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Ultimate strength of locally damaged panels

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ABSTRACT

The behaviour and ultimate strength of locally damaged plate panels is investigated in this study. The damage is in the form of a local imperfection and represents a dent that could be caused by a fall or strike of an object. Panels are made of nine identical plates – three plates transversally and three longitudinally – and only one of the plates is damaged. The influence of several parameters has been studied to establish their interaction with the presence of the local dent. The main focus, is however the influence of the adjacent intact plates. The large panel is compared with smaller transverse model made of three plates and with a single plate model in order to evaluate the effects of adjacent plates and define the minimum size of the model necessary to obtain proper results.

1. Introduction

The lifetime of a ship is normally planned to be at least 20 years and during this period the hull structure is exposed to a variety of damages. A certain number of them is a consequence of aging like corrosion or fatigue cracks [13,14], but others are mechanical damages occurring as a result of involuntary incidents for example during loading and unloading of cargo. Due to these defects the strength of damaged elements will be reduced, which in extreme cases can compromise the strength of whole panels. Therefore, it is crucial to understand the behaviour and strength reduction characteristics of damaged structural members in order to assess the consequences after damage and to determine what kind of action is appropriate as repair or replacement can be difficult and expensive.

The typical structural elements of a ship hull are plates and stiffened panels and their strength has been studied for decades. One of the most important aspects of plate's strength is its resistance to in-plane compression since buckling and collapse of plate elements can occur at a stress level much lower than the yield stress of material, threatening the overall strength of the ship hull. Many authors studied the compressive behaviour of plates in order to establish the governing parameters and influential factors. Faulkner [6] has shown that the principal parameter governing the collapse of a plate is its slenderness. On the other hand, Kmiecik [19] showed that the strength of plates depends very much on the influence of initial imperfections. The imperfections were also studied by Guedes Soares [10] who generalised Faulkner's formula to account explicitly for these effects. This paper also reviews available experimental and numerical results and discusses the effect of boundary conditions and of residual stresses. These topics represent ongoing research items and thus more recent results are also available in Guedes Soares and Kmiecik, [17], Xu et al. [44] and [1–3], as well as the references therein.

However, this type of equation indicates the mean value of the strength of plates but the actual strength of individual plates have a variability associated with the one of the initial imperfections, as discussed by Guedes Soares and Faulkner [12]. To capture the variability of the plate strength due to the random nature of the imperfections Guedes Soares and Kmiecik [16] analysed statistically the results of a Monte Carlo simulation of the ultimate compressive strength of plates. The variability of this type of imperfections is determined for example from databases with extensive measurements such as the one of Kmiecik et al. [20], can also be combined statistically and design equations can be derived which do not account explicitly for the imperfections but consider them implicitly in a procedure described in Guedes Soares [11].

It is probably appropriate to refer that other forms of defining the initial imperfection can also be considered and combined in overall equations as done by Sadovský et al. [32,33]. Furthermore the sensitivity to imperfections is also present in cases of combined loading [15].

In addition to post-welding global imperfections, local imperfections may exist in plates as well. The comparison of the effects of these two types of imperfections on the strength of plates was done by Dow and Smith [4]. They considered different shapes and positions of the local imperfections. The consequence of combining both global and local imperfections has also been studied, however without investigating the influence of changing the

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position of local imperfection while global imperfection is already present. They concluded that the length and especially amplitude of the local imperfection, when alone, have the most influence on the results. When added to a global one, local imperfections can significantly change the collapse strength.

Paik et al. [27] carried out a series of non-linear finite element analyses of dented plates, varying several parameters of the plate and dent itself. They found that the depth of the dent has little impact as long as the diameter is small. The increase of the diameter decreases the ultimate strength significantly and the depth can amplify this effect. It has also been concluded that the longitudinal position of the dent affects the strength. The plate properties, like aspect ratio and thickness, did not appear to be influential parameters to the normalised compressive strength of dented plates. The strength reduction factor has also been introduced to predict the strength of dented plates by multiplying it with the ultimate strength of intact (not dented) plates. This paper examines dents of small dimensions, which are comparable to the smaller ones that Paik et al. [27] have studied. No attempt was given here to study larger damages.

Guedes Soares et al. [18] studied the collapse strength of a single plate having two types of imperfections: global weld-induced and local damaged-induced. They generally confirmed the previous conclusions that local imperfection, when added to global one, could cause reduction of the strength of the plate depending on its amplitude, length and position on the plate.

Other studies of dented plates have been made by Estefen and Estefen [5] and Amante et al. (2015), who have tested very small scale dented models and have also compared with numerical results. Raviprakash et al. [28] also studied plates with one central dent although they restricted themselves to square plates which is a special case of small applicability to ships. More recent work on dented plates can be found in Xu and Guedes Soares [41,42] and in Saad-Eldeen et al. [30].

The very localised impact of a small object may provoke such a large dent that it even leads to local rupture as discussed by Liu et al. [21]. This suggests that it may also be of interest to look at the limit of large damages including holes, which is not the aim of the paper, but which represent an upper limit of damaged plate strength. Studies of the strength of plates with openings were made by Suneel Kumar et al. [34] and more recently by Xu et al. [43] and Saad-Eldeen et al. [29,31].

In addition to studying a single plate with local imperfections some studies of plate panels have been made. Luís et al. [24] considered a panel made of 3 plates joined transversally to the load direction showing that such model is equivalent to a single rectangular plate model if proper boundary conditions are adopted. Luís, Guedes Soares [22] and Luís et al. [25] analysed assemblies made of 3 plates connected longitudinally. The model was validated and the results showed that even if the imperfection is isolated longitudinally it can affect significantly the collapse strength of the panel as well as the post-collapse behaviour.

In addition to the important experimental results of Smith et al. (1991), further studies of stiffened panels with various plate fields longitudinally and transversely have been made more recently by Gordo and Guedes Soares [7–9] and [38,39] experimentally and numerically [36,37,40], where a literature review can be found about other available experimental results.

Except for those references, the studies on plates normally consider a single plate model. The idea of using multi-plate panels in analyses instead of single plate comes from the fact that, unlike the post-welding global deflection, the damage-induced local imperfections do not have repetitive pattern in adjacent plates as does the weld induced ones. Common practice of representing the panel by a single plate model is limited only to cases where all plates in the panel are identical. In case of locally damaged panels the dent occurs in one plate only and the rest of the plates are intact. Hence, it can be expected that those intact plates will influence the behaviour of the damaged one and the results will differ from case where it would be consider separately. As so, it is useful to properly account for the interaction of the adjacent plates with the central dented one.

The present paper investigates the influence of small local denting damages on the behaviour and ultimate strength of large panels made of nine plates, which allows the effect of adjacent undamaged plates to be also incorporated, whilst neglecting the influence of the dividing stiffening members through the use of appropriate boundary conditions in way of. The large panel is compared with two other models, namely one span model (3 plates) and single plate model in order to study the influence of different number of neighbouring plates in the panel as well as to estimate the minimum size of the model appropriate for analysing the localised imperfections.

While the present work only deals with damages on the plates, for completeness, the reader is referred to Witkowska and Guedes Soares [35] for the situation of damages in the stiffeners.

2. General overview

The objective of this study is to analyse the compressive behaviour and ultimate strength of locally damaged plate panels. The damage is in a form of local imperfection of about 30% of the plate's breadth, and represents a dent that could be caused by e.g. fall or strike of an object.

The analysed panel is made of 9 plates joined together: 3 plates longitudinally and 3 plates transversally. In the whole panel only one dent occurs but several different positions of the dent are considered.

Fig. 1 presents the sketch of the panel with all the possible locations of the damage marked.

Some defects are places at the boundary of the plates representing potentially damaging situations. There are various situations in ships in which this may be the case and this is the reason to have those situations included. For example in container vessels there are openings in the deck for containers to be placed inside the ship and minor contacts of the container with the deck boundary may lead to those damages. The same happens with the openings in the decks of bulk carriers or of general cargo ships.

The analyses are performed using finite element modelling and for this purpose the commercial software ANSYS was employed. The plate size is fixed with width $b = 1000$ mm and the ratio of the length over the width (a/b) equal to three giving $a = 3000$ mm which corresponds to medium sized plates.

In order for a parametric study to be performed several values were used for the parameters that are necessary to define the models, like plate slenderness and the properties of the global and local imperfections. They will be described in detail later on.

The strength of the individual plate with the localised damage was obtained from the reaction forces. The load is applied as an imposed displacement δ on one of the edges of the panel and the reaction force R on each node of the opposite edge is taken for the plate where the damage is located, as shown in Fig. 2. The ultimate stress is then calculated by dividing the total reaction by the cross section area of the plate.

3. Modelling

The material is the same for all models: structural mild steel having an elastic-perfectly plastic stress–strain curve with Young's modulus (E) and yield stress (σ_0) equal to 210 GPa and 235 MPa,