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Stress–strain analysis of dented rectangular plates subjected to uni-axial compressive loading

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ABSTRACT

The aim of this work is to analyse the local and the global structural behaviour of rectangular steel plates with a local dent. Nonlinear finite element analyses have been performed to explore the effect of different dent depths on the ultimate strength and the post-collapse behaviour. The post-collapse modes are discussed and the change of the buckling mode for different plate thickness ranges is categorized. The behaviour in post-collapse regime is analysed using the defined stress–strain rate. Two relationships have been developed to estimate the ultimate strength reduction as a function of the plate slenderness and dent ratio. Based on the existing ultimate strength design formula and a new developed factor, a new formulation for ultimate strength of damaged plate has been introduced accounting for the effect of local dent. The new developed formulation is capable to account for an initial global imperfection, residual stresses, openings, corrosion deterioration and existence of dents.

1. Introduction

Plates, in either un-stiffened or stiffened are the most spread structural components of thin-walled structures, such as ship and offshore structures. Ship plates are generally subjected to several types of in-plane or lateral loads. The loads may be applied separately or in a combination with each other. The in-plane loads may be tensile or compressive depending on the current loading conditions.

In order to assess the ultimate hull girder strength, the capacity of the ship's hull girder against longitudinal bending moment has to be defined. The longitudinal bending moment, due to hogging and sagging loading conditions, causes compressive loads on the main structural elements (plates) during the life cycle. Therefore, it is important to study the structural behaviour of plates under uni-axial compression.

Due to the operational conditions, the ship structural components are subjected to different damage scenarios accounting for corrosion degradation and fatigue cracking. As a result of dropping objects, collision and grounding, local dents may be formed. All of these types of damages directly affect the structure, which in turn influences the load carrying capacity of the structure and its ultimate strength.

For plates, Dow and Smith [1] studied numerically the influence of localized imperfections on the buckling and post-buckling behaviour of long rectangular plates under uni-axial longitudinal compression. It was concluded that the amplitude of the localised imperfection is the governing factor in the collapse of plates. Moreover, changing the position of the localized imperfection does not significantly influence the strength of the plate.

Paik et al. [2] and Paik [3] investigated the ultimate strength characteristics of dented steel plates under axial compressive and shear loads. The effects of shape, size (depth, diameter), and location of the dent on the ultimate strength behaviour of simply supported steel plates are studied. A closed-form formula for predicting the ultimate strength of dented steel plates is empirically derived by a curve fitting based on the computed results.

Luís et al. [4] studied the effect of dimple imperfections caused by local accidents, on the ability of a plate assembly to resist compressive loads. It was found that the effect of the dimple imperfection is higher when is positioned near the unloaded edge of the plate and depends upon its amplitude and on the slenderness of the plate.

Raviprakash et al. [5] studied the influence of various dent parameters (dent length, dent width, dent depth and angle of orientation of the dent) on the static ultimate strength of thin square plates of different thicknesses under uni-axial compressive loading. It was found that the longer dents with variation of size and

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angle of orientation of dents drastically reduce the ultimate strength. In general, the effect of variation of dent parameters on the ultimate strength of the dented plate magnifies with an increase in the plate thickness.

For stiffened panels, Witkowska and Guedes Soares [6] and Luís et al. [7] investigated the behaviour and ultimate strength of stiffened panels with local imperfections. It was found that the dimple imperfection has a negligible effect on the rigidity of the model, but it induces a more violent collapse and the position of the dimple imperfection is an important factor. Also, depending on geometrical characteristics, stiffener deformations may significantly reduce the ultimate strength. The size of the stiffeners proved to be an influential factor to the collapse behaviour and ultimate strength of dented panels, which agrees with the work done by Amante et al. [8], where it was reported that the structural panels should be designed with stiffeners presenting additional robustness in the regions prone to the impact loads, in order to maintain an acceptable level of integrity for a damaged panel.

Xu and Guedes Soares [9] studied the influence of a local dent on the collapse behaviour of stiffened panels. The effect of residual stresses caused by the local dent on the collapse behaviour of stiffened panels was also investigated. It was concluded the residual stresses caused by the indentation, reduce slightly the ultimate strength of the dented stiffened panels.

The study presented here is a continuation of the research work done by Saad-Eldeen et al. [10], in which another scenario for reduced the ultimate strength of plates was studied; the presence of openings. The effect of the opening ratio and orientation to the ultimate strength of plates was investigated and an expression was developed to estimate the ultimate as a function of the plate slenderness and residual plate-breadth ratio.

Most of the work done in the present literature review for dented plates is dealing with the ultimate strength point, without analysing the behaviour of the plate before and after reaching it. It is important to analyse the post-collapse regime in order to understand the complexity of the structural behaviour. Therefore, the present study investigates the local (ultimate) and global behaviour of rectangular steel plates accounting for the presence of a local dent. Based on the performed analyses, several conclusions are derived and a new coefficient accounting for the effect of a local dent on the ultimate strength of the rectangular plate element is developed.

2. Finite element model

The behaviour of rectangular plate elements with and without local dent, subjected to uni-axial compression will be analysed. The analysed plates are categorised into three groups as a function of plate length, breadth, thickness, global imperfections and local dent damage. The geometrical configurations of the analysed plates are given in Table 1 and shown in Fig. 1, where a is the plate length, b is the plate width, t is the plate thickness, l is the dent length, s is the dent width, GI is the global initial imperfection and LD is the local dent depth.

The intact structural model configurations, boundary conditions and material stress–strain curve is based on a real experimental test performed by Kim et al. [11]. The configurations of the intact plate up to a 8 mm plate thickness are based on the experimental test performed in [11]. Systematic variation of the plate thickness up to 20 mm is also included in the present analysis, which may cover the diversity of engineering applications.

The principal parameter governing the buckling strength of intact plate is the plate slenderness, defined as:

$$\beta = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}} \quad (1)$$

Table 1
Plate element configurations.

Item	a	b	t	GI	LD	Units
Group 1	600	400	10	1.7	0	mm
	1000	400	10	1.7	0	mm
Group 2	800	400	4	1.7	0	mm
	800	400	6	1.7	0	mm
	800	400	7	1.7	0	mm
	800	400	8	1.7	0	mm
	800	400	10	1.7	0	mm
	800	400	20	1.7	0	mm
Group 3	800	400	4	8.50	[2,4,6,8]	mm
	800	400	6	5.63	[2,4,6,8]	mm
	800	400	8	4.22	[2,4,6,8]	mm
	800	400	10	3.38	[2,4,6,8]	mm
	800	400	12	2.82	[2,4,6,8]	mm
	800	400	14	2.41	[2,4,6,8]	mm
	800	400	16	2.11	[2,4,6,8]	mm
	800	400	18	1.88	[2,4,6,8]	mm
	800	400	20	1.70	[2,4,6,8]	mm

where t is the plate thickness, σ_y is the Yield stress, E is the material Young modulus. The plate slenderness of the analysed plates varies from 0.75 to 3.75. For ship plates, normally β varies from 1 to 5 [12,13]. The adequacy of β to represent the compressive strength of rectangular plates has been demonstrated by various design expressions and studies [14,15].

Numerical analyses of the ultimate strength of unstiffened rectangular plates are performed with a general non-linear finite element commercial code – ANSYS. The FEA utilizes the full Newton–Raphson equilibrium iteration scheme, the large deformation option was activated to solve the geometric and material nonlinearities and pass through the extreme points. The automatic time stepping features are employed allowing ANSYS to determine appropriate load steps.

A shell element was used to generate the entire FE model. The shell element, SHELL 181 is defined by four-nodded element with six degrees of freedom at each node: translations in the x, y and z directions, and rotations about the x, y and z axes. SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications and suitable for analysing thin to moderately-thick shell structures.

The material used in the FE model is of low carbon steel with the yield stress, σ_y of 290 [MPa], the Young modulus, E of 206 [GPa] and the Poisson's ratio, υ of 0.3. The stress–strain model is elastic-perfectly plastic, as defined by Kim et al. [11].

At stresses below the yield stress, σ_y the material behaviour is linear with a tangent modulus of $E = \sigma_y/\varepsilon_y$. At the level of the yield stress, the material flows without strain hardening. When the material is unloaded by reducing the stress below the yield stress, it behaves elastically in a manner unaffected by the plastic flow.

The quadrilateral element size of 5 mm has been defined as a good solution of the finite element model based on the comparative analysis with the experimental test and finite element results presented in [11], for an intact plate with a thickness of 4 mm, as described briefly in [10] and shown in Fig. 2. The model calibration leads to an element size-plate thickness ratio of 1.25, thus element size of ES = 1.25 $*$ t is used for analysing the rest of the plates with a thickness bigger than 4 mm.

One shape of initial imperfection is considered in the analyses and modelled as one half downward wave, based on the Fourier series, as given by Eq. (2), and shown in Fig. 1.

$$\omega = \omega_0 \sum_{i=1}^{m} \sin\frac{i\pi x}{a} \sum_{j=1}^{n} \sin\frac{j\pi y}{b} \quad (2)$$