steel structures exposed to the extreme atmosphere, especially marine and highly polluted industrial environment are subjected to corrosion. The conventional approach to evaluate residual capacity is to perform visual inspection of the corroded members and classify the members according to their level of damage.

For members loaded in compression, the precision obtained by this method can be inadequate because the capacity is very sensitive to geometrical imperfections. Corrosion might also modify steel from a metallurgical point of view and characteristics of steel, such as yield, ultimate strength and failure strain, can be altered. The phenomenon of corrosion is well studied but, very little research has been done on how the compressive capacity of steel members is affected once corrosion has developed. There is lack of experimental data on the relation between weight loss due to corrosion and residual strength. It has been proved that the corrosion played a significant role in the catastrophic collapse of both the Silver Bridge in 1967 and the Mianus River Bridge in 1983, USA Steel Bridge Design Handbook (NSBA, 2006). Those collapses indicated the paramount importance of attention to the condition of older bridges, leading to intensified inspection protocols and numerous eventual retrofits or replacements. Even galvanized steel experience corrosion after galvanic protection is consumed. Large network managing structures such as transmission towers and telecommunication towers, corrosion are important and need to be assessed. In order to resolve these problems, models predicting the residual capacity of structural components which has undergone various levels of corrosion are essential.

As per financial express statistics of the year 2007, India has

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been losing around Rs 1.52 lakh crore every year owing to corrosion in various sectors, including infrastructure, utility services, production and manufacturing, and defense and nuclear waste. According to National Metallurgical Laboratory (NML) around Rs 1.07 lakh crore given out by NACE International recently excluded corrosion losses being incurred by the country's Small and Medium Enterprises (SMEs) engaged both in manufacturing and utility service sectors. Conservatively estimated corrosion losses for this sector were another Rs 40,000-45,000 crore per annum. It is necessary to have a reasonable understanding of corrosion and find ways to detect and reduce or delay it. Thus the impact of corrosion could be significantly reduced by good design, proper selection of material, use of correct production methods and stringent quality assurance both during construction of a plant and after.

Rahgozar *et al*. (2009) reviewed various forms of corrosion and the effects of uniform corrosion on steel structures. They developed corrosion decay models based on the information on the locations where corrosion occurs. Numerical studies were conducted to find the effects of pitting corrosion on ultimate compressive strength and shear strength of steel plates by inducing pit holes in the geometry of the plates. There are different types and forms of corrosion, which makes the study of corroded structural members very complex. Beaulieu *et al*. (2010) studied corrosion of steel structures exposed to various environmental conditions. They estimated the residual capacity of corroded members in order to decide whether to change the member, repair it or just remove corrosion and re-protect the member. The objective of the study was to provide data to engineers on the structural behaviour of corroded steel angle members under compressive load. Landolfo *et al*. (2010) presented the modelling approaches of atmospheric corrosion damage of metal structures. A comparison among the selected degradation models to evaluate the possibility of developing a general approach to the evaluation of thickness loss due to corrosion is discussed. Based on the studies conducted by Damgaard *et al*. (2010) it was concluded that corrosion can significantly reduce the service lives of weathering steel girders. Plate thickness measurements are seen to be vital for the structural assessment of these structures, due to the high uncertainty associated with the corrosion rate. The buckling behaviour of corroded steel structural members are dealt in Jiang and Guedes Soares (2012), Sharifi and Rahgozar, (2010). The effective material properties and strength behaviour of rusted steel members are studied by Liu *et al*. (2001).

This paper briefly introduces the types of corrosion and quantitative approaches to identify the level of corrosion. Emphasis is given to experimental studies on corroded coupons and compression members made of angle and tubular sections. In all corroded specimens, corrosion is simulated in a laboratory environment. The studies were aimed to understand the mechanism of corrosion and its effects on behavior of compression members. Based on experimental studies on artificially induced uniform corrosion of coupons and angle and tubular members, it is concluded that corrosion leads to smaller resistance area, producing a decreasing effect in the structural performance in terms of reduced strength. Identifying the intensity level of corrosion such as mild, moderate and severe along with the form and location of corrosion are the other parameters discussed. Relatively uniform section loss indicates that surface is uniformly exposed to corrosive environment. All specimens are tested under monotonic loading. A drastic reduction in mechanical properties i.e., yield and ultimate strength and failure strain are observed for severely corroded specimens. From the studies, it is confirmed that corrosion in the localized regions of the structural steel components results decrease in effective area, moment of inertia and variation in slenderness ratio and thereby reduction in ultimate load carrying capacity.

2. Forms of Corrosion

Corrosion occurs in several widely differing forms. Classification by appearance, which is particularly useful in failure analysis, based on identifying forms of corrosion by visual observation with either the naked eye or magnification. The morphology of attack is the basis for classification. Fig. 1 shows the main forms of corrosion. Among the various forms of corrosion, present study focus on uniform or general corrosion, this is illustrated in detail in later sections.

2.1 Uniform Corrosion

This is a surface phenomenon, which occur through uniform attack of metal resulting from the contact with certain strongly acidic or alkaline electrolytes as well as conditions of high humidity or moisture-laden atmosphere. This is the most common form of the corrosion, which will lead to the gradual thinning of members, accordingly for the greatest destruction of metal. As it occurs evenly over the entire surface, the rate of corrosion is often presented as a weight loss. Uniform corrosion is very predictable, and is the basis of most corrosion prediction equations. Also it has been pointed out that this type of corrosion is the most serious form of corrosion observed on steel bridges. The rate of uniform corrosion loss is highly variable, depending on conditions such as temperature, time of wetness, and chemistry. It is measured by weight loss or decrease in thickness. The rate of attack usually expressed in mils per year (mpy).

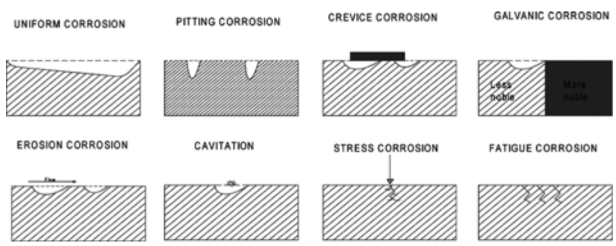

Fig. 1. Main Forms of Corrosion (Landolfo *et al*., 2010)

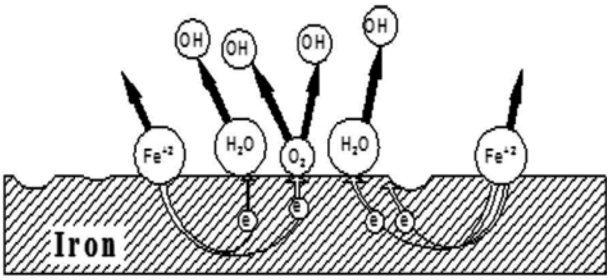

Fig. 2. Electrochemical Process of Corrosion

3. Electrochemistry of Corrosion

All corrosion reactions are electrochemical in nature, at anodic sites on the surface the iron goes into solution as ferrous ions, thus constituting the anodic reaction. As iron atoms undergo oxidation to ions they release electrons whose negative charge would quickly build up in the metal and prevent further anodic reaction, or corrosion. Corrosion consists of an oxidation reaction and a reduction reaction at the surface of the corroding material. The oxidation reaction generates metal ions and electrons; the electrons are then consumed in the reduction reaction. For environments with water present including moisture in the air, the electrons are consumed by converting oxygen and water to hydroxide ions. In iron and many iron alloys, these hydroxide ions in-turn combine with iron ions to form a hydroxide (Fe $(OH)_2$). Subsequent reactions form a mix of magnetite (Fe_3O_4) and the hematite (Fe_2O_3). This red-brown mixture of iron oxides is rust. The Fig. 2 illustrates the basic oxidation/reduction reaction behind corrosion.

4. Corrosion Rate and Map

In India, it is observed that the rate of corrosion varies from region to region and the intensity of attack is expected to be more in industrial areas along the seacoast. The maximum and minimum corrosion rate is seasonal in nature and varies with region. The corrosion map of India for mild steel brought out by (Rao and Lahiri, 1970). Afterwards (Natesan *et al*., 2006 and 2008) studied the corrosion behaviour of commercially available mild steel in marine, industrial, urban and rural environments by weight loss method at ten exposure stations in India over a period of 5 years. They updated the corrosion map of India as given in Fig. 3 based on area specific corrosion rates. From the studies it is identified that eastern coast of India is more corrosive than the western coast. During the months of March and April highest corrosion rate is observed as the temperature and chloride content are high, and humidity is above critical limit. They defined durability factor, important parameter, which may help designers in the selection of durable engineering materials for a particular area and there by design safe structures.

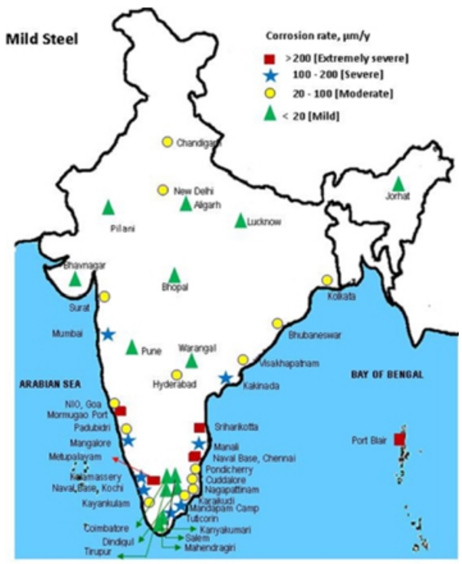

Fig. 3. Corrosion Map of India (Natesan *et al*., 2008)

5. Corrosion Modelling and Quantification

Several models concerning the evaluation of the damage produced by atmospheric corrosion are available in the literature. They are formulated according to different approaches, which depend on the objectives of the model itself. Such models can be classified as first level and second level models. The first ones are based on laws of physics and chemistry. In this case, the dissolution of metal and the formation of corrosion products are evaluated at microscope level in the sense of current. The second level models are useful for engineering applications and allow evaluation of the corrosion rate as a function of mass and/or thickness loss with time, being obtained from the observation and the interpolation of experimental data.

A review on the second level corrosion models for structural applications is discussed. In this case, the relationship between the corrosion rate and the levels of pollutants is expressed in combination with different climatic parameters. The variables affecting the corrosion rate over time are the time of wetting, the frequency and duration of drying out periods, relative humidity, temperature and temperature variation, and the composition of the atmosphere.

The corrosion rate is usually expressed as the mass loss per unit area per unit time, or as the rate of penetration, by means of the thickness loss. It is important to note that the thickness loss reported in corrosion studies is usually the average of the thickness losses of the exposed and ground ward surfaces of a specimen. In the present study, the level of corrosion damage is determined by the ratio of the mass of the steel specimen altered during corrosion to the mass of the intact steel member. The four levels of this variable considered in the present study are 0% (not corroded), $\leq 20\%$ as mild corrosion, $> 20\%$ and $< 40\%$ as moderate corrosion and $\geq 40\%$ as severe corrosion.

5.1 Corrosion Rate Expressions

Mostly the rates of corrosion of metals are expressed as mpy or mmpy (millimeter per year). The relative scale for corrosion of metal is given as Fontana, (1987) Safe: Less than 5 mpy or 0.125 mmpy , Moderate: 5 mpy to 50 mpy or 0.125 mmpy to 1.25 mmpy. Severe: Greater than 50 mpy or 1.25 mmpy. The rate of corrosion of metal is usually measured either by gravimetric method or by electrochemical methods. The conversion factors for the two methods are namely gravimetric and electrochemical. According to Gravimetric method:

$$\text{Corrosion rate(mmpy)} = \frac{87.6 \times \text{weightloss(mg)}}{\text{area(cm}^2) \times \text{time(hrs)} \times \text{density}} \quad (1)$$

According to Electrochemical method:

$$\text{Corrosion rate(mmpy)} = 3.2 \times I_{corr}(\text{mA/cm}^2) \times \frac{\text{Eq.wt}}{\text{Density}} \quad (2)$$

The corrosion rate can be used to quantify the corrosion loss of a structural element which has been exposed to atmosphere corresponding to standard corrosive categories. The laboratory simulated electrochemical corrosion rate is always higher than the natural corrosion rate.

5.2 Thickness Loss

The average thickness ratio can be used as a measure of the level of corrosion damage for assessing the strength of a corroded member. Corrosivity of atmosphere plays a key role in thickness loss. The thickness loss of a structural steel can vary significantly when it is exposed at different sites of the same environment. Based on the thickness loss, the level of corrosion damage can be classified as:

$$\text{Mild corrosion level, } \mu > 0.75 \quad (3)$$

$$\text{Moderate corrosion level, } 0.75 \geq \mu \geq 0.5 \quad (4)$$

$$\text{Severe corrosion level, } \mu < 0.5 \quad (5)$$

where

$$\mu = \frac{t_{Avg}}{t_o}$$

t_{Avg} = Average thickness of the corroded member
t_o = Original thickness of the member

Klinesmith *et al.*, (2007) developed a model for the atmospheric corrosion of carbon steel taking into account the effects of four environmental variables (TOW; sulpher dioxide, salinity and temperature). The general form of the degradation model is given below.

$$y = A.t^B\left(\frac{TOW}{C}\right)^D\left(1 + \frac{[SO_2]}{E}\right)^F\left(1 + \frac{[Cl]}{G}\right)^H e^{J(T+T_0)} \quad (6)$$

Where,
A, B, C, D, E, F, G, H, J, T_0
= Empirical coefficients whose numerical values can be found in reference Klinesmith *et al.* (2007)
Cl = Is chloride deposition rate (mg/m^2/day)
SO_2 = Sulfur dioxide concentration (μg/m^3)
t = Exposure time (years)
T = Air temperature (°C)
TOW = Time-of-wetness (hours/year)
y = Corrosion loss (micrometers)

6. Experimental Set-up of Corrosion

Towards achieving various level of corrosion, galvanostatic method is adopted in the present study. The cell set-up consists of applying a constant current from a DC source to induce significant corrosion in a short period. After applying the current for a given duration, the degree of induced corrosion is determined theoretically or the percentage of actual amount of steel loss in corrosion is estimated with the help of a gravimetric test. In the present experimental study, the corrosion cell consists of the following:

- **Anode**: The metal to be subjected to corrosion is considered as anode.
- **Cathode**: Another specimen extracted from same parent material is used as cathode
- **Electrolyte**: NaCl dissolved in distilled water is used as electrolyte. The percentage of electrolyte in water is taken as 3.5%.

For inducing corrosion, impressed current method is adopted which consists of a DC power source, a counter electrode, and an electrolyte. The positive terminal of the DC power source is connected to the anode and the negative terminal is connected to the counter electrode (cathode). The current is impressed from counter electrode to the steel specimen with the help of the electrolyte. The Fig. 4 shows the general schematic representation of electrochemical corrosion by galvanostatic method.

The system under the regulated power, supplies the constant current. The applied current can be monitored by using the digital display unit. The potential difference between electrodes (anode and cathode) is measured with respect to Standard Calomel Electrode (SCE) under two conditions such as with and without current. The current supplied between the electrodes is

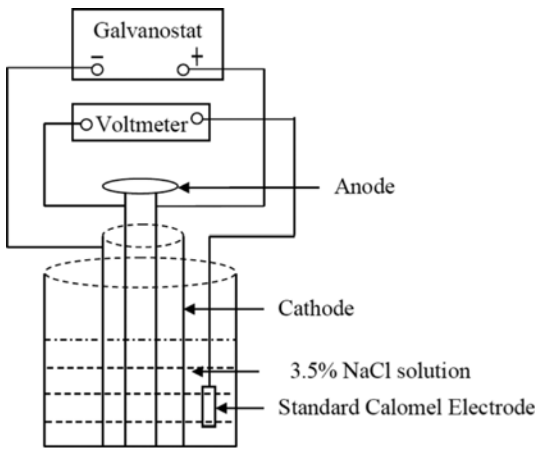

Fig. 4. Schematic Representation of Electrochemical Corrosion Test Set-up

measured using the multimeter. The rate of corrosion is found to be influenced by change in temperature and humidity. During accelerated corrosion process the temperature variations observed as 28ºC-32ºC and relative humidity variation as 47%-60%RH.

7. Experimental Investigation

In the present study galvanostatic method is adopted to corrode structural steel specimens by keeping the current as constant. The specimens are considered to be exposed to marine atmosphere. A total of, three angle and three hollow steel tubular specimens were designed and tested. Four coupon specimens from angle members and seven coupon specimens from tubular members were extracted and tested.

Coupon specimens were extracted from the parent specimens; they were machined in accordance with the ASTM E8M specifications. The coupons extracted from angle specimens were 200 mm long with a mid-gauge length of 50 mm. The coupons extracted from tubular sections were 250 mm long with a mid-gauge length of 60 mm. The coupon specimens extracted from angle sections of 50 × 50 × 6 mm were named as C-1, C-2, C-3 and C-4 and those extracted from tubular sections of 80NB (medium) were named as TUC-1, TC-2, TC-3, TC-4, TC-5, TC-6, and TC-7. The dimensional details of coupons extracted and tested were shown in Fig. 5.

The coupon specimen C-1 and TC-2 were corroded by alternate wetting and drying process, towards this the specimens were immersed in 3.5% NaCl solution (artificial sea-water) and dried in natural environment (i.e., dried by exposing to direct sunlight) alternatively and continued for a period of 30 days. Specimens C-2, C-3, TC-3, TC-4, TC-5, TC-6 and TC-7 were corroded by electro-chemical process. The accelerated corrosion process was carried out by keeping the test specimen as anode and a mild steel specimen of slightly large area of exposure (80 mm × 75 mm) was considered as cathode. Calomel electrode was used to measure the initial and final potential under zero current condition. C-4 and TUC-1 were uncorrode. The test set-up to induce various level of corrosion in coupons were shown in Fig. 6.

In all coupon test set-up, the cathode and anode was kept at a distance 45 mm apart in corrosion chamber. Variations between anode and cathode potential in milli-volts (mV) were measured using high impedance multimeter. Half-cell potential variation between anode and cathode with respect to reference calomel electrode was measured at every three hours. The weight of corroded specimen was measured at the end of every day and weight loss percentage was calculated. Each member was weighed before being corroded. During accelerated corrosion and at the end, the member was cleaned from corrosion with a brush and weighed. It was observed that, specimen C-2 was

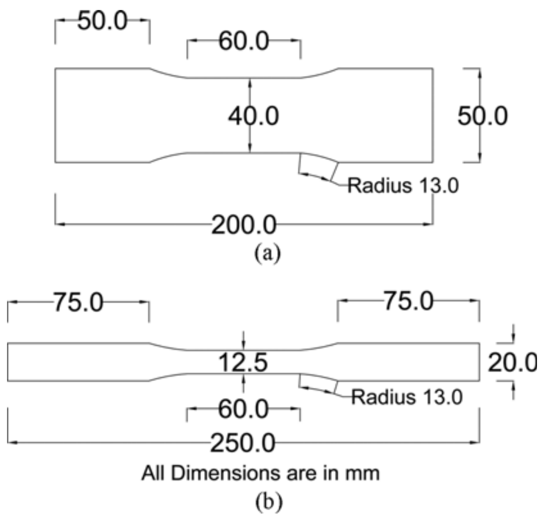

Fig. 5. Dimensional Details of Coupon Specimen Extracted: (a) Angle, (b) Tubes

Fig. 6. Experimental Set-up to Corrode the Coupons

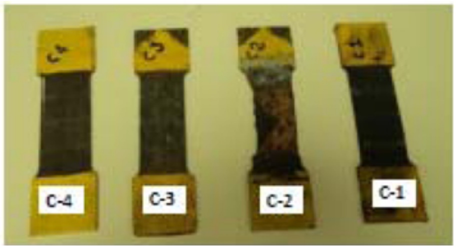

Fig. 7. Corroded Coupons Extracted from Angles

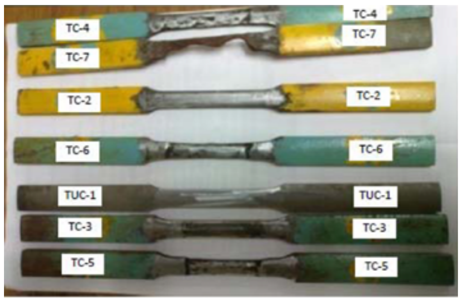

Fig. 8. Experimentally Corroded Coupons Extracted from Tubes

Fig. 9. Tensile Test Setup

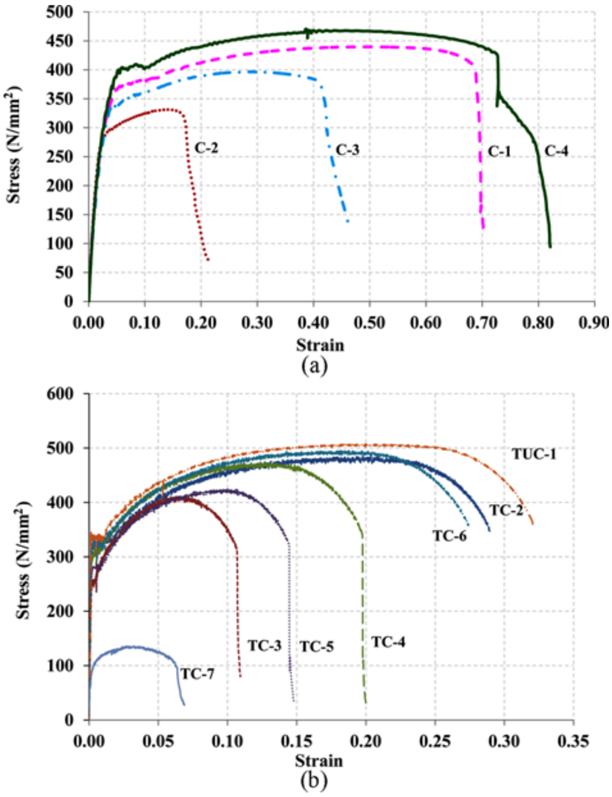

Fig. 10. (a) Stress vs Strain of Coupons Extracted from Angle Members, (b) Stress vs Strain Behaviour of Tested Coupons Extracted from Tubular Members

corroded for 30.97% weight loss and C-3 was corroded for 8.28% weight loss. Specimen C-1 corroded naturally and has under gone a weight loss of 5.75%. The observed width, thickness and weight loss and level of corrosion damage during experiments for coupons were summarized in Table 1.

The tensile tests were conducted on coupons to have an adequate understanding on material characteristics. The strain gauges were pasted to the specimens and experiments were carried out in order to find the stress vs strain behaviour. The corroded coupons from angle and tubular sections were shown in Figs. 7 and 8. In this study, the level of corrosion was determined by the ratio of the mass of the steel specimen altered during corrosion to the mass of the intact steel member. Stresses were obtained by dividing the applied load by the cross-sectional area at the average thickness along the gauge length. Ultrasonic thickness gauges and digimatic calipers were used to measure the thickness of specimens before and after corrosion. The tensile test set-up was shown in Fig. 9. The loads and strains were automatically recorded by an electronic data acquisition system. Coupon test results were presented Fig. 10(a) and Fig. 10(b) in terms of stress vs strain.

7.1 Structural Behaviour of Corroded Angle and Tubular Compression Members

The angle and tubular specimens, considered for the study,

Table 1. Specimen Details and Quantitative Measure of Level of Corrosion of Coupons

Sl No	Specimen ID	Method	C_i (mm)	C_f (mm)	μ_t	C_{wi} (mm)	C_{wf} (mm)	μ_w	w(%)	F_y (N/mm²)	F_u (N/mm²)
1	C-1	Alternate wetting and drying	4.20	4.00	0.95, mild	40.00	39.82	0.99, mild	5.75, mild	366.77	438.57
2	C-2	Electrochemical	4.10	2.89	0.70, moderate	40.00	33.39	0.83, mild	30.97, moderate	287.61	330.90
3	C-3	Electrochemical	4.20	4.00	0.95, mild	40.00	38.65	0.97, mild	8.28, mild	339.42	396.37
4	C-4	Uncorroded	4.29	4.29	1.00, uncorroded	40.00	40.00	-	-	399.93	465.76
5	TUC-1	Uncorroded	5.00	5.00	1.00, uncorroded	12.50	12.50	-	-	336.50	506.16
6	TC-2	Alternate wetting and drying	5.00	4.84	0.97, mild	12.50	10.20	0.82, mild	2.21, mild	326.21	485.19
7	TC-3	Electrochemical	5.12	3.94	0.77, mild	12.50	10.12	0.81, mild	6.74, mild	254.11	409.18
8	TC-4	Electrochemical	5.09	4.23	0.83, mild	12.50	11.10	0.89, mild	4.26, mild	310.24	468.58
9	TC-5	Electrochemical	5.14	4.00	0.78, mild	12.50	11.10	0.89, mild	2.66, mild	274.06	423.23
10	TC-6	Electrochemical	5.16	5.13	0.99, mild	12.50	12.12	0.97, mild	0.60	322.56	491.28
11	TC-7	Electrochemical	5.00	3.09	0.62, moderate	12.50	3.92	0.31, severe	10.11, mild	74.28	135.93

Note: C_i: Initial average thickness of coupon(mm), C_f: Final average thickness of coupon(mm), C_{wi}: initial average width (mm), C_{wf}: final average width (mm), μ_t: Average thickness ratio and level of corrosion damage, μ_w: Average width ratio and level of corrosion damage, w:weight loss in percentage and level of corrosion damage, F_y: Yield Stress, F_u: Maximum stress.

(a) (b)

Fig. 11. The Test Set-up to Induce Corrosion: (a) Angle, (b) Tube

(a) (b)

Fig. 12. Compression Test: (a) Angle, (b) Tube

were part of leg members of microwave tower. These specimens were artificially corroded for different percentages of weight loss by galvanostatic method. The test set-up to induce corrosion were shown in Fig. 11(a) and Fig. 11(b) for angle and tubular specimens respectively. Each specimen consists of flange plates at its end. All angle specimens initially were [as per IS:808-1989] with b/t ratio as 8.33 and slenderness ratio of 112.36. The angle specimens were named as AC-1, AC-2 and AC-3. The specimen AC-1 was considered as uncorroded and AC-2 and AC-3 were electrochemically corroded. The specimen AC-2 was uniformly corroded for middle 200 mm height for a weight loss of 10% and AC-3 was uniformly corroded at bottom 400 mm height (immediately above the bottom base plate) for a weight loss of 10%.

The three hollow steel tubular specimens [as per IS: 1161-1998] initially were with d/t ratio as 16.74. The accelerated corrosion process for tubular specimens were carried out by keeping the test specimen as anode and steel tube of 300 mm diameter as cathode. They were placed in the electrolyte of 3.5% NaCl. The pH of the electrolyte was found to be 8.4. E_{corr} (Electrochemical potential) of anode and cathode were monitored for every 2 hours. The specimen STC-2 has been corroded to achieve a weight loss of 740 gms. The specimen STC-3 has been corroded to achieve a weight loss of 1640 gms. For both the specimens, due to uniform corrosion there was a reduction in thickness of the specimens and the actual thickness after corrosion were measured by using ultrasonic thickness gauge. In order to take the average thickness a grid was formed in the corroded portion and a total 32 gauge points were considered for the measurements and the average thickness was calculated. The observed details of the angle and tubular specimens before and after corrosion were summarized in Table 2. The compression test set-up for angle and tubular members were shown in Fig. 12(a) and Fig. 12(b) respectively and slenderness ratio as 50.33. Each specimen consists of a hollow steel tube with flange plates at its end. All the specimens were 1500 mm long, 5.31 mm thick with a diameter of 88.9 mm. The flange plates were 16 mm thick with a diameter of 200 mm. The specimens were named as STUC-1, STC-2 and STC-3. Of these, STUC-1 (Steel Tube UnCorroded) indicates the uncorroded specimen. The other two specimens, STC-2 and STC-3 (Steel Tube Corroded) indicate uniformly corroded specimens with 20% and 40% of weight loss (i.e., % loss from initial theoretical weight of bottom 400 mm).

For all corroded specimens, compression experiments were carried out on a servo-controlled UTM of 250 Tonnes. The strains and deflections were measured at significant points by using strain gauges and digital deflectometers. The load vs deflection behaviour of corroded and uncorroded angle and

Table 2. Specimen Details of Angle and Hollow Tubular Sections

Details	L(m)	Corrosion induced method	W_i (kg)	W_f (kg)	W_L (%)	TL_i (mm)	TL_j (mm)	TF_i (mm)	TF_j (mm)
AC-1	1.10	Uncorroded	-	-	-	5.65	5.91	5.65	5.91
AC-2	1.10	Electrochemical (200 mm at middle height)	0.89	0.80	10%	6.00	6.00	5.64	5.64
AC-3	1.10	Electrochemical (400 mm immediately above bottom base plate)	1.78	1.60	10%	5.10	4.00	4.92	3.82
STUC-1	1.50	Uncorroded	-	-	-	5.31	-	5.31	-
STC-2	1.50	Electrochemical (400 mm immediately above bottom base plate)	3.93	3.14	20%	5.31	-	5.01	-
STC-3	1.50	Electrochemical (400 mm immediately above bottom base plate)	3.93	2.36	40%	5.31	-	4.02	-

L: Length of specimen, W_i: Initial weight, Wf: Final Weight, W_L: Weight loss in percentage, TL_i: Initial Average Thickness Leg1(mm)/hollow tube(mm), TL_j: Initial Average Thickness Leg2(mm), TF_i: Final Average Thickness of corroded Leg1(mm)/corroded hollow tube, TF_j: Final Average Thickness of corroded Leg2(mm)

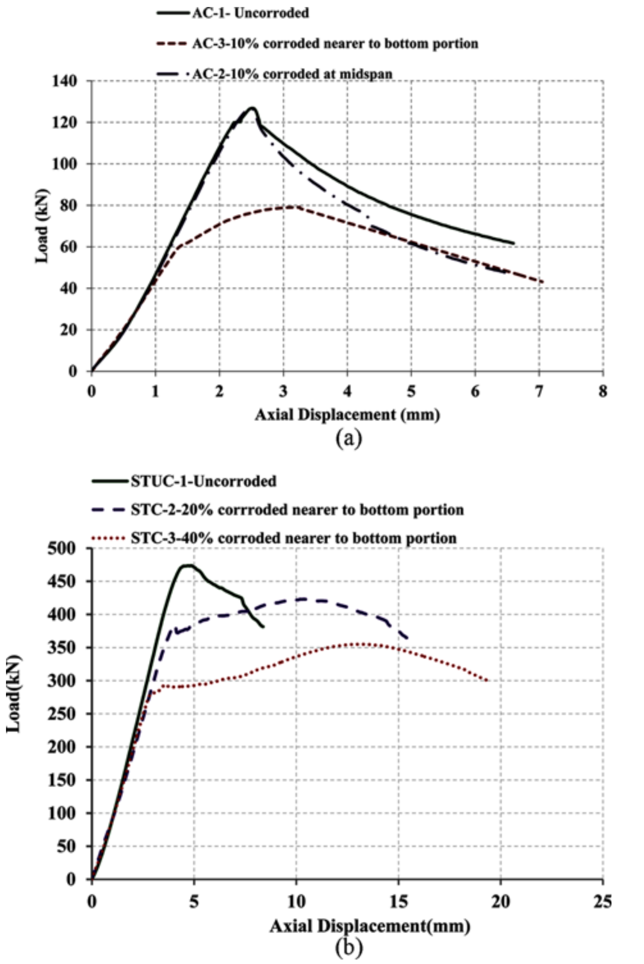

Fig. 13. Load vs Axial Deflection Behaviour: (a) Angle Sections, (b) Tubular Sections

tubular specimens were presented in Fig. 13(a) and Fig. 13(b) respecively.

8. Discussions

This study presents the various forms of corrosion and models adopted for quantitatively measuring the intensity/level of damage due to corrosion. The various parameters affecting the corrosion rate were the time of wetting, the frequency and duration of drying out periods, relative humidity, temperature and its variation, and the composition of the atmosphere. Quantitative methods were presented to identify the intensity level of corrosion damage as mild, moderate and severe. Experimental investigations carried out on corroded structural elements show that the loss of thickness of the cross-section due to corrosion attack leads to a smaller resistance area, producing a decreasing effect in the structural performance in terms of strength.

The yield strength of each corroded coupon specimens were compared with uncorroded counterparts. From the tensile test on coupons extracted from angle members, it was observed that for a corrosion damage level of mild, 15% reduction in yield and ultimate strength with18% elongation for a weight loss of 8.28% (C-3). Whereas, for a corrosion damage level of moderate it was 28% reduction in yield and ultimate strength for electrochemically corroded specimen of weight loss 30.97% (C-2). The percentage elongation for C-2 was found to be 7.7%. However, in the case of specimen which has been corroded by alternatively drying and wetting (30 days) to a weight loss of 5.75% (C-1), the observed strength reduction at yield and ultimate were 8.3% and 5.84% respectively. So further from the studies, it is evident that significant reduction in yield stress and strain for C-2 and C-3, compared to C-1 as referred in Fig. 10(a).

From the tensile test on coupons extracted from the tubular members corroded to various percentage, it was observed that 3% reduction in yield strength and 4% reduction in ultimate strength for a weight loss of 2.21% (TC-2) . The percentage elongation for TC-2 was found to be 24%. Whereas, it is 78% reduction in yield strength and 73% reduction in ultimate strength for a weight loss of 10.11% (TC-7), Fig. 10(b) and percentage elongation was found to be 5%. However, in the case of specimen which has been corroded to a weight loss of 6.74% (TC-3), the observed yield strength reduction was 7%. A significant reduction in yield stress and strain and percentage elongation in all corroded specimens except the uncorroded were observed even though the category of corrosion found to be similar except the specimen TC-7. Accordingly it is concluded that level/category of corrosion (based on thickness and width ratio along with weight percentage) and strength studies need to be explored for better quantification and residual strength prediction of corroded structural steel elements. The apparent microstructural crack formation due to corrosion may be resulted in reduction in yield strength and failure strain. Microstructural changes and chemical composition changes due to corrosion need to be addressed, which is the limitation of present study.

The compression test on angle specimens confirms that, the corrosion has drastic effect on the structural behaviour according to the location/region of corrosion in a structural member with the level of corrosion. For both specimens AC-2 and AC-3 the level of corrosion is within 10%, it can be considered as mild. Among the three specimens studied 10% corroded specimen from the bottom 400 mm shows a strength reduction of 37.9%

Table 3. Comparison of Design Load with Experiments

Sl No	IS: 800-2007		Experiment
	P_d (kN)	P_u (kN)	P_u (kN)
AC-1	102.09	126.56	125.58
AC-2			123.61
AC-3			77.99
STUC-1	331.30	438.00	470.65
STC-2			422.93
STC-3			354.82

Note: P_d: Design compressive strength, P_u: Ultimate load carrying capacity (based on coupon test, IS: 800-2007) and lateral deflection reduced by 8.157%. The distorsional buckling occured towards the bottom leg members observed to be acted as an additional stiffener till the complete failure of AC-3 takes place, Fig. 13(a). It was noticed that, the two leg members of AC-3 has undergone unequal corrosion. The 10% corroded specimen at the mid-span (AC-2) shows a similar behaviour closer to the uncorroded specimen, with a strength reduction of 1.6%. From the experiments, it is concluded that mild level of corrosion does not significantly reduce the strength, in the case of uniformly corroded members. The failure of AC-3 in addition to corrosion effect gives an insight that reduction in effective area (2-23%), moment of inertia (0-10%) and slenderness ratio varied, all these might have resulted in reduction in ultimate load carrying capacity.

From the experiments on corroded tubular sections, it was observed that uncorroded specimen had an ultimate load of 470.65 kN and the corresponding axial deflection was 4.363 mm. The ultimate load and corresponding deflection of the specimen STC-2 was 422.93 kN and 10.20 mm. The corresponding values for specimen STC-3 were 354.82 kN and 13.09 mm. The reduction in ultimate loads of both STC-2 and STC-3 was about 10% and 25%. Also, the deflection at ultimate load of both specimens differs by a multiplying factor of about 2.34 and 3.0 respectively. The failure of STC-2 and STC-3 in addition to corrosion effect gives an insight that reduction in effective area (5-23%), moment of inertia (4-20%) and slenderness ratio (0-1%) resulted in reduction in ultimate load carrying capacity. Comparisons of design load with experimental results were given in Table 3.

9. Conclusions

This paper reviews types and forms of corrosion and various corrosion models used to describe the depth of corrosion. The rate of corrosion is an area specific characteristics which varies with marine, industrial, urban and rural environments. The practicing engineers are suggested to consider durability factors based on corrosiveness (i.e., corrosion map) of the region along with judicious selection of materials or coatings or corrosion controlling methods for safe structures. The qualitative measures of corrosion is expressed with codal approaches and quantitative measures of corrosion is carried out by measuring the level of corrosion as mild, moderate and severe and strength aspects were arrived by conducting tension test on corroded mild steel coupons and compression test on angle and tubular sections. From the coupon test on eleven specimens, it is concluded that corrosion results in reduction in metal thickness followed by weight loss and reduction in mechanical strength. The drastic reductions in mechanical properties (i.e., yield and ultimate strengths and failure strain) were observed for severely corroded coupon specimens. The compression test on angle and tubular specimens reveals that, the location and loss of metal due to corrosion has significant effect on the structural behaviour. The irregularity due to corrosion results in stress concentration followed with immediate failure. The method presented to quantify the level of corrosion damage (mild, moderate and severe) in terms of thickness and weight loss can be used as a guideline for practicing engineers to predict the behavior of corroded structures. The quantified corrosion loss of angle members in terms of average thickness ratio and weight loss reveals that mild level of corrosion does not significantly reduce the strength of structural members. Though the severity of structural failure very much depend on the stress concentration effect, which has to be further investigated for corroded members. Indeed, a systematic approach with extensive experimental studies were required to categorize and predict the level of corrosion damage and stress concentration effect and thereby the remaining capacity prediction. The geometric properties that govern structural behavior such as area, moment of inertia, and the section moduli were reduced due to corrosion.

For steel angle sections of same percentage of corrosion with different locations, it is found that ultimate load carrying capacity reduced by 1.5%-37.91%. For corroded hollow tubular structural members with varying percentage of corrosion (20%-40%), it is found that ultimate load carrying capacity reduced by 10%.-25%. From the studies it is also concluded that unevenness, concentration and location of corrosion also is a serious issue which need to be addressed and explored with further research activities.

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