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Experimental and numerical analyses of the ultimate compressive strength of perforated offshore tubular members

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ABSTRACT

Tubular steel members are widely used as structural elements in offshore units. The strength capacity and design formulas for intact members, subject to axial compressive forces, have been thoroughly investigated. However, there are few studies on the behavior of perforated tubular members from offshore aged units and on their remaining load capacity assessment. Perforation damage leads to deterioration of strength capacity and life-time shortening of the structures. The aim of this paper is to present an experimental campaign and a numerical finite element model to obtain the ultimate strength of tubular structures with circular perforated damage subjected to axial compression. In the experimental program fifteen tubular scaled specimens are tested and results are compared with the ones from geometrical and material non-linear finite element model considering reconstructed geometries, variable thickness distribution and actual material stress-strain curves. Shell elements are used and the finite element meshes are obtained from detailed external wall 3D laser scanning of the experimental samples and ultrasonic thickness measurements in several cross-sections. Spatial thickness interpolation is performed to define the thickness in all meshed nodes. Results from numerical model analyses demonstrate considerable accuracy and good agreement with those directly measured from experimental perforated tubular member's samples in terms of axial load-displacement and strains. From the results, it has been concluded that the perforation size is the most important variable in determining the extent of the compressive strength degradation.

1. Introduction

Aging offshore units may suffer from structural deterioration associated with various types of inflicted damage, including deflected members, dents, tears, cracks, deformed shapes, missing members, loss of material and perforations. Each of these may affect the structure strength differently, and must be analyzed by specific techniques.

Integrity assessment of existing offshore platforms is necessary to ensure the structure fitness for purpose in view of demanding operating conditions associated to severe sea environment, which imposes fatigue damage and extreme loads. In addition, the structural elements are exposed to highly corrosive medium or may suffer vessel's impact, for instance. Often, platform retrofitting is required to allow accommodation of new operational conditions, therefore deck load increases as well. Experimental results of structural remaining strength capacity of damaged offshore tubular members facilitate the structural integrity assessment process.

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Objective data from numerical simulations may increase quality of decision and improve maintenance and repair strategies if the numerical model presents reliable results validated by experimental data. The prediction of member behavior by specific patterns of damage and determination of structure's health condition can be achieved with confidence, reducing costs and necessity to develop large series of experiments. Several works related to structural health assessment of damaged elements can be found in literature [1–6], but there is a lack of experimental work on damaged structures to allow numerical and/or analytical models' verification [7].

Tubular members are widely and advantageously used as structure components in offshore units due to low drag resistance and ease of handling [2]. There are several studies on the buckling strength of intact steel tubular columns and thin shell structures, and design formulas have been proposed. However, there are fewer studies on the mechanics of perforated cylindrical structures [8–13]. Studies related to damaged shells and/or tubular members can be classified according to the nature of damage, with physical or physical-chemical damage, respectively associated to material loss and change in material properties.

Perforations in tubular steel offshore structures are mainly generated by chronological presence of corroded areas, induced accidentally or by ineffective protection, therefore some models assess the remaining compressive strength for corroded members [4,5,14,15]. However, fewer articles address the behavior of perforated members.

References [16–18] provide equations to estimate the local buckling strength of corroded members as a function of the thickness loss. The member with the reduced thickness can then be evaluated as an undamaged member. This reduced thickness approach is generally conservative, as discussed in Ref. [19]. No information is available on the effect of localized corrosion on overall member strength. In this case, finite element analysis or a numerical segment approach based on empirical or analytical moment-axial force-curvature relations can be used according with the ISO 19902 [20].

Nishimura et al. [8] and Murakami et al. [21] developed experimental and numerical works for perforated tubular structures, considering only basic aspects related to the effects of size and localization of the perforation, where the mid-length of the member yields the lowest strength resistance. Another important research regarding perforated members was carried out by Okada et al. [22], who regarded the deterioration of tubular members as part of a reliability-based design of aged jacket structures. They used a modified Perry-Robertson's method, remarking that analytical formulations are in comparatively good correspondence to numerical simulations based on non-linear finite element models.

More recent studies, as references [23] and [24], deal experimentally with effects of corrosion derived from its distribution along the member or the imposed axial cyclic loading respectively, or examine numerically the effects of corrosion into ultimate strength and buckling behavior of locally corroded tubular members, such as reference [2].

The present work considers a study of tubular members from aged offshore units that reaches high concentration of corrosion during operating life, resulting in an extended perforation through the wall thickness. The study campaign aims at verifying experimentally and numerically the compressive strength reduction of damaged tubular members. Effects of some parameters that have not been addressed before, e.g. slenderness ratios, thickness variations and geometrical imperfections of the tubes are considered in order to obtain more reliable information for the numerical models.

The perforations simulated in the experimental and numerical models at half length of the tubular member mimics a heavy corrosion process that culminates in localized holes with a near circular profile. This phenomenon has been observed in actual flare booms, severely impacting the member's axial compressive load bearing capacity, which motivated this research program. It is not intention of this work to address the complex tubular member joint stress concentration effects, which may be object of future development.

Experimental and numerical investigations for fifteen perforated tubular samples are carried out. Perforations in twelve reduced scale samples are imposed by machining processes, also special fixation bases are designed and manufactured to allow free rotation w.r.t. one axis at the ends of the samples. Finite element numerical models are developed, the as measured surface reconstruction employed for actual mesh generation uses a reverse engineering prototyping by spatial mapping of external wall and thickness variations of all samples. Material constitutive behavior is also obtained for all tubular specimens. Finally, correlation between numerical predictions and experimental measurements are presented in terms of axial load versus end shortening and strains in several locations.

2. Experimental methodology

2.1. Experimental setup

Axial compressive experiments of tubular member samples were carried out in a 2.5 MN capacity MTS-311.14 rig frame testing machine (Fig. 1-a) at Ocean Structures Nucleus laboratory (NEO) of COPPE/Federal University of Rio de Janeiro.

As testing models, seamless tubular member samples (steel API 5L grade B) were used to represent structural prototypes. The models were tested under concentric axial compressive loads in which the boundary conditions (BCs) were simulated by structural bases designed to allow free rotation w.r.t. one axis at the ends of the samples (Fig. 1-b and c).

Fig. 1 shows details of the experimental setup. Fig. 1-a presents a sketch of the sample mounting scheme and the main rig frame arrangement. At the upper and lower sides of the sample, axial load cells of 400/200 kN and 2.50 MN are installed, respectively. Between the load cells and the sample, rotating bases are installed to ensure no bending moment at the ends. Fig. 1-b and c show details of the structural rotating bases which allow the specimens to rotate ± 40 deg about the X-axis but otherwise prevent any displacement. A schematic drawing of the fixation base is shown in Fig. 1-d. It can be observed that different supports allow testing of three tubular members with different dimensions (herein referred as classes A, B and C). A detailed scheme of the mechanism of fixing end rotation and its connections to the fixation base is presented on Appendix A.