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Numerical Study on Combined Effect of Uniform and Pitting Corrosion on Steel Tubular Members

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ABSTRACT : Steel tubular compression members are widely used in different steel structures and can be corroded by the different environmental circumstances which may lead to reduction in its remaining strength capacity. The present study is focused on assessing the remaining strength of the tubular compression member which is subjected to the combination of uniform and pitting corrosion. A three hollow steel tubular sections are fabricated and corroded by galvanostatic method. The tensile tests were carried out for the coupons extracted from the parent specimens which are corroded in various levels of corrosion and the obtained stress strain characteristics are incorporated in the numerical model. The combination of uniform and pitting corrosion is simulated in center portion of the tubular member by varying percentage of 10-40%. The result shows that a drastic reduction in remaining strength capacity of the tubular compression members with increase in rate of corrosion, i.e. uniform and pitting corrosion together.

KEYWORDS: uniform corrosion, pitting corrosion, tubular sections, remaining strength.

I. INTRODUCTION

Corrosion in steel structures appears to be the most important degradation mechanism in determining the remaining life of these structures. The consequences of corrosion are many and varied. The consideration of effects on safe, reliable and efficient operation of structures is better than simply losing the volume of metal. Various kinds of failures and the need of expensive replacements may occur even though the amount of metal destroyed is quite small. Corrosion damage leads not only to a decrease in the service life of the structure, but also to a lowering of the characteristics of the static strength and, consequently, to an increase in the probability of structural failure, causing severe disastrous and hazardous injuries to the mankind. Therefore, understanding of the influence of damage due to corrosion on the remaining strength capacity is a necessary task for the maintenance management of steel structures. It has been proved that the corrosion showed a disastrous role in the collapses such as Silver Bridge collapse in 1967, Mianus River Bridge in 1983 and Mississippi River Bridge collapse in 2007 [8]. Those collapses indicated the supreme importance of attention to the condition of older bridges, leading to intensified inspection protocols and numerous eventual retrofits or replacements. So, there is a need of quick and careful estimation method which can be used to make trustworthy decisions regarding the cost and safety.

During the past few decades, several experimental studies and detailed investigations of corroded surfaces were done by some researchers in order to adopt the methods of estimating the remaining strength capacity of corroded steel members. Athanasios Kolios et al. 2014 [4] assessed the stress concentrating effects of pitting corrosion and it's various randomized characteristics on the stress concentration factor through numerical simulation. Ahmmad et al. 2010 [6] proposed a empirical formulae to estimate the reduction in deformability and energy absorption



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capacity due to pitting corrosion and general corrosion under uniaxial tension. T. Kaita and J.M.R.S. Appuhamy et al. 2011 [2] investigated the corrosion influence on Annai River Bridge. L.D. Lutes et al. 2001 [3] analysed the relationship between the compressive strength and loss of wall thickness due to corrosion with the consideration of Euler global buckling, inelastic global buckling. Damgaard et al. 2010 [5] examined the effects of corrosion products and pitting on weathering steel plate thickness measurements and they concluded that corrosion can significantly reduce the service lives of weathering steel girders. Therefore, it is very important to evaluate the remaining strength of existing structures for proper maintenance of infrastructures and to ensure their safety. This paper aims to study the effect of combined uniform and pitting corrosion on the remaining strength capacity of the tubular compression member through a numerical analysis.

II. EXPERIMENTAL STUDY

In the present study, the galvanostatic method is adopted to corrode the tubular specimens. A total of three hollow steel tubular specimens were fabricated and corroded. Seven coupon specimens from tubular members were extracted and corroded. Coupon specimens were extracted from the parent specimens; they were machined in accordance with the ASTM E8M specifications. The Experimental Set-up to Corrode the Coupons extracted from tubular members is shown in Fig. (b) [1].The coupons extracted from tubular sections were 250 mm long with a midgauge length of 60 mm. The coupon specimens 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 alternate wetting and drying process is adopted to corrode the coupon specimen TC-2 in order to simulate the natural corrosion. 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 to simulate the corrosion to marine atmosphere. Specimens 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 × 75mm) was considered as cathode. The initial and final potential under zero current condition was measured by Calomel electrode.



(a)



(b)



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Fig.1 (a) Experimental setup to corrode the coupons (b) Corroded Coupons Extracted from Tubes (c) Tensile test-setup (d) Stress strain curve obtained from the tested coupons

The tensile tests were conducted on coupon specimens to have an adequate understanding on stress-strain characteristics of the material. The strain gauges were pasted to the specimens and experiments were carried out in order to obtain the stress vs. strain behaviour. The corroded coupons from tubular sections were shown in Fig.1(b). The thicknesses of specimens before and after corrosion were measured by Ultrasonic thickness gauges and digimatic calipers. The tensile test set-up is shown in Fig. 1(c). Each member was weighed before being corroded. The thickness and weight loss percentage was calculated. The stress and strain were automatically recorded by an electronic- data acquisition system. Stress strain obtained from the coupon tests are represented in Fig.1(d). The Specimen Details and Quantitative Measure of Level of Corrosion of Coupons are presented in Table 1.

Table.1. S	pecimen	Details and	Ouantitative	Measure of	of Level	of Corr	osion of	f Cour	oons
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SI. NO	Specimen ID	Method	C _i (mm)	C _f (mm)	μι	C _{wi} (mm)	C _{wf} (mm)	$\mu_{\rm w}$	W%	Fy (N/mm ²)	Fu (N/mm ²)
1	Tuc-1	Uncorroded	5.00	5.00	1.00,uncorroded	12.50	12.50	-	-	336.50	506.16
2	Tc-2	Alternate wetting and drying	5.00	4.84	0.97, mild	12.50	10.20	0.82	2.21, mild	326.21	485.19
3	Tc-3	Electrochemical	5.12	3.94	0.77, mild	12.50	10.12	0.81	6.74, mild	254.11	409.18
4	Tc-4	Electrochemical	5.09	4.23	0.83, mild	12.50	11.10	0.89	4.26, mild	310.24	468.58
5	Tc-5	Electrochemical	5.14	4.00	0.78, mild	12.50	11.10	0.89	2.66, mild	274.06	423.23
6	Tc-6	Electrochemical	5.16	5.13	0.99, mild	12.50	12.12	0.97	0.60	322.56	491.28
7	Tc-7	Electrochemical	5.00	3.09	0.62,moderate	12.50	3.92	0.31	10.11, mild	74.28	135.93



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Note: Ci: Initial average thickness of coupon(mm), Cf : Final average thickness of coupon(mm), Cwi : initial average width (mm), Cwf : final average width (mm), μ : 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, Fy: Yield Stress, Fu: Maximum stress.

The structural steel specimens (80NB medium) were corroded for different percentages of weight loss by galvanostatic method. Each specimen consists of flange plates at its end. The three hollow steel tubular specimens [as per IS: 1161-1998] [9] 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 immersed in the electrolyte of 3.5% NaCl solution. The pH of the electrolyte was found to be 8.4. Ecorr (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. The ultrasonic thickness gauges were used to measure the reduction in thickness of the specimens after corrosion. 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. 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 400mm). For all corroded specimens, compression tests were carried out on a servo- controlled UTM of 250 Tonnes. The strain gauges and digital deflectometers were used to measure the strains and deflections at significant points. Below figure shows that the compression experiments of uncorroded and corroded steel tubes.



Fig.2 Compression experiments (a) Compression test and failure modes of corroded steel tubes (b) Load deflection curve for uncorroded and corroded steel tubes

III. NUMERICAL STUDY

ABAQUS general purpose finite element analysis software is used for the numerical simulation of tubular member of the telecommunication towers (Fig.3). In the present study a standard tubular cross section of 80NB (medium) from IS 1161: 1998[9] is considered and it is subjected to axial compressive forces. The Buckling Analysis is performed using STATIC, RIKS procedure to account for the non-linear properties. The model created to simulate the combined form of uniform and pitting corrosion. The young's modulus and poison's ratio of the material was taken as 210x103N/mm2 and 0.3 respectively. The stress-strain values corresponding to the tensile coupon test are taken. In linear elastic bodies, the displacements are proportional to the applied loads. But in the case of buckling, even if the stress-strain relation



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remains linear, large deformations and the changing geometric configuration cause the structure to behave non-linearly. The actual behaviour can be predicted accurately only by the non-linear analysis.



Fig.3. Numerical model (a) Finite element model used (b) Failure mode of the uncorroded member

The static risks method uses the load magnitude as an additional unknown and it solves simultaneously for loads and displacements. Therefore, another quantity must be used to measure the progress of the solution. ABAQUS uses the "arc length," l, along the static equilibrium path in load-displacement space. This approach provides solutions regardless of whether the response is stable or unstable. To simulate the experimental set up in FEA the cross-section centroid of the top end of the flange plate was defined as a reference point for loading. A structural coupling constraint was defined to constrain the motion of the top surface to of that the single reference point, where all three translational and rotational degrees of freedom were specified in fig.3(a). 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 model is discretised using the element C3D8R i.e. 8-noded linear brick elements with reduced integration. Using the non-linear static Risks analysis the ultimate strength and failure mode of uncorroded model is obtained. Fig. 3 (b) shows the failure mode of uncorroded tubular member. The maximum load as obtained from the analysis is 455.55KN.

In uniform corrosion there is a uniform removal of material from the surface of the member. Since in tubular member, the outer surface is most susceptible area for corrosion. The uniform corrosion is simulated by considering the thickness reduction varying from 10-40% for depth of 500mm in the centre portion of member. The simulation of uniform corrosion in ABAQUS was shown in fig.4 (a). In pitting corrosion, surface of the corroded member is characterised by the formation of smaller pits resulting in the damage of the material property. Here the pitting corrosion is numerically modelled by reducing a thickness of 2mm in the pitted region. The simulation of pitting corrosion in ABAQUS was shown in fig.4 (b).



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(a)





Fig.4. Numeical simulation (a) simulation of uniform corrosion (b) simulation of pitting corrosion (c) simulation of combined uniform and pitting corrosion

Generally the pitting is random in nature, so 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 - 40%.

Where, % of pit corrosion = No. of pitted elements Total No. of elements

The combination of uniform and pitting corrosion is simulated by considering the thickness reduction throughout the centre portion of the member and the thickness reduction in the randomly selected mesh elements in the centre portion respectively. The simulation of combined uniform and pitting corrosion in ABAQUS was shown in fig.4. (c)



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IV. RESULTS AND DISCUSSIONS

From the results, it is observed that the load carrying capacity of corroded tubular member decreases significantly with increase in rate of corrosion. The mode of failure is buckling which occurs at the corroded region due to the reduction in in thickness, the geometric properties such as area, moment of inertia, radius of gyration, section modulus changes. It is observed that the buckling occurs at the location of corrosion and also that the stress concentration and the displacement is more in the corroded portion.

Table 2 Details of Weight loss with respect to corrosion

Increase in corrosion	Weight loss due to Uniform corrosion (%)	Weight loss due to Pitting corrosion (%)	Total weight loss (%)
0	0	0	0
10	5.69	6.31	12
20	11.82	13.27	25.09
30	18.77	21.02	39.79
40	26.60	29.70	56.30

Fig.5 Failure modes of the tubular members with (a) 10% corroded (b) 20% corroded (c) 30% corroded (d) 40% corroded

The weight loss is calculated specifically for the region considered for uniform and pitting corrosion. The weight loss



of the tubular member with respect to corrosion was tabulated in Table 2. The remaining capacity of the tubular compression member is reduced up to 57% for 40% of combined uniform and pitting corrosion. The remaining strength



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obtained for 40% of corrosion is found to be lesser than design strength of the actual member [7]. The remaining strength capacity of the tubular member with respect to increase in corrosion is tabulated in Table 3. The reduction in ultimate strength was shown in fig 6(a). The load displacement curve for the tubular member with varying rate of corrosion was shown in fig. 6 (b).

Table 2 Remaining strength capacity of the tubular member With respect to increase in corrosion

Specimen Id	Increase in Corrosion (%) Remaining strength capacity (%)	y 500 450 ~
	0	100	
80NB Tubu	ar 10	90.32	250 200 150
section	20	84.39	
	30	76.70	0 10 20 30 40 50 Increase in corrosion (%)
	40	57.58	(a)



(b)

Fig .6 Numerical results (a) Reduction in ultimate strength with respect to increase in corrosion (b) Load displacement curve obtained from the numerical model.

V. CONCLUSIONS

In the present study, numerical model created for the tubular compression member which is corroded by combination of uniform and pitting corrosion by varying percentage of corrosion from 10-40% for centre portion of the member. The remaining strength capacity of corroded tubular compression members for varying rate of combined uniform and pitting corrosion was presented. The result indicates that the remaining strength capacity reduces significantly with respects to increase in corrosion. The remaining strength reduces up to 55% for 40% of combined corrosion. In this case of strength reduction, the retrofitting of the member will not be possible. If this form of corrosion occurs in the



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structure, it may result sudden collapse of structures without indicating warnings. So the maintenance engineers need to be equipped with monitoring devices which will enable them to make decisions on necessary retrofitting, replacement or to stop the spreading of corrosion on steel structures exposed to aggressive environment to corrosion.

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