Marine Structures 57 (2018) 121–132

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

Experimental and numerical analysis of residual stresses and strains induced during cold bending of thick steel plates

Bin Liu[a,b], R. Villavicencio[c,1], C. Guedes Soares[d,*,2]

[a] Key Laboratory of High Performance Ship Technology of Ministry of Education, School of Transportation, Wuhan University of Technology, Wuhan 430063, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE), Shanghai 200240, China
[c] Global Technology Centre, Lloyd's Register EMEA, Southampton S016-7QF, UK
[d] Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisboa 1049-001, Portugal

ARTICLE INFO

Keywords:
Thick steel plate
Marine structure
Residual stress and strain
Cold bending
Experiment
Finite element simulation

ABSTRACT

The paper presents an experimental and numerical analysis of the residual stresses and strains induced during the cold bending of thick steel plates. Cold bending technique is widely used in the shipbuilding and offshore industry, and thus it is important to know about the changes in the material characteristics induced during the metal fabrication process. For this purpose, firstly, three-point cold bending experiments are conducted with a relatively small indenter on the specimens cut from a thick steel plate (54 mm), and afterwards, tension tests are carried out on tensile coupons cut from the already bent specimens. Thus, the mechanical properties (engineering stress-strain curve) of the tensile coupons cut from the loaded and unloaded locations are compared so that to determine the residual stresses and strains resulting from the bending process. A numerical simulation is performed with the explicit LS-DYNA finite element solver to replicate the experimentally determined residual stresses and strains. The simulation provides information of the distribution of the residual stresses and strains along the span and through the thickness of the specimens. It is found that the local deformation underneath the indenter harms severely the structural integrity, producing large residual stresses and strains during the bending process. This work illustrates the potential use of finite element analysis to evaluate the residual stresses and strains in metal fabrication processes.

1. Introduction

The cold bending of plates and stiffeners is a common process for manufacturing ships and offshore structures. Thick steel plates also represent structural components of marine offshore structures, since, commonly, high-order curvature hulls of offshore platforms are fabricated by forming and bending. Although the cold bending techniques have shortcomings, it is more efficient to fabricate steel plated structures by cold bending, instead of line heating, to reduce a serious oxidation of steel components. The structural cold-bending involves loading of the metal into the plastic range, followed by elastic unloading, affecting the material's mechanical properties. Such large induced inelastic deformations result in structural residual stresses and strains, potentially affecting the structural integrity and service life of the structure. Consequently, attention is to be paid to the residual stresses and strains as they

* Corresponding author.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).
[1] Member ISSC2018 Committee III.2 Fatigue and Fracture.
[2] Chair ISSC2015, Chair ISSC-ITTC Joint Committee.

http://dx.doi.org/10.1016/j.marstruc.2017.10.005
Received 24 July 2017; Received in revised form 12 September 2017; Accepted 9 October 2017
0951-8339/

play an important role in the design of steel structures [1].

The development of cold bending techniques necessitates an accurate representation of the changes in material properties induced by the structural fabrication. For the purpose, it is necessary to evaluate: built-in residual stress patterns and mechanical properties, such as uniaxial stress-strain behaviour, including values for the proportional limit, the yield and ultimate stresses, the extent of yielding plateau and strain hardening parameters [2].

While attention on the residual effects has been paid by the pipeline and bridge industry [3–6], there is not much relevant investigation on these effects for the structural fabrication of ships and offshore platforms. It is known that the residual stresses and strains affect strongly the nonlinear mechanical behaviour of structures, when subjected to fatigue, ultimate and impact loads, and thereby they are considered in the limit state design, as the variation of residual stresses leads to early yielding on the faces of cold-formed steel structures, and the plastic strain induced by the cold bending reduces the material ductility, increasing the risk of fatigue problems and ultimate capabilities.

The fabrication of structural components by cold bending may result in similar mechanical characteristics of dented structures, as initial imperfections and residual strains in the dented plates also affect their ultimate strength [7–9], impact resistance [10], and fatigue performance [11]. This also transmits the importance of evaluating the residual stresses and strains incurred during the cold bending process.

In the cold bending process the residual stresses and strains vary through the thickness, affecting the structural ultimate strength due to the yielding at the plate surfaces [12]. The bend portion of thick steel plates is only partially plastic, unlike the thin steel plates bent where a fully plastic behaviour is observed.

The most accurate method to evaluate the residual effects of cold bent structures is experiments, as those reported in Refs. [5,6,12]. On the other hand, the finite element analysis can provide a better understanding of the fabrication process when they are validated against experimental data [3,6,13]. The material nonlinearities, in particular the plastic strain hardening, play an important role in the simulations. Analytical formulae have been also proposed to calculate the residual stresses and strains for idealized steel plate bending [12,14–16].

For a standard and known structural deformation, the residual stresses can be found by summing the loading and unloading stresses in the cold bent plate (see Fig. 1), on the other hand, the residual strains are close to the effective plastic strains that occur from the cold bending process. However, for cold bent thick steel plates, the indenter easily produces local deformation of the plate underneath the indenter, inducing even larger residual stresses and strains, and thus the analytical formulae cannot evaluate well the strength of thick steel plates.

The present paper investigates the residual stresses and strains incurred during the cold bending of thick steel plates. This is done through three-point bending experiments, tension tests, and a finite element simulation of the bending tests so that to propose experimental and numerical evaluation procedures for the residual effects induced by the structural cold-bending.

The experiments evaluate the changes in the material mechanical properties and the built-in residual stresses and strains of the cold bent plates. Firstly, three-point cold bending tests with a relatively small indenter are conducted on four specimens cut from a 54 mm thick steel plate. Afterwards, tension tests are carried out on tensile coupons cut from the already bent specimens to evaluate the changes in the material's mechanical properties at different locations. Thus, the experimental evaluation of the residual stresses and strains is done by comparing the mechanical properties of intact and the deformed materials, and the variation of the yield strength and the residual stresses and strains in the deformed sections are established based on the experimental stress-strain curves. The finite element simulation helps to determine the magnitudes and distributions of the residual stresses and strains through the thickness, and also to compare the residual stresses and strains at the end of the fabrication process.

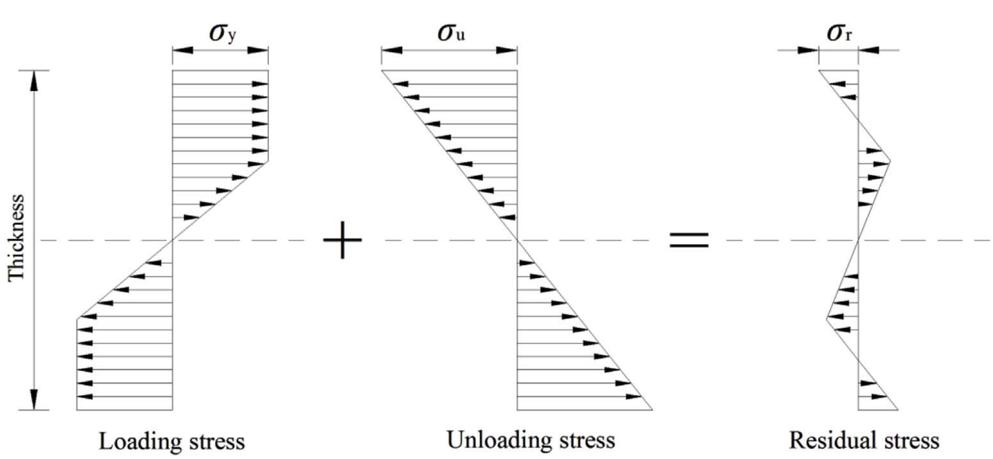

Fig. 1. Loading, unloading and residual stresses through plate thickness in plastically deformed section.