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Structural capacity of plates and stiffened panels of different materials with opening

S. Saad-Eldeen[1], Y. Garbatov, C. Guedes Soares*

Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001, Lisboa, Portugal

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ABSTRACT

This work experimentally investigates the influence of different opening sizes and shapes, different steel materials and structural configurations on the ultimate strength of steel plates. A series of experiments have been carried out for unstiffened plates and stiffened panels having an opening of different shape and size in addition to different constructional steels; high tensile and mild steel. The effect on the ultimate load carrying capacity of the opening sizes and shapes, different steels and structural configurations, post-collapse deformations and strain energy density are investigated and analysed. Several relationships of the ultimate stress ratio, ultimate load carrying capacity ratio for different steels as a function of the residual breadth ratio are presented and discussed. A relationship showing the effect of different structural configurations on the ultimate load carrying capacity ratio is presented. Several observations and concluding remarks are derived from the experimental results.

1. Introduction

Plates and stiffened panels in both intact or with an opening are the main structural components of many steel structures such as ships, offshore structures and bridges. These types of structural components are subjected to several types of loads. For intact plates and stiffened panels, large experiences have been accumulated regarding its ultimate strength as the work done by Guedes Soares and Søreide (1983), Smith et al. (1991), Ueda and Yao (1991), Guedes Soares (1992), Guedes Soares and Kmiecik (1993) and Paik and Thayamballi (1997).

The existence of openings in thin-walled structures is necessary for inspection, passing pipes or to be used as a weight reduction solution. The shape, size and location of the opening differ according to the purpose of the opening and the applied loads. For the ultimate strength of unstiffened plates with an opening, many numerical analysis have been performed i.e. Shanmugam et al. (1999), Harada and Fujikubo (2002), El-Sawy et al. (2004), Paik (2007a, b), Wang et al. (2009), Yu and Lee (2012) and Saad-Eldeen et al. (2014). Several affecting parameters as different loading and boundary conditions, plate slenderness, opening size, shape and orientations are considered. Several conclusions were obtained; the plate with a circular opening has better strength than the one with a square opening. For a shear loading, the plate aspect ratio is not a sensitive parameter and on the contrary to the compressive loading. The vertical orientation of the opening has a significant effect on reducing the ultimate strength rather than the horizontal one. As the plate thickness and the opening size increases, the yield strength at the effective cross-section becomes the upper limit of the ultimate strength. By increasing the plate slenderness, the buckling stress decreases, showing a constant reduction for larger slenderness and small opening sizes. Several expressions have been developed for estimating the residual strength of plates with an opening.

Experimentally, Saad-Eldeen et al. (2016a, b, c) carried out a recent series of ultimate strength tests for in-service unstiffened plates with different opening shapes (circular and elongated circle) and sizes, in addition to the presence of several damage scenarios as corrosion degradation and locked cracks. The following conclusions have been obtained, for the plates with an elongated circular opening Saad-Eldeen et al. (2016c), as the residual breadth decreases, the reduction of the ultimate load carrying capacity increases linearly. For a small opening size, the specimen behaves as a plate, but by increasing the opening size, the specimen acts as a column, which leads to the occurrence of a column-buckling mode, accompanied by twisting.

With the existence of symmetrically locked crack oriented at 45° from the plate's longitudinal axis, Saad-Eldeen et al. (2016a) observed that the resilience of the plate with a combined action of an elongated circular opening and cracks is decreasing linearly as the crack length increases. On the other hand, as the crack length increases, the

* Corresponding author.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).
[1] On leave from the Naval Architecture and Marine Engineering Department, Faculty of Engineering, Port Said University, 42526, Port Fouad, Egypt.

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toughness decreases in a nonlinear manner. A decrease of the proportional limit and ultimate stress occurs as the crack length increases. For plates with a circular opening, corrosion degradation and locked cracks, Saad-Eldeen et al. (2016b) indicated that the complexity of the deformed shape (crack and imperfection) in addition to the plate thickness may enhance the capability of the plate to withstand more loads, conditionally that the crack dominates the final collapse mode. At the crack ends, with decreasing the breadth ratio, the ultimate stresses increase nonlinearly, taking into account the effect of corrosion degradation on the material properties.

For stiffened panels with and without cut-out, a series of experimental tests under uniaxial compressive loading has been performed by Alagusundaramoorthy et al. (1995). They concluded that the strength reduction due to cutouts is more to the plate initiated failure (24–37%) than for the stiffener-initiated failure (20%–21%).

Kim et al. (2009) carried out a series of experimental and numerical analyses on both buckling and ultimate strength of plates and stiffened panels with an opening, subjected to axial compressive loading. It was stated that the opening location has a slight effect on the plate buckling strength. The effect of an opening on reducing the ultimate strength is less for stiffened panel than plates.

For high-tensile steel, Saad-Eldeen et al. (2017a) investigated experimentally the compressive capacity of reinforced high-tensile steel panels with a large lightening opening. A series of experiments have been carried for circular and elongated circular opening of different sizes. Based on the experimental results it was concluded that for a large opening used as a solution for weight lightening, the elongated circular opening is more effective than the circular one with 37% of weight reduction, keeping the same strength capacity.

For reinforced plates with more than one elliptical opening, Cheng et al. (2014) concluded that the reinforcement with continuous longitudinal stiffeners is most efficient for perforated plates with continuous elliptical holes, followed by the flat stiffeners reinforcement. In addition, the effect of both opening spacing and plate aspect ratio on the ultimate strength is negligible.

Kim et al. (2015) studied the optimal reinforcement method that maximizes the buckling and ultimate strength of a perforated plate. It was stated that the doubling plate method around the opening is most effective for longitudinal compression loading, which agrees with the work done by Saad-Eldeen et al. (2017b) for strength enhancement of cracked swash bulkheads of jack-up spud-can. In case of in-plane edge shear, the face plating or collar plate method is more effective.

Other structural components such as curved plate girders with web openings were tested by Lian and Shanmugam (2003). The experimental results showed that the ultimate load capacity of the girders dropped linearly with increasing the opening size. For smaller web openings, as the degree of curvature increases, the ultimate load carrying capacity decreases.

For box girder structures, Saad-Eldeen et al. (2015, 2016d) performed a series of static nonlinear finite element analyses for box girders with one and multiple openings. Different locations of the opening around the midsection, along with the side shell and different flooding levels were studied. For openings around the mid-section, the opening in the sheer strake and deck stringer plates shows a higher strength reduction, higher stresses, stiffener tripping and plate distortion. For openings along the side shell, by increasing the opening size, the corresponding curvature to the ultimate bending capacity decreases, which indicates the lower energy needed to reach the ultimate strength as the opening size increases.

Li et al. (2016) tested experimentally the overall buckling behaviour of high tensile steel welded box columns and flame-cut H columns with a yield stress of 690 MPa. It was concluded that the flame heating treatment for straightening is prohibited because it reduced the yield strength by 20%.

Ban and Shi (2018) performed a parametric analysis of high steel columns with various steel grades, where several welded cross-sectional geometric parameters, slenderness and initial imperfections were considered. It was concluded that the effect of initial geometric imperfections on the overall buckling behaviour of high tensile steel column is slightly lower than mild steel.

The analysis presented here is a continuation of a long-term study dealing with steel structures with openings and subjected to different degradation and deterioration scenarios. The focus of this research is on the effect of the opening with different sizes on the ultimate strength of high tensile steel specimens. In addition, the effect of different steel materials and opening shapes on the residual strength and the structural behaviour of unstiffened plates. The effect of different structural configurations of plates with a circular opening, on the structural response and the load carrying capacity, is analysed.

2. Experimental tests description

The ultimate compressive strength tests were carried out for three groups of specimens; group 1 are plate specimens made of high tensile steel HTS_P-P-C_i, with a circular opening of different sizes. For the second group, the plate specimens of mild steel material contain an elongated circular opening with variable sizes MS_P-P-E_i, where the third group is for stiffened panels of high tensile steel with different sizes of a circular opening HTS_{SP}-SP-C_i. The testing machine used in the experiment is a universal machine as shown in Fig. 1, where the specimen has been mounted between two stiff supporting clips, using bolt connections. The used supports impose conditions of constrained lateral displacement and rotation within the depth of the support of 20 mm. The specimen is subjected to a uni-axial compressive load, developed by a 250 kN hydraulic jack with a rate of 0.5 kN/s. The load is transmitted to the specimen through a horizontal thick plate as shown in Fig. 1.

Two instruments are mounted to the tested specimens during the test in order to measure the lateral displacement; displacement gauge and the local strain; mechanical strain gauge, see Fig. 1 (left). In addition to the recorded axial displacement by the machine itself. The specimens of group 1 and 3 are made of high tensile steel material HTS with a yield stress and Young's modulus of 690 MPa and 206 GPa, respectively, while the material of group 2 is low carbon mild steel MS with a yield stress and Young's modulus of 235 MPa and 206 GPa, respectively.

Fig. 2 shows the geometrical configurations of the tested specimens; plates and stiffened panels with circular and elongated circular opening, where a is the specimen length, b is the specimen breadth, a_1 is the opening length, b_1 is the opening breadth, d is the opening diameter and b_R is the residual breadth of the specimen due to the opening. The geometrical characteristics of the tested specimens as groups are given in Table 1. To introduce the openings with different shapes and sizes, a laser-cutting has been used, in order to avoid any additional deformation and residual stresses due to the cutting process. Before the ultimate compressive test, the initial imperfections have been checked; the first group specimens with a circular opening and HTS material, P-C_i showed almost flat shape with a zero imperfection. For the second group with an elongated circular opening and MS material P-E_i, the recorded initial imperfection for all specimens is 1 mm with an almost symmetric upward half wave, as mentioned in Saad-Eldeen et al. (2016c). The third group specimens show different upward initial imperfection amplitude of 4 mm, 4 mm and 3 mm for specimens SP-C1, SP-C2 and SP-C3, respectively, Saad-Eldeen et al. (2017a).

3. Experimental results

The experimental tests for the three groups of specimens were carried out in the same conditions, in order to satisfy a reasonable comparison. A uni-axial compressive load was applied along the breadth (short edge) of the specimen, see Fig. 1, while the unloaded edges along the length of the specimen are totally free. These types of free boundary conditions may simulate a structural configuration of structural