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Experimental investigation on the residual strength of thin steel plates with a central elliptic opening and locked cracks

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This work investigates the residual structural capacity of experimentally tested steel plates with a large central ellipsoidal opening with and without locked cracks, subjected to uni-axial compressive load. A series of experimental tests have been carried out. The tested plates were a part of a real box structure, which represents a scaled midship section of single hull tanker ship, exposed to a corrosive seawater environment. A plate with one large opening with different crack lengths is analysed. The influence of the combined effect of the plate opening and different crack lengths on the residual strength is investigated. The experimental results; force–displacements relationships, dissipated energy, stress–strain relationships, resilience and toughness are presented and analysed. The stresses at particular locations along the plate specimens are estimated and analysed. Several collapse modes are observed and discussed. The experimental results of the tested specimens have been compared with other test results for plates with different opening sizes, confirming the significance of the combined effect of an opening with simultaneous locked cracks on the local and global structural behaviour.

1. Introduction

Plates, stiffened panels and box girders may be perforated purposely by openings for passing pipes, inspections, reducing steel weight or other design reasons. Due to the complex and severe operating conditions, several damage scenarios may occur and cracks may initiate simultaneously with the openings.

There are many reasons that may cause a crack initiation, as a local stress intensity, pitting corrosion and welding defects. The orientation of the crack is haphazard and depends mainly on the type and direction of the acting loads. The mechanism of the crack propagation depends on plate dimensions, initial imperfection and applied loads; therefore, the assessment of the residual strength of the plate with an opening and a presence of a crack is an important issue to be analysed.

Several research analyses are dealing with the residual strength of steel plates with cracks i.e. Riks et al. (1992) studied buckling and post-buckling behaviour of centrally cracked plates under tension, using the finite element method. It was indicated that the stress intensity around the crack can be magnified as a result of the buckling and deformed shape and increases with increasing the crack length.

Vafai and Estekanchi (1999) analysed the responses of cracked plates and shells in the elastic range under axial tensile loading, considering the effect of mesh refinement at the crack tip, boundary conditions, Poisson's ratio, crack length and shell curvature. It was stated that the effect of boundary condition vanishes, when the plate aspect ratio is bigger than two. By increasing the crack length, the compressive stresses at the crack centre increase. Considering the same affecting parameters in compression and tension, Brighenti (2005) concluded that for cracked plates, the buckling phenomenon depends on the plate's boundary conditions in case of compressive stresses. It was observed that the crack closure effect is less sensitive to the initial imperfection in case of compressive loads and more sensitive with tensile loads.

The effect crack location, orientation and size has been studied experimentally and numerically by Paik et al. (2005), for plates subjected to axial compression. It was concluded that the ultimate strength of the plate reduced significantly in case the cracks were located at the longitudinal edge of the plate.

The residual strength and stiffness degradation of a centrally cracked steel plates subjected to shear loading have been studied by Alinia et al. (2007), through varying both crack length and orientation. It was concluded that the crack effect is very sensitive to the orientation, especially in the compression portion. Regardless the individual effect of the crack length and orientation, the

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combination between them may magnify the degradation effect on the ultimate strength.

For aluminium plate components, Seifi and Khoda-yari (2011) analysed experimentally and numerically the effects of crack length/orientation, plate thickness, aspect ratio and loading conditions, on the ultimate strength. It was concluded that with increasing the crack length as well as the angle between the cracks and loading direction, the buckling load decreases. It was observed that the effect crack orientation on the buckling load is negligible, when the crack length to plate width ratio is smaller than 0.1.

Regarding the ultimate strength of cracked stiffened plates, Margaritis and Toulios (2012) concluded that, if the crack faces came into contact, and depending on the aspect ratio and crack length, the structural stiffness may slow down, or even temporarily reverse the rate of collapse, or results in a small increase of the ultimate strength. Also, the failure mode may depend on the crack length.

Bayatfar et al. (2014) analysed the influence of crack lengths and locations on the ultimate compressive strength of imperfect unstiffened and stiffened plate elements. It was observed that the effect of crack on the reducing the ultimate strength is increasing as the crack located near the crest of the initial imperfection, rather than the location with zero imperfection.

For cracked stiffened panels, Paik and Kumar (2006) investigated numerically the ultimate strength of a longitudinally stiffened panel with cracks subjected to axial compressive or tensile loads. It was concluded that the crack significantly reduces the ultimate strength of the stiffened panel as out-of-plane deformation increases.

Xu et al. (2014) analysed numerically the residual ultimate strength of stiffened panels with locked cracks under axial compressive loading. The influence of various geometrical characteristics of cracks and panels was investigated. It was concluded that the effect of the crack length on the residual ultimate strength depends on the crack orientation, where a slight effect occurs for longitudinally oriented crack and significant one for the transversely oriented crack.

For large scale structural components as box girders, Shi and Wang (2012) explored the ultimate strength of an intact open box girders with cracks, subjected to different loading conditions, as a function of crack length and locations. It was concluded that the box girders with a crack located at the edge show the biggest reduction of the ultimate strength in torsion, compression and bending loads.

Considering both corrosion and crack effects, Saad-Eldeen et al. (2015) assessed numerically the residual strength of a corroded box girder subjected to compressive load and a non-propagating crack, accounting for different crack sizes and locations, different global initial imperfection shapes at the deck panel. It was concluded that the ultimate bending moment is decreasing non-linearly with increasing the crack length. Up to certain crack length of 0.5 m, the deformed shape of the box girder changes, showing a lower reduction of the ultimate bending moment, compared to other cases with a small crack length. The closing and opening of the crack is following the initial imperfection shape and the imperfection shape is a dominating factor in the final collapse mode.

Most of the experimental tests for unstiffened and stiffened plates, stiffened panels and box girders are based on new built specimens, which taking into account only the strength of these structural elements of the zero service life. These specimens are not capable of representing the real behaviour of the structural during the service life, due to the presence of many factors that affects the global and local behaviour of the structural elements that cannot be reproduced by such specimens.

From this perspective, Saad-Eldeen et al. (2012) analyse the initial and post-collapse plate deflections, based on measurement records of the experimental tests of three corroded box girders (Saad-Eldeen et al., 2011, 2013), which represent a scale model of single hull tanker ship, subjected to pure vertical bending loading. A relationship between different structural responses, the shape of the initial imperfections and the plate slenderness (function of thickness reduction due to corrosion) has been derived, led to a slenderness criterion, from which the post-collapse deformation shape can be predicted.

All above discussed research work dealt with the strength of structural components with cracks only and there is no any research done that is dealing with the residual strength of the plates having openings simultaneously with cracks subjected to compressive loads. The study presented here is a continuation of the one that is dealing with damaged steel structures, including corrosion deterioration, denting and collision. The present study focuses on the assessment of the local and the global structural behaviour, the residual strength of in-service steel plates under the combined action of an opening and locked cracks with different crack lengths, subjected to uni-axial compressive loading.

2. Experimental test setup

The experimental compressive test setup of the plate specimen is shown in Fig. 1, in which the plate has been mounted between two stiff supporting clips, using bolt connections. The supporting clips imposed conditions result in constrained lateral displacements and rotations within the depth of the support of 20 mm, where the unloaded edges are totally free. The plate is subjected to uni-axial compressive loading, generated through a 250 kN hydraulic jack and transmitted to the plate through a horizontal thick plate, as shown in Fig. 1.

A displacement gauge has been mounted in the mid-length-residual breadth of the plate specimen; in order to measure the lateral displacement due to the applied load, see Fig. 1 (right). In addition to that, one mechanical strain gauge has been mounted on the other side of the mid-length-residual breadth of the plate, with a distance of 15 mm from the plate edge, to measure the strain, as may be seen from Fig. 1 (right). The vertical displacement generated by the movement of the hydraulic jack piston is measured by the testing machine. The output results; force, vertical/lateral displacement and strain measurements are directly recorded by a computer system.

The tested specimens were a part of box girder that was built from normal steel with a yield stress and Young's modulus of 235 MPa, 206 GPa and a plate thickness of 4.5 mm, respectively. The box girder was initially tested in a corrosive environment in direct contact with open seawater, representing an initial corrosion degradation level, as described in details in (Saad-Eldeen et al., 2011), after that the box girder has been tested under vertical bending moment by Saad-Eldeen et al. (2010). The tested plates were cut by a laser cutting machine from the areas of the box girder that was only subjected to tensile load during the ultimate bending test. Before the compressive test, a survey of thickness measurements has been performed to measure the remaining thickness of the tested plates, resulting in an average thickness of 3.9 mm.

The opening and cracks have been introduced using a laser cutting technique, to avoid any deformation and residual stresses. One ellipsoidal opening has been introduced at the centre of the plate with simultaneous four cracks, which are symmetrically oriented at 45°; measured from the plate's longitudinal axis, as presented in Fig. 2. The geometrical characteristics of the analysed plate specimens are given in Table 1 and shown in Fig. 2. A limited