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Plastic analysis and performance-based design of coupled steel plate shear walls

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ABSTRACT

The coupled steel plate shear wall (C-SPSW) configuration consisting of two SPSWs linked by coupling beams at the floor levels, in addition to providing architectural flexibility, has been shown to exhibit superior seismic performance. While the shear strength of the infill panels due to tension field action is the primary source of lateral load resistance in a C-SPSW, the moment resisting actions of the boundary frames and the coupling beams connections provide substantial strength for the system. As such, in order to achieve material-efficient designs, rational procedures are needed to explicitly account for this strength, while maintaining the desirable performance for various hazard levels. Similar to planar SPSWs, the C-SPSW systems have been designed using the conventional force-based design approach, which typically requires several iterations to optimize the design for performance and efficiency. This research employs the principles of plastic analysis to quantify the contribution of the frame action to the overall strength of C-SPSWs and adopts the philosophy of the performance-based plastic design (PBPD) methodology to develop procedures for the efficient seismic design of such systems. To investigate the effectiveness of the proposed design procedure, 8- and 12-story case study C-SPSWs were designed, and their numerical models were analyzed using pushover and response history analyses. The seismic performance of the prototypes were evaluated using two suits of ground motions representing 10/50 and 2/50 hazard levels. The analysis results indicated that the C-SPSWs designed using the proposed approach successfully met the desired performance objectives for both seismic hazard levels considered.

1. Introduction

Steel plate shear walls (SPSWs) have been efficiently used as robust and economical seismic force resisting systems for buildings located in earthquake-prone areas. A conventional SPSW consists of thin unstiffened infill panels surrounded by horizontal and vertical boundary elements (HBEs and VBEs). The shear strength of a typical SPSW is provided by the tension field action of the infill panel and the moment-resisting action of the HBE-to-VBE connections. Unlike reinforced concrete shear walls, in which the entire width contributes to overturning resistance, SPSWs resist overturning moments primarily through the axial forces in their VBEs. The relatively low overturning stiffness of SPSWs in comparison with reinforced concrete shear walls is considered a potential drawback and a major detraction to the system's application, especially in taller buildings [1]. On the other hand, architectural requirements (e.g., openings to accommodate doorways and windows) often do not allow the entire width of the bay to be infilled with solid steel panels.

To address the above-mentioned issues, a number of researchers investigated alternative SPSW configurations such as steel plate shear walls with outriggers (SPSW-O) systems [2,3] and the coupled steel plate shear wall (C-SPSW) configuration [4–7]. A C-SPSW, as shown in Fig. 1, consists of two SPSW piers linked by coupling beams (CB) at the floor levels. The C-SPSW configuration allows for the placement of two adjacent SPSWs within a single span, accommodating doorways and windows. Previous researchers have reported that the C-SPSW system maintains the ductile and robust seismic performance of conventional SPSWs while improving material efficiency [5,6]. These researchers extended the capacity design method used for conventional SPSWs to design the C-SPSW systems and investigated the degree of coupling (DC) as an important metric, which affects the behaviour and efficiency of C-SPSWs.

The C-SPSW configuration is inherently a dual system in which a substantial portion of the story shear is carried through the moment-resisting actions of the boundary frames of the individual SPSW piers and the CB-to-VBE connections. Wang et al. [8] conducted a detailed numerical study to estimate the contribution of the boundary frame in a series of six-story C-SPSW systems and concluded that the frame

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Notations

A_{HBE}	cross-sectional area of HBE
A_{VBE}	cross-sectional area of VBE
E	Young's modulus
E_e	elastic component of the internal work
E_p	plastic component of the internal work
F_D	design lateral force
F_{Di}	design lateral force at story i
F_i	lateral force at story i
F_p	plastic strength of single-story C-SPSW
F_{Pi}	lateral force needed at level i to develop plastic mechanism
F_y	yield stress of steel
g	gravitational acceleration
H	height of the structure
h_i	elevation of floor level i from ground
h_n	elevation of floor level n from ground
h_{si}	height of the story i
I_{HBE}	moment inertia of HBE
I_{VBE}	moment inertia of VBE
L	bay width of the steel plate shear wall
M	total mass of the system
M_{CB}	plastic moment capacity of coupling beam
M_{CBi}	plastic moment capacity of coupling beam at floor level i
M_{HBE}	plastic moment capacity of HBE
M_{HBEi}	plastic moment capacity of HBE at floor level i
$M_{VBE(Ext)}$	plastic moment capacity of external VBE
$M_{VBE(Int)}$	plastic moment capacity of internal VBE
N	number of stories
R_μ	ductility reduction factor
S_a	pseudo-spectral acceleration
S_{DS}	design spectral acceleration parameter at short periods
S_{D1}	design spectral acceleration parameter at period of 1 s
S_v	design spectral pseudo-velocity
T	fundamental period of structure
t	thickness of the infill plate
t_i	thickness of the i^{th} story infill plate
V_e	elastic base shear
V_i	story shear at level i
V_P	plastic strength of the system
V_y	base shear at yield
W	total seismic weight of the system
w_i	weight of the structure at level i
w_n	weight of the structure at level n
Z	plastic section modulus
α	tension field inclination angle in a single-story system
α_i	tension field inclination angle at i^{th} story
β_i	shear distribution factor
γ	energy modification factor
Δ_u	target drift
Δ_y	yield drift
η	energy reduction factor
θ_p	plastic rotation; plastic drift ratio
θ_u	target drift ratio
θ_y	yield drift ratio
κ	percentage of the total lateral design force assigned to infill panel
$\kappa_{optimum}$	percentage of the total lateral design force assigned to infill panel in optimum case
λ_i	lateral force distribution factor
μ_s	structural ductility factor
μ_{max}	maximum plate ductility
ξ	strength ratio between the CB and HBE
Φ	resistance factor for steel
φ	design base shear parameter
Ω	system overstrength
ω_h	horizontal component of tension field force along HBE
$\omega_{h(i)}$	horizontal component of tension field force along the i^{th} HBE
ω_v	vertical component of the tension field force along HBE

elements resist more than 50% of the story shear in majority of cases. The authors suggested that the design of C-SPSWs should be done by an elastic analysis procedure proposed by Sabelli and Bruneau [9] for planar SPSWs. According to this procedure, it is preliminarily assumed that the total lateral design force is resisted by the infill panels and the initial plate thicknesses are selected accordingly. The boundary frame elements are then designed according to the capacity design procedure to resist the maximum tension field forces generated by the infill plates.

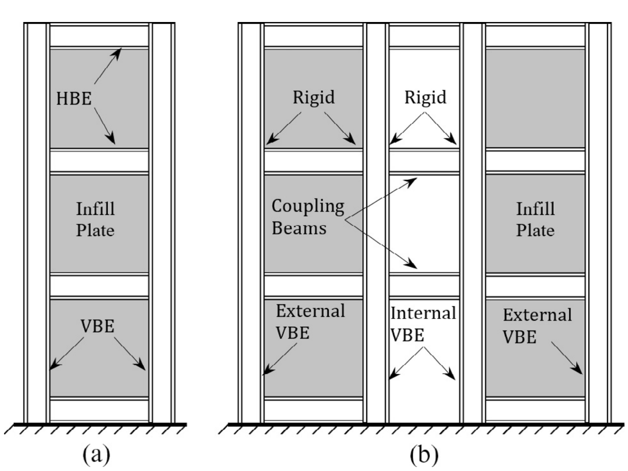

Fig. 1. SPSW systems: (a) conventional SPSW; (b) C-SPSW configuration.

Next, an elastic analysis is performed to determine the portion of the total story shear that is resisted by the infill panels. The plate thicknesses and the boundary frame elements are subsequently revised based on the updated story shear. The procedure is repeated to optimize the design in an iterative manner.

However, since the coupling beams add even more strength to the system in the C-SPSW configuration, the contribution of the frame action to the overall lateral load resistance is quite significant, as such, several design iterations may be needed to optimize the design. Because any changes in the plate thickness and consequently the boundary elements in each design iteration require recalculation of the tension field angles and reanalysis of sharing of story shear forces between the infill panels and frames, this procedure can result in a lengthy design process. In addition, estimating the relative contributions of the frame action and tension field action to the overall strength of a C-SPSW, which is expected to undergo significant inelastic deformations, using an elastic analysis might not be the most reasonable approach. On the other hand, since the force-based design approach prescribed by the codes attempts to capture the inelastic nature of the response in an "indirect" manner—i.e., calculating design base shear and nonlinear response by initially assuming an elastic system then modifying them using force- and response-modification factors—additional effort is often needed to satisfy the drift requirements while optimizing the design [10]. Although the above-mentioned procedure has been shown to produce C-SPSWs with satisfactory seismic performance, the quest for more rational and efficient design procedures to be used within the context of performance-based seismic design is an ongoing process.