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Elastic shear buckling of sinusoidally corrugated steel plate shear wall

Chao Dou [a,b,*], Zi-Qin Jiang [c], Yong-Lin Pi [d], Yan-Lin Guo [e]

[a] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, PR China
[b] Beijing's Key Laboratory of Structural Wind Engineering and Urban Wind Environment, Beijing 100044, PR China
[c] College of Architecture & Civil Engineering, Beijing University of Technology, Beijing 100124, PR China
[d] School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[e] Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China

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ABSTRACT

This paper deals with elastic shear buckling behavior of infill panels in sinusoidally corrugated steel plate shear walls, and fitting equations predicting the shear buckling loads are presented. Firstly by using finite element analyses (FEA), the previous formulae for bending rigidities of sinusoidally corrugated plates are revised, then pure shearing model are established to study the effects of key parameters on elastic shear buckling of sinusoidally corrugated infill panels, such as the aspect ratio, corrugation ratio, corrugation depth to plate thickness ratio and corrugation repeating number. Based on extensive FEA numerical results, fitting equations with good accuracy are proposed to estimate elastic shear buckling loads of sinusoidally corrugated panels, which are improved much compared with the solutions in previous studies. It is found that, the formulae for bending rigidities of corrugated plates revised in this paper are accurate compared with the previous ones. For sinusoidal corrugated infill panels, only global buckling and local buckling can be observed in the lowest buckling mode of eigenbuckling analysis, while interaction buckling is not obvious. The parameter of corrugation repeating number has a significant influence on elastic shear buckling loads, whereas it was neglected in previous studies.

1. Introduction

Steel plate shear walls (SPSWs) have been widely utilized as an effective lateral load-resisting system for high-rise buildings in high-risk seismic regions, due to the proper lateral stiffness, ductile behavior and large energy dissipation capacity [1–9]. Steel plate shear walls are traditionally infill flat steel plates framed by surrounding beams and columns. Thin flat SPSWs are widely used nowadays due to the high bearing efficiency and good economy, but still the following disadvantages exist: (1) The post-buckling diagonal tension field of infill panels induces large tension forces on the frame, which brings high demand for the stiffness and may harm the structural behavior of the beams and columns. (2) Due to the diagonal tension field effect, the hysteresis loops severely pinch under cyclic loading and this impairs the energy dissipation capacity. (3) Infill panels buckles under very low loading, and the unpleasant sound during buckling deformation impairs the comfortability in practical use. Accordingly, stiffened flat SPSWs were proposed to enhance the buckling load and energy dissipation capacity. However, adding stiffeners will increase the fabrication cost.

For the above reasons, corrugated steel plate shear walls were introduced. The out-of-plane stiffness of infill panels is significantly increased due to the corrugation profile compared with ordinary flat SPSWs, leading to better lateral load-resisting performance with no need for using stiffeners or thicker plates. Corrugated plates have been widely applied in engineering practice as the web in steel girders, but as far as the authors know, there has not been current engineering use of corrugated SPSWs in high-rise buildings yet, due to the immaturity in developing practical design methods.

There are different corrugation shapes for infill panels of corrugated SPSWs, such as triangular corrugation, trapezoidal corrugation and sinusoidal corrugation. The structural behavior and seismic performance are influenced by corrugation shapes and geometric parameters such as the overall width and height, thickness, corrugation depth and wavelength. Berman and Bruneau [10] conducted tests on three light-gauge SPSWs subjected to cyclic lateral loading. Two specimens had flat infill panels and the third one used an inclined corrugated thin infill plate at an angle of 45°. Emani and Mofid et al. [11] and Emami and Mofid [12] presented an investigation into the cyclic behavior of vertically-placed and

* Corresponding author at: School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, PR China. Tel.: +86 10 51684954.
E-mail address: douchao@bjtu.edu.cn (C. Dou).

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Nomenclature

E	modulus of elasticity
v	Poisson ratio
C_a	sinusoidal corrugation depth
C_l	sinusoidal corrugation wavelength
L	panel overall width
H	panel overall height
t	panel thickness
e_l	length of a quadrangle element
τ_{cr}	buckling shear stress
τ_{cr0}	accurate solution of buckling shear stress
D_x	bending rigidity of corrugated panels with bending moment direction parallel the corrugation line
D_y	bending rigidity of corrugated panels with bending moment direction perpendicular to the corrugation line
S_c	developed length of the axis of one repeating corrugation
D_f	bending rigidity of flat plates
I_y	moment of inertia of one repeating corrugation section
f_y	steel yield stress
$\tau_{cr,g}$	global buckling shear stress of corrugated panels
$\tau_{cr,f}$	buckling shear stress of flat plates
C_a/C_l	corrugation ratio of corrugated panels
L/H	aspect ratio of panels
H/C_l	corrugation repeating number of corrugated panels
k_g	elastic global buckling coefficient
$\tau_{cr,l}$	local buckling shear stress of corrugated panels
k_l	elastic local buckling coefficient

horizontally-placed trapezoidally corrugated SPSWs, and it was shown that the energy dissipation capacity, ductile ratio and the initial stiffness of corrugated SPSWs were much higher than the corresponding flat SPSWs. Kalali et al. [13] conducted a numerical study on the hysteretic performance of SPSWs with trapezoidally corrugated infill panels based on finite element analyses, and pointed out optimal selection of geometric parameters is essential to good performance of corrugated SPSWs. Edalati et al. [14] investigated the material and geometric nonlinear behavior of corrugated SPSWs under monotonic lateral loading using the finite element method. Comparisons had been made between SPSWs with sinusoidal corrugation and with trapezoidal corrugation, which found that trapezoidally corrugated SPSWs show higher energy dissipation, ductility and ultimate bearing capacity than the counterparts with triangular or sinusoidal corrugation [14,15].

As the basis to ultimate strength and seismic design of corrugated SPSWs, many researchers have made contributions to the elastic calculation and buckling analyses of corrugated plates. Since the use of the finite element method leads to high amount of calculation intensity due to the corrugation profile of infill panels, simpler and more economic approaches were sought for analyses of corrugated plates by using equivalent orthotropic plates. The equivalent rigidities are the first key to the simplified analysis. Easley and McFarland [16] and Easley [17] derived equations for overall buckling loads of corrugated metal shear plates using the Rayleigh–Ritz method, and the proposed simplified equations have been adopted by other researchers since then [18–23]. Briassoulis [24] derived new and more precise expressions for the extensional rigidity and flexure rigidity of sinusoidally corrugated plates, after comparing the existing expressions with the computation results. Shimansky et al. [25] derived an analytical model for the initial transverse stiffness of sinusoidally corrugated plates incorporating deformations due to extension, shear and bending. Wennberg et al. [26] studied the analytical expressions for the mechanical properties of corrugated sheets in extension, free vibration and buckling, and it was found that the orthotropic models did not give an accurate twisting behavior. With respect to investigation to simplified calculation methods, Davis [27] and Nilson and Ammar [28] adopted orthotropic plane stress elements for the stability analysis of corrugated shear diaphragms. Samanta and Mukhopadhyay [29] carried out nonlinear geometric analyses of trapezoidal corrugated sheets based on the equivalent orthotropic model and flat shell elements developed. Ye et al. [30] derived an equivalent plate model of corrugated plates using the variational asymptotic method, in which the extension-bending coupling stiffnesses were obtained. Liew et al. [31,32] dealt with elastic buckling and vibration analysis of stiffened and unstiffened corrugated plates using a mesh-free Galerkin method based on the first-order shear deformation theory, and the corrugated plates were approximated by orthotropic plates of uniform thickness and the stiffness matrix was obtained. The proposed calculation method showed good agreement with the ANSYS solutions but was less computing-consuming and more flexible in adding the stiffeners.

Elastic buckling analysis is important for structural performance of corrugated SPSWs, in which key geometric parameters that affect the stiffness and stability can be sought. Moreover, from the elastic buckling load, the modified plate slenderness of infill panels can be obtained, which is an integrated index for the stability of SPSWs in design [2–4]. Thus simplified solutions for predicting the buckling load of infill panels in corrugated SPSWs are necessary for engineers. However, despite the various simplified and economic analytical method for corrugated plates based on derived equivalent orthotropic plate models, Easley [17] and Tong and Guo [33] derived the simplified equations with similar forms to approximate global shear buckling load of corrugated plates in SPSWs using the energy approach and by regarding the corrugated plate as an orthotropic plate. And many other researchers adopted the equations proposed by Easley [17] in their studies on buckling and strength of corrugated SPSWs [18–23].

However, it is found by the authors that, the classic formulae for shear buckling loads given by Easley [17] is not consistent with the numerical results obtained from ANSYS software based on detailed models with 3-dimensional representation of the corrugation. Furthermore, for local shear buckling of corrugated SPSWs, the classic equation for flat plates has been always adopted [18–23], which is not appropriate as well. It is necessary to seek for new equations with better predictions. Therefore, this paper focuses on elastic shear buckling of horizontally-placed sinusoidally corrugated SPSWs shown in Fig. 1. For SPSWs with trapezoidally corrugated infill panels, studies are to be carried out in a related paper.

Firstly by using finite element analyses (FEA), the previous formulae for bending rigidities of sinusoidally corrugated steel plates are reviewed and upgraded, then the pure shearing FE model is adopted to study the effects of key parameters on elastic global and local shear buckling of sinusoidally corrugated infill panels, such as the aspect ratio, corrugation ratio, corrugation depth to plate thickness ratio and corrugation repeating number. Based on the numerical results by FEA, fitting equations are proposed to estimate the elastic shear buckling loads of sinusoidally corrugated panels with good accuracy.