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# Artificial neural networks and their application to assessment of ultimate strength of plates with pitting corrosion

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**Abstract**

The potential for the structural capability degrading effects of both corrosion and fatigue induced cracks are of profound importance and must be both fully understood and reflected in vessel's inspection and maintenance programme. Corrosion has been studied and quantified by many researchers, however its effect on structural integrity is still subject to uncertainty, particularly with regards to localized corrosion. The present study is focused on assessing the effects of localized pitting corrosion on the ultimate strength of unstiffened plates. Over 265 non-linear finite-element analyses of panels with various locations and sizes of pitting corrosion have been carried out. The results indicate 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. In addition, artificial neural network (ANN) method is applied to derive a formula to predict ultimate strength reduction of locally corroded plates. It is found out that the proposed formulae can accurately predict the ultimate strength of locally corroded plates under uniaxial in-plane compression.


*Keywords:* Corrosion; Pitting corrosion; Localized corrosion; Ultimate strength; Artificial neural network; Empirical formulation; Unstiffened plate; Finite-element analysis

## 1. Introduction

Over last decades there have been significant development of computer hardware and finite-element analysis (FEA) software. The FEA is now becoming the most common, powerful and flexible structural analysis tool in structural analysis and makes it possible to predict the strength of complex structures more accurately than the existing classical theoretical based calculations. Although finite-element method can be used, in principle, to predict buckling and post-buckling strengths, it still requires quite much computational time and cost. This means that some useful empirical formulae to assess structural integrity during the initial design, inspection and maintenance are always necessary for effective and on-site decisions.

The first step toward the development of artificial neural networks (ANN) was introduced by Warren McCulloch and Pitts (1943). They modelled a simple neural network with electrical circuits. In 1959, Widrow (1960) and Widrow and Hoff (1960) developed "Adaline" and "Madaline" models. These models were named for their use of the so-called Multiple Adaptive Linear Elements. "Madaline" was the first neural network to be applied to a real world problem. Since the late 1980s the technology and the application of ANN have been developed and employed remarkably in many fields of science and engineering.

Recently ANN methods have been introduced in structural engineering problems. Hajela and Berke (1991) used back propagation neural network to represent the force–displacement relationship in static structural analysis. Such models provide computationally efficient capability for reanalysis and appear to be well suited for application in numerical optimum design. Shao and

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Murotsu (1997) have applied ANN to predict the reliability of structures. In their paper, a ANN model was used to approximate the limit state function, then the reliability of the structure was evaluated by a First Order Second Moment Method (FORM). This methodology was applied to a couple of simple examples and to a portal frame. The results obtained from ANN models are considered to be reasonably accurate. Jenkins (1999) considered the method of structural reanalysis based on use of a neural network on a cable-stayed structure and on a truss structure. Wei (2000) investigated a two-layered back-propagation neural network to predict the local and distortional buckling behaviour of cold formed steel compression members.

Some recent developments in the application of ANN methodology in marine and offshore structural field have been carried out which include structural reliability analysis by Papadrakakis et al. (1996), Papadrakakis and Lagaros (2002), Shao and Murotsu (1997), Hurtado and Alvarez (2001), Gomes and Awruch (2004) and Deng et al. (2005). It is found out that an ANN-based response surface method (RSM) is much more accurate and efficient than conventional polynomial-based RSM in structural reliability analysis (El-hewy et al., 2004; Pu et al., 2005). The ANN method also has been used to estimate the ultimate strength of unstiffened plates by Pu et al. (2005) and Wei and Zhang (1999). They found that ANN-based predictions generally produce better results than those from empirical formulae derived from conventional regression analysis.

Other attempts to use ANN in naval architecture and marine engineering are introduced by Ray et al. (1996), Mesbahi and Bertram (2000), Zubaydi et al. (2002) and Alkan et al. (2004), and Ok (2006) in wave and motion analysis by Xu and Haddara (2001), Londhe and Deo (2003), Agrawal and Deo (2004), Mazaheri and Downie (2005).

The objectives of this paper are to investigate the effects of localized pitting corrosion on ultimate strength of unstiffened plates under uniaxial in-plane compression and to apply ANN technique to derive empirical formulae to predict ultimate strength reduction due to this type of corrosion. Over 265 non-linear finite-element analyses have been carried out to systematically investigate the effects of plate slenderness, locations, sizes and depths of pitting corrosion on the ultimate strength of unstiffened plates under uniaxial in-plane compression. A few of the important parameters in developing ANN formulae will be discussed. Formulae for predicting ultimate strength reduction due to corrosion on single edge and on both edges will be proposed. It should be pointed out that the datasets for developing ANN models are mainly FEA results.

## 2. Existing methodologies and guidances to assess localized corrosion

Generally in the case of uniform corrosion, the buckling or ultimate strength of stiffened and unstiffened plates can be easily estimated by reducing the plate thicknesses from their original values. Several empirical formulae are available to obtain the ultimate strength of plates under general corrosion (Faulkner, 1975; Soares, 1988; DNV, 1995; Fujikubo et al., 1999; NK, 2001; Paik and Thayamballi, 2003). However, the calculation of strength degradation due to localized defects, such as pitting corrosion, is more difficult and complicated than that due to general area-wide corrosion, and relatively few research activities and guidelines have been published until now (Chapkis, 1967; Flaks, 1978; TSCF, 1984; Daidola et al., 1997; IACS, 2003a, b; Paik et al., 2003a, b, 2004).

Daidola et al. (1997) 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 the 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%.

IACS (2003a) S31 specifies that if pitting intensity is higher than 15% in area, thickness measurement is to be taken to check pitting corrosion and the minimum acceptable remaining thickness in pits or grooves is equal to 75% of the as-built thickness for pitting or grooving in the frames, brackets, webs and flanges or 70% of the as-built thickness for pitting or grooving in the side shell, hopper tank and topside tank plating attached to the side frame, over a width up to 30 mm from each side of it. IACS (2003b) Z10.1 also requires that any bottom plate with a pitting intensity of 20% or more, with wastage in the substantial corrosion range or having an average depth of pitting of 1/3 or more of actual plate thickness is to be noted.

Paik et al. (2003a, b, 2004) performed a series of experimental and numerical studies on steel-plated structure with pits under axial compressive loads and edge shear. They found that the ultimate strength of a steel plate with pitting corrosion under edge shear is governed by the degree of pit corrosion intensity, whereas the ultimate strength of a pitted plate element under axial compressive loads is governed by the smallest cross-section area of plate taken through the pitted region. A simplified strength knockdown factor for plates with various pitting corrosion was introduced using the following formulation:

$$R_{\mathrm{xr}} = \frac{\sigma_{\mathrm{xu}}}{\sigma_{\mathrm{xuo}}} = \left(\frac{A_0 - A_{\mathrm{r}}}{A_0}\right)^{0.73}, \tag{1}$$

where $R_{\mathrm{xr}}$ is a factor of ultimate compressive strength reduction due to pitting corrosion, $\sigma_{\mathrm{xu}}$ is the ultimate compressive strength with pitting corrosion, $\sigma_{\mathrm{xuo}}$ represents the ultimate compressive strength for an uncorroded member, $A_0$ indicates the original cross-sectional area of