EFFECT OF STIFFENERS ON THE ANGLE OF INCLINATION IN STEEL PLATE SHEAR WALLS

Ahmad RAHMZADEH
Earthquake Engineering Graduate Student, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran
a.rahmzadeh@ut.ac.ir

Mehdi GHASSEMIEH
Associate Professor, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran
mghassem@ut.ac.ir

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ABSTRACT

Steel plate shear walls (SPSW) are an efficient but largely underused building lateral force resisting system. The system comprises of a moment frame (the boundary frame) with slender steel web plates that are welded or bolted inside the boundary frame. The resulting structure is similar to a vertical plate girder. The system resists lateral load primarily through tension field action of the post-buckled web plate. The magnitude and orientation of this tension field is governed by the relative stiffness of the web plate and boundary frame. The 2010 Seismic Provisions currently require that the tension field inclination angle be either 40° or computed using a formula derived from elastic analysis. This paper presents a new relationship for the diagonal tension angle considering effect of stiffeners. It is demonstrated that the tension field inclination may move, from an initially low angle under an elastic post-buckled state, toward 45° as the plate is loaded plastically.

INTRODUCTION

The steel plate shear wall (SPSW) recently came into view as a commercially executable building lateral system in the United States when it was included in the 2005 American Institute of Steel Construction (AISC) Seismic Provisions for structural steel buildings, in which they are expressed as special plate shear walls. By that time it had been instrumented only sporadically in the United States. The seismic response of SPSWs has not been studied as extensively as other lateral systems and there is limited data available on SPSW earthquake performance. However, a considerable amount of analytical and experimental research from Japan, Iran, Turkey, Canada, the United Kingdom, and the United States has been undertaken since the early 1970s, the majority of which has occurred over the last 15 years. The results of this body of research is that the system has very good ductility and energy dissipation capacity and is a cost-effective lateral system for new construction.

Stiffened SPSWs have been preferred in Japan where elastic buckling of structural elements providing lateral load resistance is not permitted. Given the requirement that steel plates must achieve their full plastic shear strength, other types of structural configurations have emerged in which shear yielding elements are introduced, without being SPSWs in the sense considered in here. Such concepts include small shear-yielding panels connected to beams at midspan or inserted at midheight of special intermediate columns, and designed as hysteretic dampers.

In contrast to these advantages, it is yet to attract expansive acceptance by the design and construction communities in the United States. Furthermore, SPSWs are more challenging to analyze and design than most other lateral-force resisting systems.

The analytical difficulty results from the web plate behavior and its complicated interaction with the boundary frame (the HBEs and VBEs). The web plate is the main lateral-load-resisting component of the wall, typically resisting 50–80% of the story shear. The web plate is allowed to buckle in shear at very low lateral load and resist lateral forces through tension field action, hence the plate-girder analogy. The web plate tension field assumption is the basis of the conventional method used to model web plates, both in commercial practice and in research, i.e., the web plate strip (or truss) model. The magnitude and orientation of the assumed tension field influences many aspects of the structural design. The conventional approach for modeling a postbuckled web plate is with a series of inclined truss elements. The area of each truss element is the product of the plate thickness and the truss element spacing. A minimum of 10 parallel truss elements are typically used to model a single web plate. These elements are inclined in both directions when performing response history analysis so that tension field formation is modeled for both directions of loading. The alternative to the truss model is the continuum model, which uses nonlinear, large deformation shell elements. In adopting the truss element approach, some aspects of the real behavior captured by a continuum model are traded with the computational efficiency of a truss element. The complex snap-through buckling and two-dimensional plastic stretching that occurs in cyclic analysis cannot be mimicked with a conventional truss element, nor can any changes in the principal orientations of the web plate stress field (the tension field inclination).

THE ANGLE OF INCLINATION IN STIFFENED SPSW

The inclination of the tension field is measured from the vertical and typically denoted as α in the literature. This tension field mechanism has been recognized as early as the 1930s in aerospace engineering (Wagner, 1931) and as early as the 1960s in steel building construction, when it was incorporated into the design process of plate girders (Basler, 1961). However, note that plate girder design equations should not be used to design SPSWs because they can be misleading and give strengths inappropriate for capacity design purposes (Berman and Bruneau, 2004). One important reason for this is that HBEs and VBEs in SPSW are designed with sufficient strength and stiffness to allow the web plates to yield over their height and width, which is not possible for the flanges of plate girders.

An equation of the diagonal tension angle was provided by Timler and Kulak (1983), based on an elastic analysis and an assessment of the strain energy absorbed by the HBEs, the VBEs, and the web plate. Using least work principles, the tension field angle that minimizes the internal strain energy of the system is that which will form under elastic postbuckled conditions. Several assumptions and simplifications are made in the development of this equation; most concern the boundary conditions and the kinematics of the subassemblage and are reasonable. However, in the context of seismic design, the assumption of elastic web plate behavior is not appropriate. The equation is applicable only for predominantly elastic behavior, which is contrary to its present application. Elastic behavior is often assumed in design for convenience and a desire for analytical simplicity. In truss element modeling of web plates, the angle predicted by the aforementioned equation is typically used to incline the elements. The 45° assumption has sometimes been adopted for convenience.

To obtain angle *α*, AISC Design Guide 20 (Sabelli and Bruneau, 2007) recommends that two angles should be considered, one of which is derived for the thin SPSWs from AISC 341 (2010) equation (17-2). The other one is an angle obtained based on the plate girder design. To better illustrate this procedure, the following equations define the diagonal tension angle:

$$\tan\alpha = \begin{cases} \sqrt[4]{\dfrac{1+\dfrac{tL}{2A_c}}{1+th\left(\dfrac{1}{A_b}+\dfrac{h^3}{360 I_c L}\right)}} & \text{Global buckling of the infill plate (a)} \\ or & \\ \dfrac{d}{b}\,\text{(Subpanel aspect ratio)} & \text{Buckling in subpanels (b)} \end{cases} \qquad (1)$$

Then the angle, of which the resultant forces are greater, will be taken into consideration in the design process. However, using Eq. (1) has not been examined yet.

The aim of the subsequent investigation is to develop a formula for the tension field angle in a buckled stiffened SPSW, i.e. when $\tau_{cr} < \tau_y$. For a single story stiffened SPSW subassemblage, the energy within the frame consist of contributions from the web, the stiffeners, one beam, and two columns. The work components of each will be evaluated separately and then summed to give the total internal work done by the subassemblage when subjected to the shear stress. Thus,

$$W_{total} = W_w + W_{\substack{s,v \\ Axial}} + W_{\substack{s,h \\ Axial}} + W_{b,Axial} + W_{c,Axial} + W_{c,Bending} \tag{2}$$

The work done by the web can be evaluated from general expression for internal work, i.e.

$$W_w = Lht\int_0^{\varepsilon_i} \sigma_i d\varepsilon_i \tag{3}$$

in which, σ_i and ε_i are, respectively, stress and strain intensity and, h and L are, respectively, height of the story and bay width.

İt is assumed that stiffeners are strong enough to not buckle with the web plate. The axial stress in each vertical and horizontal stiffener are expressed by, respectively,

$$\sigma_{s,v} = \frac{\sigma_{DT} td \cos^2\alpha}{A_{s,v}} \tag{4}$$

$$\sigma_{s,h} = \frac{\sigma_{DT} tb \sin^2\alpha}{A_{s,h}} \tag{5}$$

where σ_{DT} is the stress along angle α due to the diagonal tension part of the applied stress, $A_{s,v}$ is cross-sectional area of vertical stiffener, and $A_{s,h}$ is cross-sectional area of horizontal stiffener. Substituting these values into the general expression for the internal work, results in the following equations for the work done by axial stresses in the vertical and horizontal stiffeners, respectively,

$$W_{\substack{s,v \\ Axial}} = \frac{nk^2\tau^2t^2d^2h}{2EA_{s,v}\sin^2\alpha} \tag{6}$$

$$W_{\substack{s,h \\ Axial}} = \frac{mk^2\tau^2t^2b^2L}{2EA_{s,h}\cos^2\alpha} \tag{7}$$

in which, n and m are, respectively, number of stiffeners in the longitudinal and transverse direction, k is the diagonal tension factor and τ is the applied shear stress .

Lastly, the contributions of the columns and the beam into the total work are considered same as Timler and Kulak by the following simplified expressions:

$$W_{c,Axial} = \frac{k^2\tau^2t^2L^2h}{4A_cE\tan^2\alpha} \tag{8}$$

$$W_{c,Bending} = \frac{k^2\tau^2t^2h^5\tan^2\alpha}{720EI_c} \tag{9}$$

$$W_{b,Axial} = \frac{k^2\tau^2t^2Lh^2\tan^2\alpha}{2A_bE} \tag{10}$$

in which, I_c is the moment of inertia of the column, A_c is the cross-sectional area of the column, and A_b is the cross-sectional area of the beam.

To find the critical value of α, the expression for the internal work of each component is differentiated with respect to α and the summation of them is set to zero. It is assumed that only the plate deforms plastically and the stiffeners and the boundary frame remain elastic. Finally, by setting the resulted relationship for first derivative of the total work equal to zero and solving it for α, give:

$$\tan^4\alpha = \frac{1+\left(\frac{E_t}{E}\right)tL\left(\frac{1}{2A_c}+\frac{n}{(n+1)^2}\frac{1}{A_{s,v}}\right)}{1+\left(\frac{E_t}{E}\right)th\left(\frac{h^3}{360I_cL}+\frac{1}{A_b}+\frac{m}{(m+1)^2}\frac{1}{A_{s,h}}\right)} \tag{11}$$

where E_t is tangent modulus of the web plate.

In the case of thin SPSW, $n = m = 0$, Eq. 10 yields in an equation which was originally derived by Timler and Kulak (1983) for the elastic behavior of the web plate and recently improved by Webster et al. (2014) for the inelastic behavior of the web plate. However, it is more general since it includes the effects of stiffeners as well.

Eq. 10 implies that as the plate deforms plastically, the angle of inclination moves toward 45° because E_t/E ratio reaches zero. This result can be seen in final stage of a test specimen (Fig. 1) which was performed by Takahashi et al. (1973). Recently, Webster et al. (2014) came to this result through an experimental study (Fig. 2) and showed that Eq. (1) accurately predicts α in a postbuckled elastic state but not in an inelastic state.

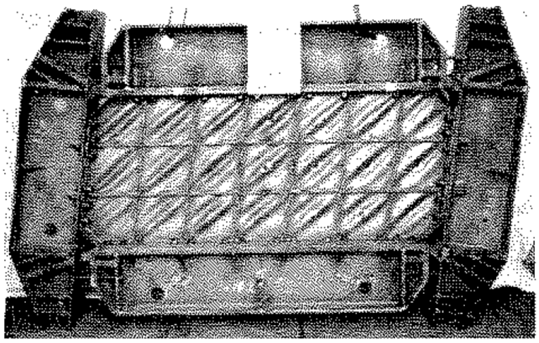

Figure 1. Specimen PR-2.3-M2-60 at its final stage (Takahashi et al., 1973).

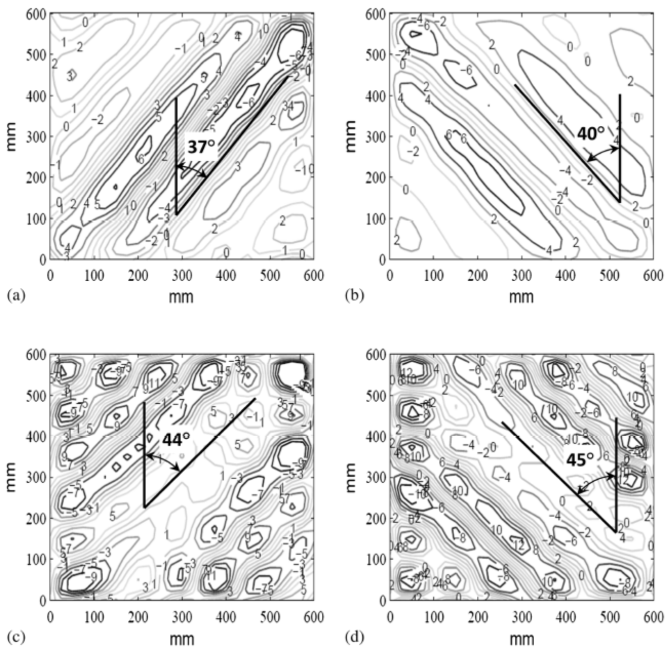

Figure 2. Immigration of the angle of tension field within the experimental test (Webster et al., 2014).

Values of the diagonal tension angle in the thin SPSWs commonly fall between 38° and 45° (Bruneau et al., 2011). In the stiffened SPSWs, based on Eq. (10), the diagonal tension angle is slightly larger, due to the fact that usually stiffeners are designed with the same dimensions, i.e. $A_{s,v} = A_{s,h}$, and $n \geq m$.

CONCLUSIONS

In this paper, by using least work principle, a general formula for the angle of diagonal tension in SPSWs was obtained for both elastic and inelastic regions. It was discussed that the AISC 341 equation for the angle of inclination is not applicable in inelastic region. Also, It was shown that stiffening SPSWs, usually, increase the angle of diagonal tension orientation.

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