Thin-Walled Structures 125 (2018) 152–163

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Performance of steel plate shear walls with axially loaded vertical boundary elements

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ARTICLE INFO

Keywords:
Steel plate shear walls
Vertical boundary elements
Flexibility coefficient
Axial load ratio
Cyclic test

ABSTRACT

This paper presents a study of the applicability of the flexibility coefficient limit for vertical boundary elements (VBEs) in steel plate shear walls (SPSWs). One 1/3-scale, one-bay, and two-storey SPSW specimen was tested under quasi-static cyclic loading. The specimen had the flexibility coefficient and axial load ratio of the VBEs of 2.2 and 0.3, respectively. The results show that axial loads on the VBEs exacerbate the failure of SPSW structure. At the drift ratio of 0.9%, VBEs subjected to the axial load of $0.3f_yA_g$ exhibited considerable inward deformation equivalent to 1/400 of the column height. Besides, a finite element model (FEM) of SPSW structure was established and validated by test results. A parametrical study of SPSW specimens with various width-to-height ratios of infill steel plates and axial load ratios of VBEs was subsequently conducted by the FEM. The influence of VBEs with different axial loads on the structural performance of SPSWs was also discussed. Without considering the effect of axial load, the VBE flexibility coefficient limit of 2.5 is applicable for the SPSWs with the width-to-height ratio of 1.0 for the infill steel plate. However, with an increase of the width-to-height ratio of the infill steel plate, the development of the tension field tends to be inadequate, while the shear capacity and stress uniformity of the infill steel plate decrease. As a result, the flexibility coefficient limit of 2.1 is recommended for the design of VBEs in SPSW structures. Contrarily, considering the axial load effect, axial loads acting on the VBEs significantly decrease the shear capacity and stress uniformity of SPSWs with levels depending on the width-to-height ratio of infill steel plates and the flexibility coefficient of VBEs. To fully develop the tension field in infill steel plates for lateral resistance of SPSWs, axial load ratio, width-to-height ratio, and column flexibility coefficient should be taken into consideration in the design of SPSW structures.

1. Introduction

Steel plate shear walls (SPSWs) is a type of lateral-resistance structural system put into use in the 1970s. SPSWs have advantages of high initial lateral stiffness, stable hysteresis behaviour and good energy dissipation [1]. Numerous studies have been conducted to investigate the structural performance of SPSWs [2–5]. Lubell et al. [6] reported that vertical boundary elements (VBEs) in SPSWs exhibit obvious inward deformation under the action of the tension field of infill steel plates due to their weak rigidity. The stress in the middle of steel plate walls is reduced due to the large inward flexural deformation of the VBEs. However, the stress at the corners of the infill steel plates increases, promoting the formation of the plastic hinges at both ends of columns. The deformation of VBEs presents an obvious hourglass shape and eventually causes the failure of SPSW structures. To satisfy the requirement of rigidity of VBEs, both CAN/CSA S16-01 [7] and AISC 341-10 [8] specifies the flexibility coefficient limit of 2.5 for VBEs based on the plate girder theory. Habashi et al. [9] investigated the interaction between the frame and infill steel plates by numerical analysis, and proposed that the infill steel plates bear most of the shear force at the initial stage of loading. Once the tension field forms in the infill steel plates, the lateral resistance of SPSWs mainly relies on the frame. Li et al. [10] studied SPSWs with various VBE flexibility coefficients, and reported that the VBEs with a flexibility coefficient lower than 2.5 exhibit limited inward deformation. Conversely, obvious inward deformation was observed in VBEs with a flexibility coefficient above 2.5. This implied that the flexibility coefficient of VBEs significantly affects the structural performance of SPSWs. However, this conclusion was mainly validated for SPSWs with a small width-to-height ratio of steel plates, e.g. 1.0. The applicability of the VBE flexibility coefficient for SPSWs with a larger width-to-height ratio of infill steel plates needs further investigation.

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https://doi.org/10.1016/j.tws.2018.01.021
Received 3 October 2017; Received in revised form 17 December 2017; Accepted 14 January 2018
0263-8231/

Nomenclature

f_{yp}	yield strength of the steel plate material
f_{vy}	shear yield strength of the steel material
h	height of the infill steel plate
q_{cyj}	the load acting on the vertical direction of the column
q_{bxj}	the load acting on the horizontal direction of the beam
t_w	thickness of the web plate
t_{wp}	thickness of the infill steel plate

Capital letter

A_g	cross-sectional area of the column
L	beam height
L_p	width of the infill steel plate
I_t	moment of inertia of the top flange
I_b	moment of inertia of the bottom flange
I_c	moment of inertia of the column
S	spacing of beam stiffeners

Greek letters

δ	the local deflection of the flanges between neighbouring stiffeners caused by web tension
ε	tensile strain in the diagonal direction
ω_t	flexibility coefficient of the flange
ω_{tp}	flexibility coefficient of the VBE
γ	stress uniformity ratio of the average stress to the maximum stress in the web plate (Eq. (4))
γ_p	stress ratio of the horizontal component of principal tensile stress σ to the theoretical shear strength τ_u of infill steel plates
σ	the horizontal component of principal tensile stress in the infill steel plate
$\sigma_{average}$	the average stress of web tension field paralleling with the stiffener
σ_{max}	the maximum stress in the web tension field paralleling with the stiffener
τ_u	the theoretical shear strength of the infill steel plate
α	the angle of inclination of the tension strips to the x-axis
α_p	the angle of inclination of the uniform loads to the vertical direction
β	the ratio of the shear strength of the infill steel plate to the shear yield strength f_{vy}
β_{lim}	the lower limit of the shear strength ratio
η	axial load ratio
Δ	overall deflection of the plate girder due to lateral loads

SPSWs are inevitably subjected to different levels of axial load, depending on the adopted construction sequence for infill steel plates and frame. Generally, there are two construction methods for SPSW structures according to the sequence of installing infill steel plates. For the first method, the infill steel plates are installed after the construction of the frame. There is no axial load applied on the infill steel plate. For the second method, infill steel plates and frame are simultaneously installed, resulting in axial load imposed on the infill steel plates. However, axial load applied to the infill steel plates can be neglected if the VBEs have high axial stiffness. In the above two common cases, the presence of axial load on the VBEs is inevitable, which is affected by the construction sequence and axial stiffness of the VBEs. Zhang and Guo [11] and Lv et al. [12] demonstrated that the presence of axial load on the columns influences the shear resistance of the SPSWs. To reflect the actual loading conditions of SPSWs, it is necessary to investigate the effect of VBE axial load on the performance of SPSW structures. Qu et al. [13] and Li et al. [14] investigated the structural performance of SPSWs with the consideration of the effect of axial load applied on the columns. However, the VBE flexibility coefficient limit adopted in the study of Qu et al. [13] is much smaller than 2.5. Li et al. [14] investigated the flexibility coefficient limit for the concrete-filled steel tube columns in SPSWs, which is different from that for the steel columns. Therefore, the applicability of the VBE flexibility coefficient limit for SPSWs with axial loads should be further investigated.

Li et al. [10] and Kuhn and Peterson [15] confirmed that the flexibility coefficient limit of 2.5 for the columns in SPSWs can prevent serious inward deformation of columns, and thus avoid the “hourglass” failure phenomenon. The existing studies have pointed out that the width-to-height ratio of infill steel plates and axial load ratio of VBEs affect the applicability of the column flexibility coefficient limit for SPSW structures. However, as summarized in Table 1, parameters considered in previous studies vary among each other. Specifically, the effect of axial load acting on VBEs on the performance of SPSWs is not widely discussed in the literature [6,16,17]. Thus, there is still a lack of a systematic study on the influence of each parameter on the structural performance of SPSW structures, especially regarding the applicability of flexibility coefficient limit for VBEs in the design of SPSWs.

This paper experimentally investigates the structural performance of a one-bay, two-storey SPSW specimen. The specimen was designed with a flexibility coefficient and axial load ratio of 2.2 and 0.3, respectively. Failure modes of SPSW specimen under cyclic horizontal loads are discussed based on the inward deformation of VBEs. Subsequently, a finite element model for SPSW specimen was established and verified by testing. A comprehensive study on the applicability of flexibility coefficient limit for the VBEs in SPSWs with different width-to-height ratios of infill steel plates was conducted. The influence of axial loads on shear capacity and stress uniformity of infill steel plates in SPSWs is also studied.

Table 1
Summary of SPSW specimens from literature.

Ref.	Specimen	Scale	Width-to-height ratio	Height-to- thickness ratio	Flexibility coefficient	Axial load
Lubell et al. [6]	SPSW2	1:4	1.00	549	3.35	No
Tsai et al. [10]	SPSW N	1:1	0.66	1144	2.50	No
	SPSW S	1:1	0.66	1143	3.01	No
Qu et al. [13]	–	1:1	1.00	1123	1.95	Yes
Li et al. [14]	WCB	1:1	0.88	1309	3.29	Yes
	NCB	1:1	0.88	1309	3.43	Yes
	NSB	1:1	0.88	1309	3.71	Yes
Lin et al. [16]	S	1:2	2.00	511	1.01	No
Park et al. [17]	SC2T	1:3	1.47	500	1.24	No
	SC4T	1:3	1.47	250	1.44	No
	SC5T	1:3	1.47	167	1.58	No