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Design of horizontal stiffeners for stiffened steel plate walls in compression

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ABSTRACT

The compressive stress is remarkable in design of steel plate walls (SPWs) for high-rise buildings. Stiffeners are required to avoid the compressive buckling in service limit state. This paper first studies the elastic stability of horizontally stiffened steel plate walls (S-SPWs) in compression. The effect of stiffener torsional stiffness on elastic buckling stress is presented. Then the study extends to the elastic-plastic stability of imperfect S-SPWs. Comparing the elastic and elastic-plastic behaviour, the increased ultimate compressive strength is smaller than the increased elastic buckling stress due to the column type buckling behaviour of wide plate. Stiffener torsional stiffness can also increase the ultimate capacity. Formulas to predict the stiffness requirement on horizontal stiffeners are proposed based on the philosophy similar to the stiffness requirement on brace for columns in compression. With some minor modifications, the proposed formulas show good accuracy compared with numerical results.

1. Introduction

Steel plate walls (SPWs) enjoy growing interests among designers as a lateral load resistant system due to their ductile behaviour, quick construction and floor space saving. Previous studies have revealed that slender SPWs can achieve high shear strength utilising the tension field action [1–3]. Detailed numerical analysis is conducted in [4] to assess the design criteria for slender plates. Moreover, SPWs can be effectively used in seismic retrofitting of existing reinforced concrete frames because of their high strength, stiffness and strong ductility [5–8].

In engineering practice, compressive stresses are unavoidable in SPWs, especially in new high-rise buildings, because live loads and dead loads of non-structural elements and walls are applied after SPWs have been fixed. The unavoidable compressive stress can impair the initial shear capacity of SPWs [9]. To mitigate this, the final fixing between the SPWs and the boundary frame is usually put off until most of the dead loads above the SPW storey have been in place. In spite of this measure, stiffeners are sometimes required to avoid compressive bucking in the erection stage and in the service limit state.

Although studies on SPWs in the past two decades were mainly focused on the shear capacity and shear behaviour of unstiffened SPWs, the real situation in practice is that the shear demand is not the dominating factor in designing a building, especially in a high-rise building. Just as a steel beam is rarely controlled by shear strength of its web, SPWs in multi-storey or high-rise buildings are seldom governed by lateral shear forces. One can imagine that a high-rise residential building of 30-storey with a 25 m × 25 m plan, the gravity load is about 25 m × 25 m × 8 kN/m^2 × 30 = 15 × 10^4 kN and the estimated period is 0.12 × 30 = 3.6 s. In an area of maximum ground acceleration of 0.2 g (according to the return period of 475 years), the design base shear is about 0.032 × 15 × 10^4 = 4800 kN. Assuming that at least four 5 m long SPWs with thickness of 8 mm are used, the average shear stress in the S-SPWs is only 30 MPa, far less than the shear yield strength of material (199 MPa for Q345 steel) and the shear capacity of an unstiffened SPW ($0.42f_y$ = 0.42 × 345 = 145 MPa). So the SPWs have surplus capacity and stiffness to carry vertical loads and overall bending moments [10,11].

As reported by Nie et al. [12], the 74-storey Tianjin Tower adopted the stiffened steel plate walls (S-SPWs) with four vertical stiffeners on both sides of the plate to meet the design requirement. Under given gravity loads, the comparative low-cycle lateral load tests on both SPWs and S-SPWs showed that the vertically stiffened SPWs had higher stiffness in elastic range and better energy dissipation capacity than unstiffened SPWs [12].

Compared with vertical stiffeners which carry unavoidably vertical loads simultaneously with SPWs, the stiffness and strength of horizontal stiffeners can be fully utilised to provide lateral support to SPWs. This is similar to the exterior tube of a buckling-restrained brace that provides full stiffness to restrain the buckling of the interior core. In this meaning, horizontal stiffeners can be seen as buckling-restraining elements of the SPWs.

Timoshenko and Gere [13] investigated the elastic buckling of

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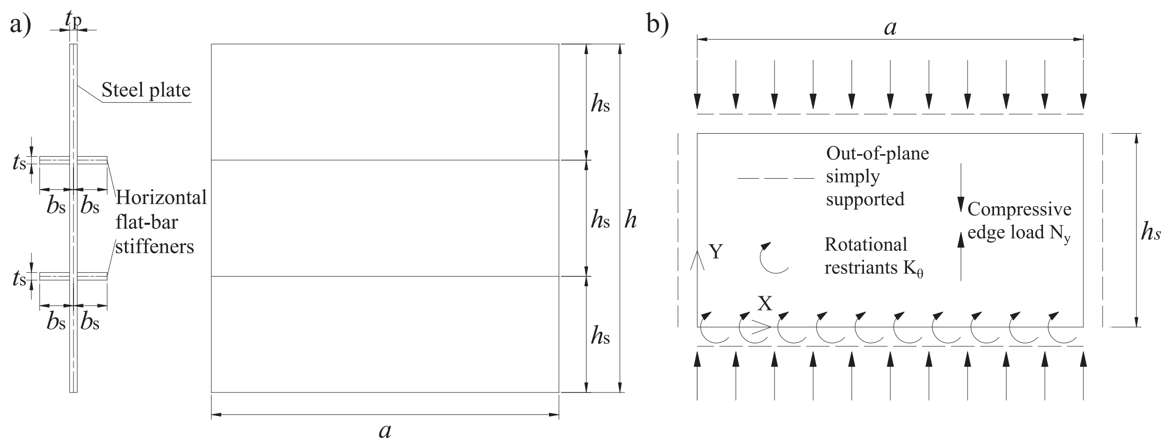

Fig. 1. a) Notation of horizontally stiffened plate, b) plate with rotational restraints on one loaded edge.

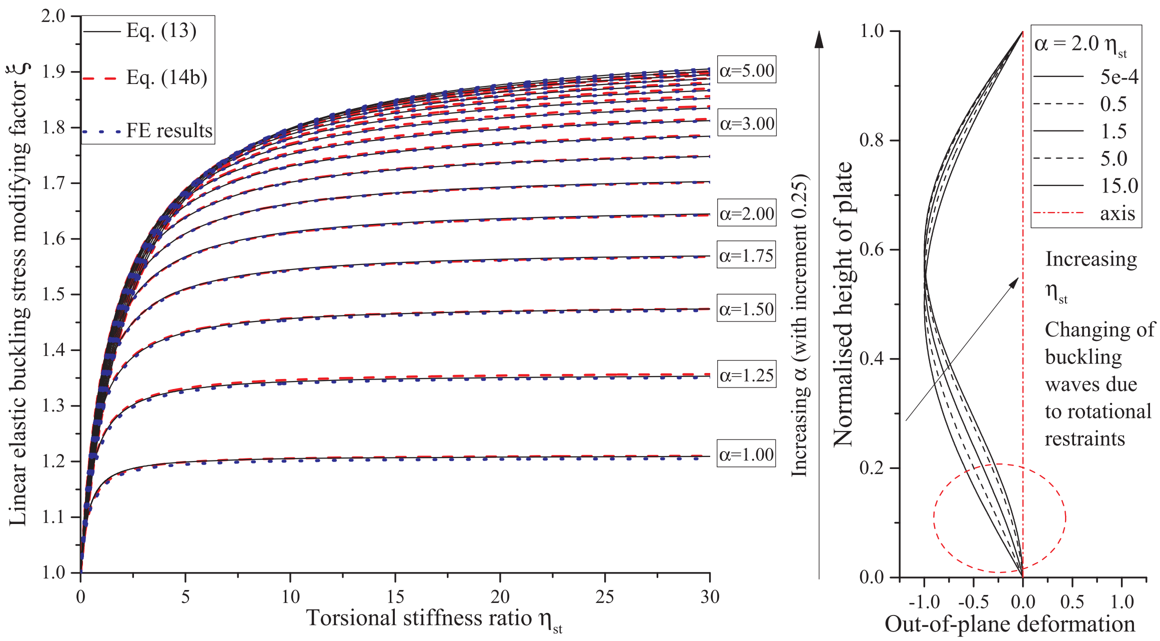

Fig. 2. a) Relationship between modifying factor ξ and torsional stiffness ratio η_{st}, b) Changing of buckling waves with increasing η_{st}.

transversely stiffened plate analytically. Mínguez [14] found that the torsional stiffness provided by closed section stiffeners can increase both the critical buckling stress and ultimate strength. Choi et al. [15] investigated the stiffness requirement for transverse stiffeners of compression panels in box girders. However, the transverse (perpendicular to the direction of stress) stiffeners in box girder flanges are used to reduce the effective length of longitudinal stiffeners under compression. The width to length ratio of the panels in flanges of box girders are usually much smaller than those in SPWs, which leads to different buckling modes and stiffness requirement on transverse (horizontal) stiffeners. The stiffeners in SPWs are also both sided to avoid eccentrically loading situation. Stiffeners can effectively prevent the out-of-plane deflection and improve the shear capacity of SPWs as well [16,17].

The present study focuses on the stiffness and strength requirements on the horizontal stiffeners as a partial buckling-restrained element of vertically compressed SPWs. Both elastic buckling and elastic-plastic post-buckling behaviour are investigated. The effect of torsional stiffness on elastic buckling stress and elastic-plastic ultimate strength are presented. Two types of threshold stiffness that correspond to elastic buckling stress and post-buckling capacity of the subpanels are determined.

2. Linear elastic buckling theory of plate

Fig. 1a shows a SPW with two horizontal flat-bar stiffeners. The aspect ratio of the subpanels is defined as:

$$\alpha = \frac{a}{h_s} \tag{1}$$

where a and h_s are the width and height of the subpanel respectively. The stiffener to plate bending stiffness ratio γ is:

$$\gamma = \frac{E_s I_s}{Da} \tag{2}$$

where E_s and I_s are Young's modulus and moment of inertia of the stiffeners respectively. D is the flexural rigidity of the SPW:

$$D = \frac{E_p t_p^3}{12(1-\mu^2)} \tag{3}$$

where E_p and t_p are Young's modulus and the thickness of the plate respectively. μ is Poisson's ratio. The stiffener's torsional-to-bending stiffness ratio K_s is defined by: