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EFFECT OF PITTING CORROSION ON ULTIMATE STRENGTH AND BUCKLING STRENGTH OF PLATES – A REVIEW

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The plate structures have become a great importance of study due to their wide use in field of marine and offshore structure. Moreover, in several structural engineering applications, the thickness of the plate used has a variable thickness mainly resulted from metal surface losses due to corrosion .Out of all deteriorating factors, the main focus is on corrosion because they have large effect on strength, serviceability, stability of the offshore steel structures. And there is an abreast development in the FE analysis technique used to study the corrosion effect on the plates. The dominant technique adopted in most of the papers considered is non-linear analysis using software like ANSYS, ABAQUS and few developed their own finite element algorithm. In this paper, a literature review is made on localized corrosion. The main attention is given to localized corrosion such as pitting which varies the thickness non-uniformly in the structural plate region effect and its effect on the ultimate and buckling strength of thin plates is studied.

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1 Introduction

Corrosion can be defined as the degradation of a material due to a reaction with its environment. Degradation implies deterioration of physical properties of the material. This can be a weakening of the material due to a loss of cross-sectional area, it can be the shattering of a metal due to hydrogen embrittlement, or it can be the cracking of a metal due to sunlight exposure. The corrosion is dominant in marine and offshore structures because of the well known fact that the sea water is an aggressive corrosive environment. And moreover it is a good electrolyte and contains corrosive salts. This means that corrosion in marine structures, which are generally fabricated from various grades of steel and low alloy steel, is often very severe, not only under sustained immersed condition but also under general exposure to atmospheric conditions. The forms of corrosion can be grouped into general corrosion, localized corrosion and mechanical corrosion. Localized corrosion is the accelerated attack of a passive metal in a corrosive environment at discrete sites where the otherwise protective passive film has broken down. Common forms of localized corrosion include pitting on a boldly exposed surface, corrosion in a creviced region shielded from the bulk environment, inter-granular corrosion of an alloy with a susceptible grain boundary region, exfoliation corrosion, filiform corrosion, stray current corrosion that occurs when sources of direct current are connected to gate structures. The third type is mechanical corrosion which includes erosion, fretting and cavitation corrosion. In the general corrosion, the thickness of the plate varies uniformly and in localized corrosion, the thickness varies non-uniformly. Clearly either general or localized corrosion will reduce the residual strength of ageing ship structures. For general corrosion, the ultimate strength of the corroded plate can be assessed based on the thickness. Until now, there is still no acknowledged method to assess the ultimate strength of the plate with pitting corrosion.

The method of ultimate strength assessment for the pitted plate has been developed from the effective thickness method to the method in which many factors have been considered to represent the characteristics of pitting corrosion. However, for pitting corrosion, the corrosion form is complicated and the thickness of the whole plate is not uniform. Improperly maintained ageing ship structure could finally lead to disastrous casualties in rough seas and heavy weather. Thus it is important to assess the ultimate strength of ageing ship structure properly. To estimate the strength, there has been significant development of computer hardware and finite element analysis (FEA) software. The finite element analysis method has now become the most common, powerful and flexible tool in rational structural analysis and makes it possible to predict the strength of complex structures more accurately than existing classical theoretical methods. People have paid increasing attention to the corrosion caused structural damage in recent half century. Corrosion-caused thickness loss makes the ultimate and buckling strength of typical thin-walled ship structural plates degraded significantly. In this paper, the various procedures adopted by researchers to study corrosion were reviewed. Especially localized corrosion and its effect on plates are studied in depth.

2. Pitting corrosion and its formation

Certain conditions, such as low concentrations of oxygen or high concentrations of species such as chloride which compete as anions, can interfere with a given alloy's ability to re-form a passivating film. In the worst case, almost all of the surface will remain protected, but tiny local fluctuations will degrade the oxide film in a few critical points. Corrosion at these points will be greatly amplified, and can cause corrosion pits of several types, depending upon conditions. While the corrosion pits only nucleate under fairly extreme circumstances, they can continue to grow even when conditions return to normal, since the interior of a pit is naturally deprived of oxygen and locally the pH decreases to very low values and the corrosion rate increases due to an auto-catalytic process. In extreme cases, the sharp tips of extremely long and narrow can cause stress concentration to the point that otherwise tough alloys can shatter, or a thin film pierced by an invisibly small hole can hide a thumb sized pit from view. These problems are especially dangerous because they are difficult to detect before a part or structure fails. Pitting remains among the most common and damaging forms of corrosion in passivated alloys, but it can be prevented by control of the alloy's environment, which often includes ensuring that the material is exposed to oxygen uniformly (i.e., eliminating crevices)

3. Strength assessment techniques for pitting corrosion

Hadi Amlashi and Torgeir Moan [1] studied the strength assessment of the stiffened plates used in offshore and marine structures, which are subjected to biaxial compression loading. They studied this effect by both FE analysis and Numerical method. For this study, they considered 2m x 0.5m x 0.01m stiffened plate and a four noded quadrilateral shell element. Especially, they investigated the effect of DOP (Degree of Pitting) and depth of pits on the ultimate strength of these plates. And it can be found from the table that as the level of DOP and the depth of pit increases there is reduction in the ultimate strength. A brief study on the variation of Residual stress due to pitting corrosion was made.

To determine the effect of pitting corrosion on ultimate strength, a new FEA algorithm was developed by A.U.Ibekwe et al [2] who investigated the corroded plates using Finite Element Analysis. In their study, they modeled the varying thickness profile as 3rd degree polynomial. They divided the plate into rows and columns and importantly, the varying thickness was measured randomly along the length. The least square method was used to fit a curve through data points obtained for each row. From the polynomial curve, the equivalent thickness of elements was obtained as simple averages of its corresponding boundary edges. Then they developed finite element algorithm using Visual Basic 6.0 (programming language) by employing triangular elements. That analysis was carried out using input data, that fully described the idealized structure and its loading and boundary conditions built up in various subroutines. Finally, they compared the result obtained from the newly developed finite element algorithm and the analytical formula i.e., Navier solution and the error was found to be less than 2%.

Ibrahim A. Assakkaf and Jaime F. Cárdenas-García [3] proposed a reliability design of the doubler plates which are dominantly found in ship structures. A doubler plate is nothing but a plate that is added to top of the defective area and welded around the plate's perimeter. Critical buckling strength of damaged column structure was estimated thorough Finite-difference and finite-element analysis and further evaluation was made on the buckling strength of the unstiffened panel-doubler plate structure by placing the doubler plate at different locations within the unstiffened panel. They studied the effect of doubler location on the critical buckling strength of unstiffened plate (doubler on one side only). Then, they adopted, the LRFD (Load and Resistance Factor Design) approach is called a Level 1 reliability method. Usually, Level 1 reliability methods utilize partial safety factors (PSF) that are reliability based; but the methods do not require explicit use of the probabilistic description of the variables**.** They determined partial safety factors for a uniaxially loaded and damaged unstiffened panel with doubler plate, to satisfy the requirements of the LRFD general design formats for ship hull structural components as given by limit state 1 and limit state 2.

Ok, Pu and Incecik [4] studied on assessing the effects of localized pitting corrosion which concentrates at one or several possibly large area on the ultimate strength of unstiffened plates by over 256 nonlinear finite element analyses of panels with various locations and sizes of pitting corrosion. The multi-variable regression method was applied to derive new formulae to predict ultimate strength of unstiffened plates with localized corrosion. Higher strength steel of 1m x 1m plate with a yield stress of 355 N / mm^2 was used for this study. Five different B/t ratios (41.7, 45.5, 50.0, 55.6, and 62.5) have been chosen by changing plate thickness.

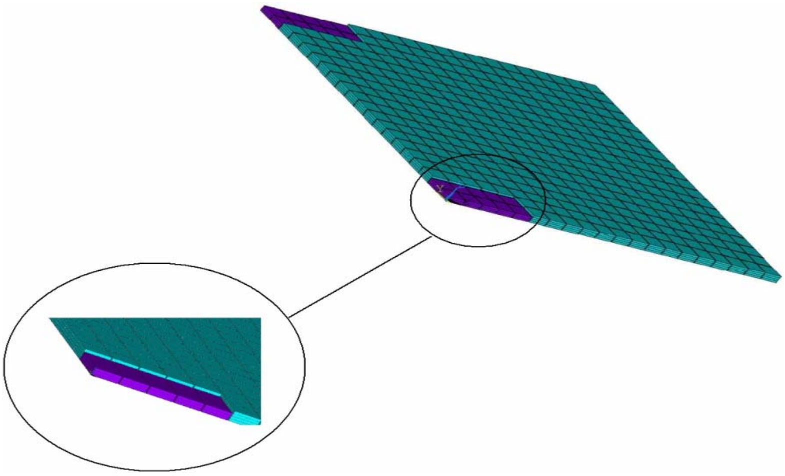

Fig. 1. Finite element analysis modeling detail for pitting corrosion

The location of pitting corrosion was assumed to start at aft bay (aft end) and the sizes of pitting corrosion have four different length values (0.25L, 0.5L, 0.75L, 1.0L), in which *L* is the total length of the plate. The depths of pits are classified into two cases (0.25t and 0.5t). For simplifying the finite element analyses the area of pitting corrosion is assumed to have rectangular shape with single side or both sides corroded pattern as illustrated. The results indicated that the length, breadth and depth of pit corrosion have weakening effects on the ultimate strength of the plates while plate slenderness has only marginal effect on strength reduction. Transverse location of pit corrosion is also an important factor determining the amount of strength reduction. When corrosion spreads transversely on both edges, it has the most deteriorating effect on strength. It was also found out that the proposed formulae can accurately predict the ultimate strength of unstiffened plate with localized corrosion.

Diadola et al [5] proposed that an initial determination of the acceptability of a plate panel with pitting can be made on the basis of the pit depths. They proposed that individual pits with a depth less than 50% of the residual thickness can be repaired by epoxy and individual pits with a depth greater than 50% of the residual thickness may be welded if at least 6.5 mm of material remains at bottom of pit, the distance between adjacent pits is at least 76 mm, the maximum diameter of any welded pit does not exceed 305 mm and the total cross sectional area lost in any section of the pitted plate should not be more than 15%.

Paik and Thayamballi [6] analyzed the ultimate strength of ship panels with pitting corrosion under axial compressive loads using ANSYS. The rectangular was used to model the shape of pits. The results indicated that one isolated small corrosion pit located anywhere in the plate may not reduce the plate ultimate compressive strength to any significant extent. However, such a pit does affect post-ultimate strength behavior for the plate. Subsequently, Paik, Lee and Ko [7] proposed a new parameter, i.e. the smallest cross-sectional area, to represent the ultimate strength reduction characteristics due to pitting corrosion. It was proved that the proposed parameter-based approach is more useful than the traditional approach based on effective thickness in terms of the accuracy of ultimate strength predictions of pitted plates.

Dunbar, Pegg et al. [8] investigated the effect of localized corrosion in stiffened plates by finite element analyses. A stiffened plate was divided into four main sections, each of which was further divided into four sub-sections in longitudinal direction and three sub-sections in the transverse direction. 10%, 50% and 75% by volume of the initial plate thickness over local sub-section were applied and it was found that 10% of corrosion has little effect on the ultimate strength of stiffened plate. Corrosion at higher levels (50% and 75% volume) caused local buckling at the corroded region, which affected the global collapse mode of the stiffened panel and the ultimate load was decreased as the corrosion location was closer to the centre of the panel span.

Nakai et al.[9,10] discussed the structural integrity of hold frames of aged bulk carriers and shapes of corrosion pits observed on hold frames of bulk carriers. They found that the shape of the corrosion pits is a circular cone and the ratio of the diameter to the depth is in the range between 8 to 1 and 10 to 1. A series of actual test with structural models and finite element analyses have been carried out to investigate the effects of pitting corrosion on collapse behaviour and lateral distortional buckling behaviour. The ultimate load of the structural models with regular pittings on the web under the compression load was found to be almost the same as that of the structural models whose web has uniform corrosion corresponding to the average thickness loss.

Flaks [11] in his study on Correlation of pitting corrosion of aluminum plates and reduction of load-bearing capacity under tension, described a mathematical method for assessing the influence of pits on the ultimate strength of aluminum plates under tensile loads. A coefficient which accounts for the loss of tensile strength, yield strength and hardness under tension was derived from experimental testing of naturally corroded aluminum plates. TSCF [12] carried out experimental and theoretical investigations on the strength of steel plating with pit corrosion and under bending. Based on the insights developed by the experimental and theoretical study, they suggested an equivalent plate thickness formula for bending capacity assessment of a pitted plate, which is a function of many parameters such as bending stiffness, mass, boundary condition and dimensions of the plate as well as features of pitting damage.

P. A. Slater et al [13] conducted nonlinear FE buckling analysis on the corroded plates. These plates that are affected by corrosion reduce their overall thickness making them susceptible to buckling-related failures. The uniaxial buckling of simply supported square plates is studied for several corrosion patterns. The mechanics of buckling load variations by corrosion was discussed in detail. The spatial location of the corrosion patch appears to have a significant effect on the buckling strength. It was noted that the case of uniform corrosion is not the most detrimental case, rather corrosion confined in a corner or central area appears to be more critical. The finite element method is employed for computing buckling loads of corroded plates with different boundary conditions. Numerical results are presented in the form of generic plots of buckling load versus volumetric metal loss for several corrosion patterns considered in the paper.

Paik et al., [14] present paper is to investigate the ultimate strength characteristics of steel plate elements with pit corrosion wastage and under in-plane shear loads. A series of the ANSYS nonlinear finite element analyses for plate elements under in-plane shear loads are carried out, varying the degree of pit corrosion intensity and the plate geometric properties. For this study they considered, a simply supported rectangular plate with pit corrosion and under edge shear, as considered in the present study. They varied the DOP and depth of pit and studied their effect on ultimate strength. The distribution of pits is regular, i.e., with the same distance between individual pits and random pits were also taken into consideration. They concluded that the ultimate strength of a plate element was significantly decreased due to pit corrosion. The ultimate strength of a plate element with pit corrosion and under edge shear is determined by the DOP (degree of pit corrosion intensity). But, in the case of a pitted plate element under axial compressive loads, the ultimate strength is governed by the most corroded (pitted) plate section. They also developed the plate ultimate strength design formulae that can be utilized for the ultimate limit state based reliability or risk assessment of plated structures with pit corrosion wastage.

SSC-443 [15] formulated design guidelines for doubler plate repairs of ship structures with criteria such as buckling, and fatigue. In the buckling analysis, they considred The scope of this analysis considered the effect of (i)doubler to base plate thickness ratio, (ii) corrosion feature location with respect to stiffener, and (iii) doubler plate versus corrosion feature geometry. For studying thiese effect through FE analysis they considered a constant corrosion feature width (152.4, 457.2 and 762 mm), aspect ratios of 4, 2, 1 and 0.5 were considered. Based on the design considerations, the doubler edge distances of 25.4, 50.8, 101.6 and 254 mm were considered and doubler thickness was assumed to be 100%, 75% and 50% of the stiffened panel thickness. At first corroded and uncorroded stiffened plates without doubler were studied, and found that corroded plates have lesser critical buckling strength than the uncorroded plates. Then, the effect of varying doubler thickness on the critical buckling load was studied. They also investigated the combined effect of doubler thickness and dimensions of corroded features.

4. Conclusion

In this survey, it can be studied that the pitting corrosion reduces the ultimate strength of the plate. The main factors which reduce the ultimate strength of the plates are the pitting corrosion width, depth, length, DOP. The other factor is the location of the pit because the presence of the corrosion patterns in the edges results in deteriorating effect on load carrying capacity. And in this review it was found that FE analysis was a suitable method adopted by all researchers for the determination of ultimate strength. Likewise the ultimate strength, the buckling strength also depends on the width, depth, and length of the corroded feature. In the study, it was noted that presence of doublers on the plates has considerable effect on the buckling strength of the plate. Usually for larger doubler thickness, the buckling strength tends to increase. When the thickness of the doubler is less than the thickness of corrosion feature on the plate, the buckling strength is reduced.

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