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Thin-Walled Structures 45 (2007) 135–148
THIN-WALLED STRUCTURES
www.elsevier.com/locate/tws

Plastic mechanism analysis of fabricated square and triangular sections under axial compression

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Received 24 December 2006; received in revised form 13 February 2007; accepted 13 February 2007
Available online 3 April 2007

Abstract

This paper presents a plastic mechanism analysis to predict the complete load-shortening behaviour of fabricated square and triangular section (FSTS) stub columns. Very high strength (VHS) circular steel tubes with a nominal yield stress of 1350 MPa are placed at each corner of the section and welded to Grade 350 steel plates to form a FSTS. Three stages are considered in the analysis: (1) both the VHS tube and steel plate are elastic, (2) plastic mechanism starts to form in steel plates while the VHS tube remains elastic (3) plastic mechanism occurs in both steel plates and the VHS tubes. Discussions are made on the factors affecting the types of mechanism (“flip-disc” versus “roof-type”) in steel plates and the effect of initial geometrical imperfection of the plates on the analysis. Simplified formulae were given for an easy application of the theory developed. The predicted load-axial shortening curves are in good agreement with those obtained by experiments. The predicted ultimate load carrying capacity is about 6% to 8% lower on average than the experimental capacity.

Keywords: Plastic mechanism analysis; Yield line theory; Fabricated square and triangular sections; Geometric imperfection; Complete load-shortening behaviour

1. Introduction

This paper forms part of a research project on fabricated square and triangular sections (FSTS) utilizing very high strength (VHS) circular steel tubes. Tests on FSTS stub columns were reported by Zhao et al. [1]. Finite element analysis and rational design models were given in Binh et al. [2] and Rhodes et al. [3]. This paper presents a plastic mechanism analysis to predict the complete load-shortening behaviour of FSTS stub columns.

The plastic mechanism analysis has been widely used to study steel members and connections that involve local collapse mechanisms. The recent developments in this method were reviewed by Zhao [4] where an extensive list of references was given. The application of such method to fabricated sections that involve two components with different yield stress is not often found in the literature. The challenge is how to consider the interaction of the two elements. The yield stress of the VHS tubes is around 1350 MPa which is more than 3 times that of steel plates. Three stages are considered in the analysis: (1) both VHS tube and steel plate are elastic, (2) plastic mechanism starts to form in steel plates while VHS tube remains elastic, (3) plastic mechanism occurs in both steel plates and VHS tubes. Elastic analysis is used for stage one followed by plastic mechanism analysis in stages 2 and 3 to generate a complete load-shortening response of FSTS stub columns.

The factors affecting the types of mechanism (“flip-disc” versus “roof-type”) in steel plates are discussed in the paper. It seems that the restraint against rotation (RAR) provided by the VHS tubes plays an important role in forming the roof-type mechanism. The mechanism in the VHS tubes is a parabolic-type of mechanism. Initial

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doi:10.1016/j.tws.2007.02.006

Nomenclature

A_t	measured cross-sectional area of one very high strength (VHS) circular steel tube in the specimens
A_p	measured cross-sectional area of one steel plate in the specimens
A_{HAZ}	estimated heat-affected zone (HAZ) area in a VHS tube
a	mechanism dimension in the X direction of the VHS tube plastic mechanism (see Fig. 3)
B	measured plate width (see Fig. 2)
B_e	effective plate width
c	measured mechanism dimension of the plate folding mechanism (see Fig. 2)
c_e	effective mechanism dimension in the Y direction
d	outer diameter of VHS tube
e	axial shortening of the specimens
E	elastic modulus of the plates and the VHS tubes
f_{HAZ}	measured yield stress for HAZ in VHS tubes
f_{yp}	measured yield stress for steel plates
f_{yt}	measured yield stress for VHS tubes
h_1, h_2	mechanism dimensions in the X direction of plates (see Fig. 2)
L	length of the specimens
n	number of plates (or VHS tubes) in a specimen
P_1	axial load component corresponding to one steel plate
P_{1inner}	axial load component corresponding to the plate folding mechanism for the inner region
P_{1edge}	axial load component corresponding to the plate folding mechanism for the edge region
P_2	axial load component corresponding to one VHS tube
P_{total}	total axial load corresponding to the FSTS stub columns
r	mechanism dimension in the Y direction of the plastic mechanism for VHS tubes (see Fig. 3)
t	measured VHS tube thickness
T	measured plate thickness
z	mechanism dimension of the VHS tube plastic mechanism (see Fig. 3)
β	angle defined in Fig. 3 for the VHS tube plastic mechanism
$\Delta_{0\,max}$	maximum measured initial geometric imperfection of the plate in a specimen
Δ_1	local lateral deformation at centre of the plate folding mechanism (see Fig. 2(b))
Δ_2	local lateral deformation in the plate folding mechanism (see Fig. 2(b))
Δ_3	local lateral deformation defined in Fig. 3 for the VHS tube plastic mechanism
ε	strain
ε_p	strain in steel plates
ε_t	strain in VHS tubes
λ_1, λ_2	mechanism length in the X direction of the plate folding mechanism defined in Fig. 2
λ_e	plate element slenderness
λ_{ey}	the element yield slenderness limit given in the Australian Standard AS4100
θ	inclined angle of hinge lines AB and GH in Fig. 2
θ_1	inclined angle for hinge lines MN and QN of the VHS tube plastic mechanism in Fig. 3
σ	stress
σ_p	stress in steel plates
σ_t	stress in VHS tubes

geometrical imperfection of the plates and the HAZ softening in VHS tubes due to welding are also taken into account in the plastic mechanism analysis.

A comparison was made between the predicted complete load-shortening response and the experimental results of 20 specimens reported in Zhao et al. [1]. The predicted curves had a reasonable agreement with the experimental ones. Simplified formulae were also presented for an easy application of the theory developed.

2. Experimental observation and assumed plastic mechanism models

2.1. Material properties

The average yield stress of steel plates is f_{yp} of 415 MPa [1] whereas that of the VHS tubes is f_{yt} of 1352 MPa [5,6]. The average Young's modulus of steel plates and VHS tubes in the above references is adopted, i.e. E of 211,300 MPa. The yield stress in the HAZ of VHS tubes was found [7] to be about 50% of that of VHS tubes. It is also assumed in the analysis that the stress in HAZ is 50% of that in VHS tubes even before yielding based on the experimental observation in Ling [8] where eight tensile coupons of VHS tubes and corresponding welded VHS tubes were tested.

The stress–strain relationship for steel plate and VHS tubes given in Rhodes et al. [3] is adopted, i.e.

$$\varepsilon_p = \frac{\sigma_p}{211300} + 0.002\left(\frac{\sigma_p}{415}\right)^{15.4}, \tag{1}$$

$$\varepsilon_t = \frac{\sigma_t}{211300} + 0.002\left(\frac{\sigma_t}{1352}\right)^{26.9}. \tag{2}$$

Because of the deformation compatibility, the strain in plate (ε_p) can be considered the same as the strain in VHS tube (ε_t). The steps taken in analysis up to the yielding of the VHS tubes are: first of all, specify a value of strain, then solve Eq. (2) numerically for the VHS tubes stress. For the