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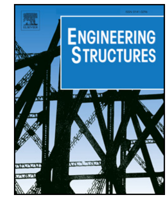

Local buckling of steel plates in concrete-filled steel tubular columns at elevated temperatures

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ABSTRACT

Local buckling remarkably reduces the strength of steel plates in rectangular thin-walled concrete-filled steel tubular (CFST) columns at ambient temperature. This effect is more remarkable at elevated temperature. However, there have been very limited experimental and numerical investigations on the local and post-local buckling behavior of steel plates in CFST columns at elevated temperatures. This paper presents numerical studies on the local and post-local buckling behavior of thin steel plates under stress gradients in rectangular CFST columns at elevated temperatures. For this purpose, finite element models are developed, accounting for geometric and material nonlinearities at elevated temperatures. The initial geometric imperfections and residual stresses presented in steel plates are considered. Based on the finite element results, new formulas are proposed for determining the initial local buckling stress and post-local buckling strength of clamped steel plates under in-plane stress gradients at elevated temperatures. Moreover, new effective width formulas are developed for clamped steel plates at elevated temperatures. The proposed formulas are compared with existing ones with a good agreement. The effective width formulas developed are used in the calculations of the ultimate axial loads of rectangular CFST short columns exposed to fire and the results obtained are compared well with the finite element solutions provided by other researchers. The initial local buckling and effective width formulas can be implemented in numerical techniques to account for local buckling effects on the responses of rectangular thin-walled CFST columns at elevated temperatures.

1. Introduction

Filling concrete into a rectangular thin-walled steel tubular column as shown in Fig. 1 results in a significant increase in its ultimate strength and fire resistance as reported by Schneider [1], Sakino et al. [2], Liang et al. [3] and Dundu [4]. However, the thin steel tube walls of a rectangular concrete-filled steel tubular (CFST) column under applied loads may undergo outward local buckling, which remarkably reduces the strength of the column as discussed by Liang [5]. In a fire condition, the strength and stiffness of steel plates decrease significantly with an increase in the elevated temperature [6,7]. As a result, the local buckling of thin steel plates at elevated temperatures is more likely to occur than the ones at ambient temperatures. In addition, the local and post-local buckling strengths of a thin steel plate at elevated temperature are much lower than those of the plate at ambient temperature. It is assumed that the steel tube walls of a rectangular CFST column under axial load and bending have a clamped boundary condition that recognizes the restraint provided by the rigid concrete core and are subjected to in-plane stress gradients [5]. The CFST columns have been widely used in high-rise composite buildings that could be exposed to fire. The behavior of CFST columns at elevated temperatures has been investigated by researchers [8–11]. However, little attention has been devoted to the study of the local and post-local buckling problem of clamped steel plates under stress gradients in CFST columns at elevated temperatures. Therefore, this paper addresses this challenging problem.

The local and post-local buckling behavior of steel plates under edge stresses at ambient temperature has been investigated by many researchers [12–17]. Shanmugam et al. [16] presented an analytical study on the post-local buckling strengths of steel plates in thin-walled steel box columns under biaxial loads. The steel plates of the hollow steel box column were assumed to be simply-supported. Effective width expressions were proposed by Shanmugam et al. [16] for calculating the post-local buckling strengths of simply-supported steel plates under stress gradients. Uy and Bradford [18] and Uy [19] conducted experiments to examine the local buckling characteristics of thin steel plates in rectangular CFST columns. Liang et al. [20] developed nonlinear finite element models to study the critical local and post-local buckling

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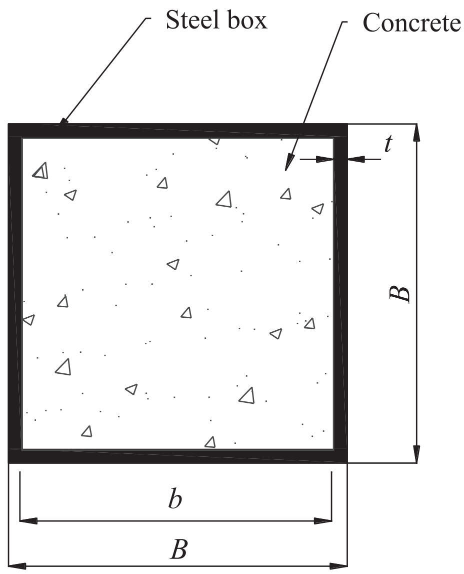

Fig. 1. Cross-section of square CFST beam-column.

strengths of steel plates in biaxially loaded CFST columns where the steel tube walls could be subjected to stress gradients. They proposed design formulas for computing the critical local and post-local buckling strengths of clamped steel plates under stress gradients. Moreover, effective width formulas were developed by Liang et al. [20] and implemented in numerical models by Liang [21,22] to account for local buckling effects on the strength and ductility of rectangular CFST columns.

Thin steel plates at elevated temperatures are more susceptible to local buckling because the elevated temperatures significantly reduce their stiffness and strength [7,23]. Heidarpour and Bradford [24] used a spline finite strip method of buckling analysis to investigate the local buckling of flange outstands subjected to elevated temperatures and proposed the plasticity and yield slenderness limits. The local buckling temperatures of plates under certain boundary conditions were also anticipated. Knoblock [7] investigated the local buckling behavior of steel sections at elevated temperatures. He suggested that the methods commonly used for calculating the strength of steel sections and for section classification subjected to elevated temperatures should be revised. Couto et al. [25] used a finite element analysis software to study the local buckling of simply-supported steel plates at elevated temperatures. These steel plates were subjected to in-plane bending or compressive edge stresses. The residual stress pattern at ambient temperatures was assumed for the plates at elevated temperatures. A constant initial geometric imperfection at the plate center was considered regardless of the plate thickness. Design formulas were proposed for determining the ultimate strength of simply-supported plates at elevated temperatures. Quiel and Garlock [26] utilized the computer program SAFIR to determine the local buckling strengths of steel plates exposed to fire. The loaded edges of the steel plate were assumed to be simply-supported while the unloaded edges were either simply-supported or fixed. However, the effect of residual stresses was not considered in their study. They proposed expressions for estimating the ultimate strengths of steel plates with various boundary conditions.

However, none of the studies reported in the literature investigated the local and post-local buckling behavior of clamped steel plates under stress gradients in CFST columns at elevated temperatures. There is a lack of effective width formulas for steel plates that could be incorporated in numerical models to account for local buckling effects on the strength of rectangular thin-walled CFST columns at elevated temperatures. Therefore, to bridge the knowledge gap, this paper utilizes the finite element program ANSYS 16 [27] to study the local and post-local buckling behavior of clamped steel plates under stress gradients in rectangular CFST columns at elevated temperatures. The effects of residual stresses and initial geometric imperfections presented in the steel plates are taken into account. Based on the results obtained from the nonlinear finite element analyses, design formulas are proposed for determining the initial local and post-local buckling strengths of clamped steel plates under stress gradients at elevated temperatures and verified by comparisons with the ones proposed by other researchers and with finite element results on rectangular CFST short columns at elevated temperatures.

2. Nonlinear finite element analysis of plates

2.1. General

The finite element analysis program ANSYS 16 [27] was employed in the present study to investigate the critical local and post-local buckling strengths of steel plates in CFST columns at elevated temperatures. The steel tube walls of a rectangular CFST column under compression can only buckle locally outward due to the restraint provided by the concrete core. This restraint effect was considered in the finite element model by incorporating an initial geometric imperfection caused by the lateral pressure applied on the plate. This implies that the steel plate can only buckle locally outward in the nonlinear analysis. The local and post-local buckling of steel plates in CFST columns at ambient temperatures has been studied by Liang et al. [20] and the effective width formulas proposed by them have been incorporated in the fiber element models to accurately account for local buckling effects on the behavior of CFST columns by Liang [21,22]. As suggested by Liang et al. [20], the four edges of the steel tube wall were treated as clamped due to the restraint provided by the rigid concrete core. The boundary conditions of the clamped plate are schematically depicted in Fig. 2. A square steel plate was chosen to simulate the webs and flanges of a CFST column at elevated temperatures. The von Mises yield criterion was used in the material models to treat the material plasticity. The four-node shell/plate element SHELL 181 in ANSYS 16 was used to discretize the steel plate into a 20 × 20 mesh. The sensitivity analysis of the element size was conducted and the results obtained are shown in Fig. 3, which indicates that the 20 × 20 mesh is suitable in terms of the computational time and the accuracy of the results.

2.2. Applied edge stresses on steel plates

The two adjacent steel tube walls of a rectangular CFST columns under axial load and biaxial bending may be subjected to non-uniform compressive stresses while the other two adjacent walls are under in-

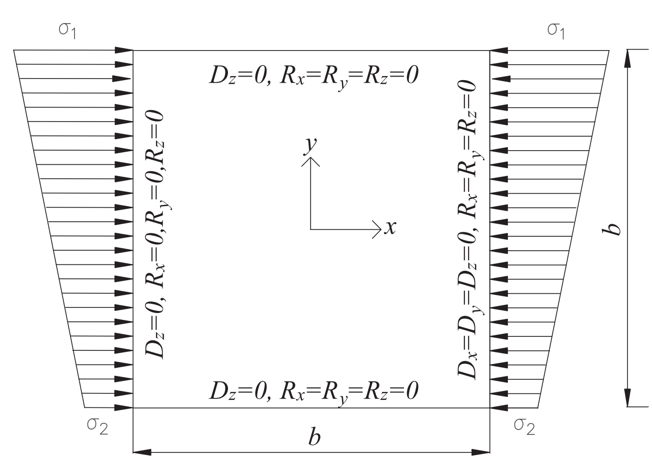

Fig. 2. Boundary conditions of clamped steel plate under compressive edge stresses.