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Experimental studies on behaviour of steel tubular compression members subjected to accelerated corrosion

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ABSTRACT

The performance of steel structural components is strongly influenced by the damage due to atmospheric corrosion, whose control is a key aspect for design and maintenance of both new and existing structures. In extreme situations, it can lead to catastrophic failure of structural components. This paper presents experimental studies on corroded compression members under stressed and unstressed condition. The study is conducted by varying the corrosion rate of specimens under uniform corrosion. Experimental studies are carried out on corroded members with different percentage in thickness and weight loss. The failure modes and the ultimate load carrying capacity of the specimen are determined numerically and validated with experimental results. A significant reduction in load carrying capacity is observed for all corroded specimens compared to uncorroded control specimen. The failure modes and load carrying capacity of corroded members for uniform, corrosion are discussed. In the light of experimental results, it is inferred that the failure of the members is due to localized axisymmetric imperfections imparted to the tubular members due to corrosion.

Keywords: corrosion, compression member, uniform corrosion, pitting corrosion, imperfections

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. 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. Rahgozar (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. 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. Raffaele et al (2010) presented the modelling approaches of atmospheric corrosion damage of metal structures. Based on the studies conducted by Damgaard et al (2010) it was concluded that corrosion can significantly reduce the service lives/ life of weathering steel girders. This paper presents the experimental studies conducted on tubular compression members subjected to accelerated corrosion of various amount locally. The failure modes and the ultimate load carrying capacity of the specimen are determined numerically and validated with experimental results.

EXPERIMENTAL SET-UP

Unstressed corrosion set-up

Among the accelerated corrosion techniques, galvano static method is adopted to corrode the desired regions of the tubular compression members. In galvanostatic method, constant current from a DC (Direct current) source is applied, till the required amount of corrosion is achieved. Fig.1 shows the experimental set –up to corrode the specimen under unstressed condition.

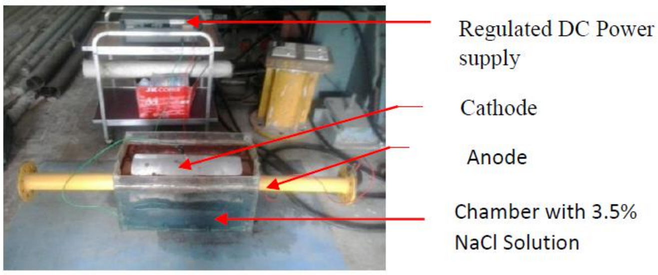

Figure1 Experimental set –up to corrode the tubular compression members under unstressed condition

Stressed corrosion set-up

In order to achieve the stressed corrosion condition, a load under service condition is applied to the joint component with the help of a reaction frame. After applying the required compressive load, the load is retained by tightening the check nuts of the upper arm of the specially fabricated load retaining frame. The corrosion chamber is fixed to the region scheduled to corrode and galvanic corrosion is carried out as per Faraday's law to achieve target % of weight loss due to corrosion i.e is 20%. Fig.2(a),(b) and (c) show the experimental set-up to corrode under stressed condition.

COMPRESSION TEST ON TUBULAR SECTIONS

The details of tubular members considered for experimental study are given in Table 1.The corrosion has been induced by two methods i.e 1) galvanostatic method and 2) alternate wetting and drying process. The uncorroded specimen is named as STJ-1 and STJ-2, corroded and unstressed specimens as STJUSC-4,STJUSC-5,STJUSNC-6 and STJUSNC-7 and STJC-5, and stressed and corroded specimen are STJSC-1, STJSC-3 and STJSC-8. The specimens are subjected to static axial compression under displacement control method by a hydraulically operated UTM of 2500kN capacity.

(a) Tubular section under service load (b) Set-up to corrode (c) After corrosion

Figure 2 Experimental set-up to corrode under stressed condition

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Table 1. Details of tubular specimens

Specimen identification	Type of tubes used	Initial thickness (mm)	Final thickness (mm)	Percentage reduction in thickness
STJ-1	65NB	3.90	3.90	0
	80NB	3.37	3.37	0
STJ-2	65NB	4.00	4.00	0
	80NB	3.30	3.30	0
STJSC-1	65NB	4.10	3.14	23.41
	80NB	3.50	3.10	11.43
STJUSC-2	65NB	3.90	3.35	14.10
	80NB	3.67	2.90	20.98
STJSC-3	65NB	4.10	3.58	12.68
	80NB	3.50	3.07	12.28
STJUSC-4	65NB	3.96	3.59	9.30
	80NB	3.33	3.03	9.00
STJUSC-5	65NB	4.00	3.67	8.25
	80NB	3.37	3.23	4.15
STJUSNC-6	65NB	4.10	3.86	5.85
	80NB	3.50	3.32	5.14
STJUSNC-7	65NB	4.00	3.89	2.75
	80NB	3.40	3.37	0.8
STJSC-8	65NB	4.12	3.87	6.07
	80NB	3.45	3.34	3.19

Note: STJ: Control Specimen stepped tubular joint, STJUSC: Stepped tubular joint unstressed and corroded, STJSC: Stepped tubular joint stressed and corroded, STJUSC: Stepped tubular joint unstressed and naturally corroded

In order to determine the properties of the steel, three tensile coupons are along the length of the sections from the tubular steel members and tested in accordance with the standard IS: 2062-2006. The average material properties observed through the tensile test are listed in Table 2. The test results are presented in the form of a stress vs. strain plot as shown in Fig.3

Table 2 Mechanical properties of steel

t (mm)	F_y (MPa)	F_u(MPa)	E_s (MPa)	Δ
5.31	336	502	$2.4x10^5$	0.32

Note: t-thickness of the coupon; F_y-yield strength; F_u-ultimate tensile strength; E_s-Young's modulus; δ-elongation ratio.

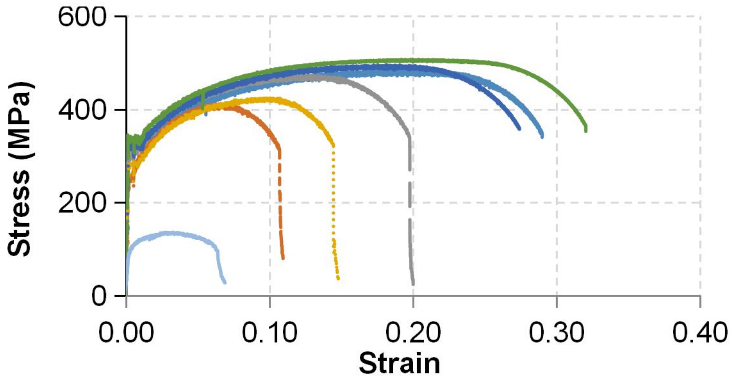

Figure 3 Stress vs. strain behaviour of corrosion induced and uncorroded steel samples extracted from tubular members.

The experimental set-up for the compression test is shown in Fig. 4. The end plate is fixed to the test frame of compression testing machine. The specimens are subjected to static axial compression under load, controlled by a hydraulically operated compression testing machine. The specimens are placed between the two heads in such a way that the centre of the flange plates of the specimen coincided with the centre of the bottom platform and the top head of the compression testing machine. Loading rate adopted for compression test is 0.5mm/minute. In order to measure the lateral deflection, two LVDTs are placed at mid-height of the corroded region of the specimen. Four strain gauges are placed in the affected regions, i.e. two gauges along the direction of load perpendicular to each other, while the other two in horizontal direction. At each of the load stages, deflection and strain measurements are recorded automatically by using a data logger connected to a computer. The tested specimens are shown in Fig.5. The axial load vs axial displacement plot is shown in Fig.6

Figure 4 Compression test on tubular member

Figure 5 Experimentally observed deformed profile of tested members

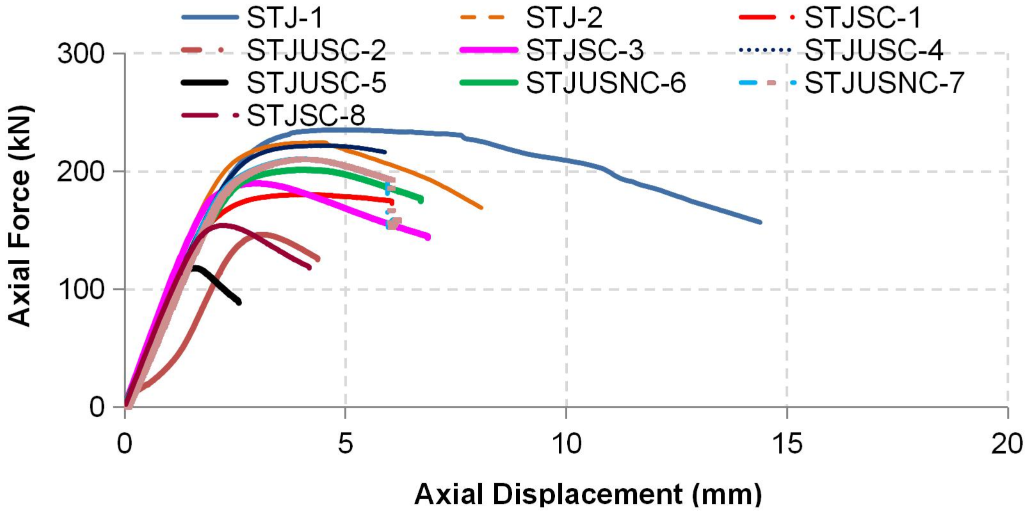

Figure 6 Comparison of axial load vs Axial deflection

NUMERICAL INVESTIGATION OF CORRODED STEEL TUBULAR SECTIONS

In the present study, numerical investigation is carried out on the corroded steel tubular sections by using the ABAQUS general-purpose finite element analysis software. A methodology is developed to simulate different forms of corrosion namely uniform, pitting and combined i.e uniform and pitting, by varying the percentage of corrosion from 10-50%. The observed strength reduction of corroded tubular leg members for varying rate of corrosion is discussed.

ABAQUS software [5] is used for the numerical simulation of behaviour of corroded steel tubular compression member (80NB and 65NB, heavy) using STATIC, RIKS procedure to account for the non-linear effects. The incremental plasticity model is considered and the stress strain values corresponding to the tensile coupon test are considered. Hence the material is modelled as elastic-perfectly plastic material. The model is discretised using the element C3D8R i.e. 8-noded linear brick elements. It is found that the solution convergences to a unique value by using the global seed size of 50.
Simulation of boundary conditions

To simulate the experimental set up in finite element analysis (FEA) the cross-section centroid of the top end of the column was defined as a reference point for creating constraint. A kinematic coupling constraint was defined to constrain the motion of the top surface to that of the single reference point, where all three translational and rotational degrees of freedom are specified. In this case, all coupling nodes on the top surface follow the rigid body motion of the reference point. All translational degrees of freedom of the reference point and also the nodes in the top surface are fixed, except the vertical displacement. The bottom of the member is fixed by restraining all degrees of freedom. The Loading is applied at the reference point to simulate the axial loading condition. The bolts are tied to the flanges using tie constraints hence it will act as a rigid connection.

Simulation of corrosion effect

Uniform corrosion

The uniform corrosion effect is simulated by equal removal of thickness from the region of interest of the member. Since in tubular sections, the outer surface is most susceptible area of corrosion. A uniform corrosion effect is modelled by reducing the thickness by 10-50% of original thickness, for a region of 235mm from either side of the mid region of the member excluding the flanges. The Fig. 7 shows the modelling of uniform corrosion effect.

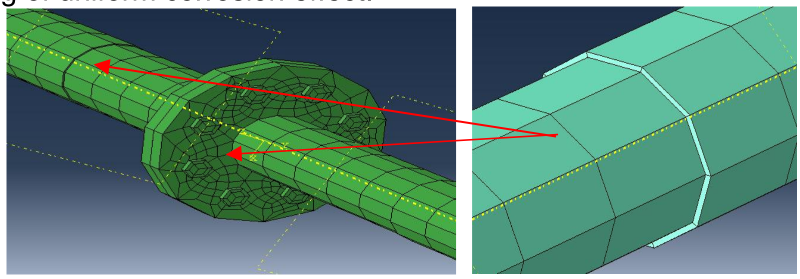

Figure 7 simulation of uniform corrosion effect

Pitting corrosion

In pitting corrosion, surface of the corroded member is characterised by the formation of smaller pits resulting in the damage of the material property. Hence in the present study instead of modelling the pit holes in the geometry, the pitting corrosion is numerically modelled by reducing thickness as 1.9mm in the pitted region of interest, as shown in Fig.8. The thickness is removed from the randomly selected mesh elements in the centre portion of the member. The percentage of pit corrosion is assigned by number of pitted elements to the total number of elements which is varied from 0 – 50%. The degree of pitting is defined as given in equ.1

$$\text{Degree of pitting} = \frac{\text{Number of elements deleted}}{\text{Total number of elements on the surface}} \quad (1)$$

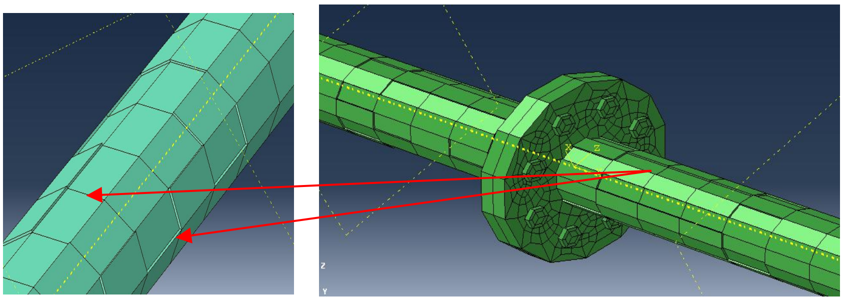

Figure 8 simulation of pitting corrosion effect

Uniform and pitting corrosion

Simulation of combined form of corrosion is carried out for a region of 235mm from either side of the mid region of the member. Initially uniform corrosion is simulated by incorporating the thickness reduction of 20% followed by the pitting corrosion effect is induced for 10 to 50% of the pit depth upto 30% of the original thickness. Fig. 9 shows simulation of combined effect of uniform and pitting corrosion.

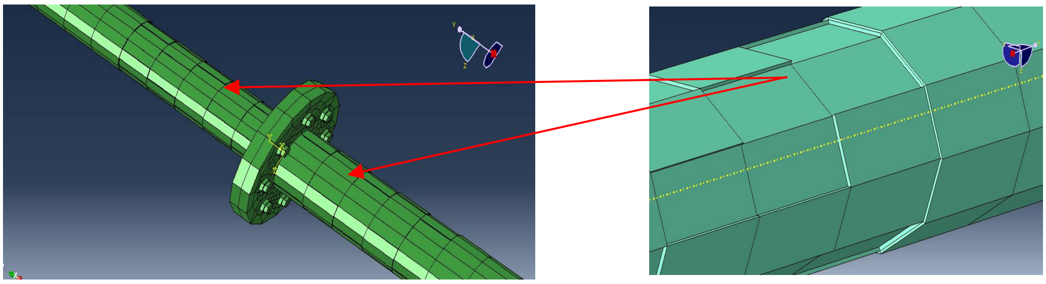

Figure 9 simulation of combined effect of uniform and pitting corrosion effect

RESULTS AND DISCUSSION

Load bearing capacity of tubular compression members

From the results, it is observed that the load carrying capacity of corroded tubular members decreases significantly for both uniform and pitting corrosion. The mode of failure is buckling which occurs at the corroded region due to the reduction in thickness, the geometric properties such as area, moment of inertia, radius of gyration, section modulus.

Validation of experimental results with FEM

The experimental results are compared with FEA results and found that both the results agrees well as given in Table .3. Table 4 gives comparison of strength loss in proportion to thickness and weight loss.

Table 3 Comparison of experimental results with FEA for columns with joints

Specimen identification	Reduction in thickness	Experiment			
		P_u test (kN)	% Remaining capacity	P_{uFEM} (kN)	% Remaining capacity
STJ-1	0%	234.75	100	240.27	100.00
STJC-2	40% Uniform	145.42	38.05	158.33	65.89
STJC-3	10% Uniform	220.87	5.91	231.93	98.40
STJC-4	30% Combined	114.37	51.28	121.24	50.46

Note: P_u: Ultimate load, PuFEM: Ultimate load observed in FEM

Table 4 Comparison of remaining strength in proportion with measurable quantities such as thickness and weight

Specimen identification	Experiment			
	P_u(kN)	% Remaining Capacity	% reduction in thickness	% reduction in weight
STJ-1	234.75	100	0	0
STJ-2	223.55	4.77		
STJSC-1	179.45	23.56	23.41	21
STJUSC-2	145.42	38.05	20.98	17
STJSC-3	189.42	19.31	12.68	12
STJUSC-4	220.87	5.91	9.30	9
STJUSC-5	114.37	51.28	8.25	6
STJUSNC-6	200.82	14.45	5.85	5
STJUSNC-7	209.54	10.74	2.75	2
STJSC-8	152.44	35.06	6.07	4

CONCLUSIONS

This paper presents experimental and numerical studies of corrosion effect on steel tubular compression members, generally used in transmission towers. The drastic reductions in mechanical properties (i.e., yield and ultimate strengths and failure strain) are observed for severely corroded coupon specimens. The study is conducted by varying the level and type of corrosion. The level of corrosion has been varied from 10 to 50%. The various types of corrosion effect studied are, uniform, pitting and combined effect of uniform and pitting. The remaining strength capacity of corroded tubular compression members for varying rate of uniform and pitting corrosion was presented and validated with experimental results. It is clear that the load bearing capacity goes on reducing as the percentage of corrosion increases. Buckling is observed at the region of corrosion. This section is considered as the critical region of the tubular compression members studied. The stress concentration is more in the regions where the pits are available. Hence there is the possibility of sudden failure. Stressed and unstressed corroded specimens behaviour and its effect on buckling of members under axial load also studied. From the experimental and numerical studies combined corrosion is more dangerous than the other forms of corrosion studied. The drastic reduction in strength may be further justified with localised axisymmetric imperfections due to corrosion along with material degradation.

Acknowledgement

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