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Effect of a central dent on the ultimate strength of narrow stiffened panels under axial compression

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A B S T R A C T

This paper studies the effect of a central dented imperfection on the load carrying capacity of stiffened panels considering the residual stress caused by the indentation, and identifying the type of boundary conditions to adopt for a model to be used in an experimental programme for damaged panels. A quasi-static nonlinear finite element analysis is used to simulate the production of the local dent, followed by an ultimate strength analysis of the stiffened panels under uniaxial compressive load. The structural plastic strain causes the residual stress and the dent, which are included in the ultimate strength analysis of the stiffened panels under compressive load. To prescribe appropriately the boundary conditions for the central span of stiffened panels, two and three spans models are adopted in the FE analyses. The effects of residual stress, geometric range and dent depth on the ultimate strength of the stiffened panels with a central dented imperfection are investigated using nonlinear quasi-static finite-element analysis.

1. Introduction

It is very important to assess the global and local residual strength of ship structures after accidental events, such as local overload, collision and grounding. FE (finite element) codes are a suitable tool for assessing the ultimate strength of ship structures, which have been used to analyses the stress distributions and deformations of very complicated structures with the accuracy demanded in engineering applications under all kinds of loading conditions. For instance, Endo et al. [1]carried out a FEA (finite element analysis) for the ultimate strength of hull girder of a damaged ship collided by another ship at side shell.

To simplify the calculation procedure, Gordo and Guedes Soares [2], Ozgur et al. [3]and Luis et al. [4,5] investigated the residual strength of a ship hull girder subjected to collision damages using an incremental-iterative approach proposed by Smith [6], in which all elements failed have been removed from the original intact structures. The failed structural component due to collision or grounding damages can be assessed by FEA (finite element analysis) for various accident scenarios, such as in [3,7]. Yoshino et al. [8] and Toh et al. [9] also used the incremental-iterative approach to assess the hull girder residual strength of damaged ship not omitting damaged parts, instead considering average stress–strain relationship of the damaged panels, which accounts for more detail of the structural damages. Underwood et al. [10] used ISUM (Idealised Structural Unit Method) to calculate the collapse strength of damaged stiffened steel panels.

To understand the influence of the local damage on the strength capacity of the ship structure, it is necessary to investigate the strength reduction characteristics of ship structural elements, such as plates and stiffened panels with damages. The collapse behaviour of stiffened panels is affected significantly by the initial imperfection and depends on the amplitude of the buckling mode component [11]. Guedes Soares [12] has derived an equation to predict the collapse strength of plates, which account for the imperfection effects and include a proper safety margin.

Paik [13] investigated the effects of varying dent parameters on the collapse behaviour of simply supported steel plates under axial thrust with FEA, including shape, size (depth, diameter) and location of the dents. Guedes Soares [14] studied the collapse strength of a single plate having two types of imperfections: global weld induced and local damaged induced. It was found that local imperfection, when added to global one, could cause severe reduction of the strength of the plate depending on its amplitude, length and position on the plate. Luis et al. [15] and Nikolov [16] simulated the collapse strength of damaged continuous plating based on FEA and concluded that the compressive strength of damaged plating is significantly influenced by the localised damage. The local damage on the stiffener can change the collapse modes of plates and decrease ultimate strength, which depends on the location of the dent and the initial global deflection [17,18].

The dent is a local imperfection and presents damage that could be caused by a fall or strike of an object. Recently, the

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Notations

β	plate slenderness
λ	column slenderness
l	length of the plate
s	width of the plate
t_p	thickness of the plate
σ_y	yield stress of material
E	Young's modulus of material
r	radius of inertia
Φ_p	effective width of the plate
C_d	imposed displacement
R_d	radius of the indenter
F_p	lateral indentation force
F_{pmax}	maximum lateral indentation force
δ	indentation
δ_d	final depth of the dent
δ_s	springback displacement
σ_r	residual stress of the stiffened panels
σ_0	flow stress of material
σ_u	ultimate strength of the stiffened panels
h_w	web height of the stiffener
σ_{ar},σ_{au}	average stress of the stiffened panels with and without considering residual stress
σ_{ur},σ_{uu}	ultimate strength of the stiffened panels with and without considering residual stress

quasi-static analyses and tests were used in the model tests, where the indenters were carefully controlled to move very slowly [19–21]. A quasi-static analysis is easier to record continuously various features of the damage process, and thereby, obtains more information for further experimental study. Hence, the quasi-static non-linear FEA is adopted here to simulate the production of the dent the stiffened panels. Most of the previous researches assumed the damage location and dent size on plates or stiffeners, which did not consider the influence of residual stresses or plastic strains caused by indentation procedures. The FEA simulation in the present paper includes the indentation process, which produces the local dent and the corresponding residual stress, following by an ultimate strength analysis under uniaxial compressive load. Using this approach, the residual stress and the dent in the stiffened panels caused by the indentation due to the plastic strain can be included in the ultimate strength analysis.

The aim of the present paper is to study the type of boundary conditions to adopt for a model to be used in an experimental programme for testing the collapse behaviour of dented narrow panels with two stiffeners. This work belongs to an extended series of investigations that include wide panels with four stiffeners [22] which allows the understanding of the effect of width on the strength of stiffened panels. The results of the narrow and wide panels are also compared here. To prescribe appropriately the boundary conditions, the FE models with three and two spans are both adopted. Two load steps are used to produce the damage of the stiffened panels by the quasi-static non-linear FE analysis. The indenter is moved towards the stiffened panels, and the contact force between the indenter and the plates would produce the dent in plates at first step. Then, the indenter is taken off to simulate the springback of the stiffened panels. After that, the plastic strain causes the residual stress and the dent in the stiffened panels, which are included in the further ultimate strength analysis under compressive load. From these results, the dent resistance of the stiffened panels and the effect of local dent on the ultimate strength are investigated.

2. Description of the models

The stiffened panel models with two and three spans are adopted here, which have the same dimensions with the intact specimens used in the tests [23], as shown in Fig. 1 and in Table 1. The collapse mode is different between the short and long stiffened panels, hence the specimens with different frame spacing are adopted to reduce the uncertainties introduced through the boundary conditions as they are important contributions to the overall uncertainty of the prediction. The results of the wide panels in Table 2 [22] are also compared with that of the narrow ones adopted in the present paper. The dimensions of the frames and the stiffeners are L $60\times40\times6$ mm^3 and I 30×8 mm^2, respectively. The letters and numbers given to as the name of the specimens are used to distinguish the specimens each other and are explained as follows:

FB2A2F6: Flat Bar;
FB2A2F6: Frame spacing: 2–200 mm, 3–300 mm, 4–400 mm, 45–450 mm, 6–600 mm;
FB2A2F6: A-two stiffeners in the transverse direction (narrow panels); B-four stiffeners in the transverse direction (wide panels);
FB2A2F6: 2-Two spans in the longitudinal direction; 3-three spans in the longitudinal direction;
FB2A2F6: F6 – L$60\times40\times6$ mm^3 frame; F8 – L$80\times40\times6$ mm^3 frame.

The principal parameters affecting the ultimate strength of plate and stiffened panels subjected to compressive load are the plate. The column slenderness are defined as follows:

$$\text{Column slenderness}: \lambda=\frac{l}{r}\sqrt{\frac{\sigma_y}{E}} \tag{1}$$

where the radius of inertia is given by

$$r=\sqrt{\frac{I}{A}} \tag{2}$$

$$\text{Plate slenderness}: \beta=\frac{s}{t}\sqrt{\frac{\sigma_{yd}}{E}} \tag{3}$$

Effective width of plate elements (Φ_p) can be calculated [24]:

$$\Phi_p=\frac{2}{\beta}-\frac{1}{\beta^2} \tag{4}$$

3. Nonlinear finite element analysis

3.1. Finite element model

The FE code ANSYS is used to assess the ultimate strength of the stiffened panels. The geometric and material nonlinearities are both taken into account, including elastic–plastic large deflection. To access the material property, a tension test had been conducted by gripping opposite ends of a test item within the load frame of a test machine [23]. A tensile force had been applied by the machine, resulting in the gradual elongation and eventual fracture of the test item. During this process, force-extension data had been recorded as shown in Fig. 2. The true stress–strain curves by the