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Effect of reinforcement on buckling and ultimate strength of perforated plates

Jeong-Hyeon Kim [a], Jun-Hwan Jeon [a], Joo-Shin Park [b], Hyang-Duk Seo [c], Hyung-Joon Ahn [c], Jae-Myung Lee [a,*]

[a] Department of Naval Architecture and Ocean Engineering, Pusan National University, 30, Jangjeon-Dong, Geumjeong-Gu, Busan 609735, Republic of Korea
[b] Samsung Heavy Industries, Co., Ltd, Geoje 656710, Republic of Korea
[c] Sungdong Heavy Industries, Co., Ltd, Tongyeong 650827, Republic of Korea

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ABSTRACT

Cutouts are widely used in ships and offshore structures. These cutouts are used mainly for inspection, and they may be fitted for various purposes, including passing pipes and weight reduction. In general, plates with cutouts (perforated plates) are given high importance at the structural design stage because they can reduce the structural strength. In this regard, local reinforced perforated plates are used in shipyards to satisfy buckling and ultimate strength requirements, but quantitative evaluations of the reinforced perforated plates have not yet been carried out. To mitigate the decrease in the strength of perforated plates, the Carling, face-plating, and doubling stiffening methods have been adopted with the goal of increasing both the buckling and ultimate strengths. In particular, the Carling stiffener has been partially adopted at holes typically found in shipyards (e.g., access holes, lightening holes), but no standard methodologies or recommendations are available for the use of this stiffener. In the present study, a series of numerical studies were undertaken to analyze the buckling and ultimate strengths for various stiffening methods (Carling, face-plating, and doubling) and loading conditions (axial compression and in-plane edge shear loading). An optimal reinforcement method was determined by comparing stiffened weights and ultimate strengths of the three methods. Finally, a design formula for calculating the ultimate strength of a perforated plate was developed on the basis of over 144 cases of finite element analysis.

1. Introduction

The basic components of ships and offshore structures are steel plates, which are cut, shaped, bent, and manufactured to meet the requirements of a desired design configuration. Stiffened plates including curved and perforated plates are the most commonly adopted structural members in the shipbuilding industry. Hull deck hatches, bottom girders, and diaphragms factor a certain extent of perforation within their geometries since perforation decreases the weight as well as natural frequency of a plate in comparison with a non-perforated plate. However, this also leads to a significant reduction in both buckling and ultimate strength. To resolve the issue, the dimension of the perforation hole is limited to a specific range at the design stage to limit the increasingly altered structural response that is associated with an increasing hole size. Thus, several studies have been reported in the literature to examine the effect of perforation on both buckling and ultimate strength of perforated plates. Wang et al. [1] investigated the complex behavior of structural plate panels with openings used in ships, to calculate buckling and ultimate strengths using parametric studies employing linear and non-linear finite element analysis (FEA) to investigate the influence that dimensions of the plate panels, shape and size of openings had on shear and compressive stresses in longitudinal and transverse directions. Simple design formulae were developed on the basis of these FEA results. Kumar et al. [2] determined the effects of a rectangular central opening on the ultimate strength of a square plate under axial compression. The effects of the plate slenderness ratio and the opening area ratio on the ultimate strength were determined using a nonlinear FEA. Shanmugam et al. [3] proposed a design formula to predict the ultimate load capacity of perforated plates subjected to compressive loading with different boundary conditions within the ABAQUS finite element package, to carry out an elastoplastic analysis on plates under uniaxial and biaxial compressions. They found that various parameters including plate slenderness ratio and opening size affected post-buckling behavior and the ultimate load capacity of perforated plates. Paik [4,5] investigated the ultimate strength characteristics of steel plates with a single circular hole under longitudinal and axial compressive loads through a series of elastoplastic,

* Corresponding author. Tel.: +82 51 510 2342; fax: +82 51 512 8836.
E-mail address: jaemlee@pusan.ac.kr (J.-M. Lee).

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large-deflection FEAs carried out in ANSYS while varying hole size as well as the plate dimensions. El-Sawy and Nazmy [6] investigated the effects of the aspect ratio, hole size, and hole location on the elastic buckling of uniaxially loaded rectangular perforated plates with eccentric holes, as evidenced by a buckling coefficient, k. Komur and Sonmez [7] also investigated the elastic buckling behavior of rectangular perforated plates using FEA by modeling circular cutouts chosen at different locations along the principal axis of the plates subjected to linearly varying loads, in order to evaluate the effects of the cutout location on the buckling behavior of the plates. They investigated the effects of the hole size and location on buckling load of rectangular plates with aspect ratios ranging from one to four. Narayanan and Chow [8] investigated the ultimate capacity of uniaxially compressed perforated plates with specific focus on examining the differences between perforated plates containing square holes and perforated plates containing circular holes, via experimental as well as theoretical methods. Dadrasi [9] investigated the effect of imperfections on the buckling load of perforated rectangular steel plates by performed numerical and experimental investigation of buckling behavior of rectangular plates with circular and square cutouts under uniaxial, in-plane, compressive loading in the elastoplastic range, within various loading bands.

As many studies have evidenced, the primary factor affecting decrease in buckling strength of perforated plates is the perforation ratio (d_c/b, i.e., the ratio of diameter of a circle hole to breadth of the plate). Additionally, there are methods for increasing the buckling and ultimate strength including by altering the hole dimension, changing the hole locations, and increasing the plate's thickness. Recently however, as weight and cost reduction of raw materials has begun to receive great attention in the engineering community, the plates used in shipbuilding industries have become gradually thinner. In this regard, it is no longer a proper resolution to increase thickness and consuming lots of raw materials in order to achieve greater strength. Therefore, researchers have studied the method of reinforcement (see Fig. 1) of perforated plates and widely applied the inferences of such studies in the shipbuilding industry to overcome reductions buckling and ultimate strength resulting from perforation in an attempt to reduce weight and cost. Cheng and Zhao [10] studied the buckling behaviors of uniaxially compressed perforated steel plates that were strengthened by four stiffener types viz. ringed, flat, longitudinal, and transverse stiffeners. Using the commercial code ANSYS, they performed a series of elastic and elastoplastic FEAs for a range of plate slenderness ratios as well as hole-diameter ratios in an effort to investigate the most efficient cut-out-strengthening methods for improving ultimate strengths. Kim et al. [11] reported experimental results involving the buckling and ultimate strengths of perforated plates in an effort to improve the current design practice, by analyzing a total of 90 unstiffened and 9 stiffened plates and additionally investigating their collapse characteristics under axial compression, using nonlinear FEA. Their study resulted in a new formula by comparing numerical and experimental results for critical buckling strength of perforated plates. Alagusundaramoorthy et al. [12] studied the ultimate strength of stiffened panels with cutouts under uniaxial compression using an approximation method based on an approach of modeling struts that modeled the ultimate strength of simply supported stiffened panels with initial imperfections and cutouts. Their proposed method compared well with experimental results for ideal stiffened panels with square cutouts in various sizes.

As many engineers have struggled to find ways that increase the buckling and ultimate strengths through methods for local reinforcement around holes, research on verifying these stiffening methods has not been conducted with sufficient scientific and methodological rigor. Further, in practice empirical designs are commonly applied on the basis of experience. Furthermore, the effect of local reinforcement methods has not yet been thoroughly investigated.

Therefore, this paper focuses on the elastic and critical buckling strengths as well as ultimate buckling strength under three different methods for reinforcing perforated plates i.e. the carling method, the doubling method, and the face-plating method. Non-linear buckling analysis was conducted using a commercial FEA code, MSC NASTRAN, for a range of important factors including stiffener height, width, and thickness. In addition, various loading conditions such as axial loading and in-plane edge shear loading condition as well as imperfections caused by welding were considered. The results of this study have potential application to the general problem of adopting perforated plates for structural design.

2. Finite element analysis

2.1. Description of target modeling

A circular, elliptical, or rectangular type of cutout may be used for ships and offshore structures, but a stadium-type opening is found most frequently in practice, so it is the only cutout considered in this study. This assumption is based on the cutout shape was found to not affect the buckling or ultimate strengths of the perforated plate. Additionally, in this study, the cutout was located at the center of the plate so in order to present a conservative analysis. A schematic for the modeled perforated plate geometry and specific dimension has been provided in Fig. 2(a) and Table 1, respectively. In the present

Fig. 1. Perforated plate in the ship and offshore structures.