AN IMPROVED PROCEDURE FOR CAPACITY DESIGN OF VERTICAL BOUNDARY ELEMENTS IN STEEL PLATE SHEAR WALLS

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ABSTRACT :

Consistent with capacity design principles, the 2005 AISC Seismic Provisions require that the vertical and horizontal boundary elements of steel plate shear walls be designed to remain essentially elastic while the web plates yield under seismic loading. However, determination of the design loads for vertical boundary elements to reliably achieve capacity design is difficult and a reasonably accurate approximate procedure is needed. This paper presents such a procedure for determining those design loads for the vertical boundary elements of steel plate shear walls so that the desired component yielding sequence is achieved. The procedure combines an assumed plastic collapse mechanism with a linear model of a vertical boundary element to determine the maximum axial forces, shear forces, and moments for vertical boundary elements considering fully yielded web plates and horizontal boundary elements hinging at their ends.

KEYWORDS: Steel plate shear walls, column demands, capacity design, shear walls, steel yielding

1. INTRODUCTION

Design requirements now appear in the 2005 AISC Seismic Provisions (AISC 2005), referred to herein as The Provisions, for steel plate shear walls (SPSWs) that are designed such that their web plates buckle in shear and develop diagonal tension field action when resisting lateral loads. Energy dissipation and ductility during seismic events is principally achieved through yielding of the web plates along the diagonal tension field. Consistent with capacity design principles, The Provisions require that the vertical and horizontal boundary elements of SPSWs be designed to remain essentially elastic with the exception of plastic hinging at the ends of horizontal boundary elements. The commentary of The Provisions provides some guidance on how to achieve this requirement. However, the methods described in the commentary do not necessarily lead to vertical boundary elements (VBEs) that meet the requirement of essentially elastic behavior under the forces generated by fully yielded web plates (Berman and Bruneau 2008).

A new procedure is proposed that uses a fundamental plastic collapse mechanism and linear beam analysis to approximate the design actions for VBEs of SPSWs for given web plates and horizontal boundary member sizes. The proposed procedure does not involve nonlinear analysis, making it practical for use in design. VBE design loads are determined for an example SPSW and the resulting design loads are then compared with the VBE design loads as determined by nonlinear pushover analysis.

2. PROPOSED VBE DESIGN PROCEDURE

The procedure proposed below to estimate VBE design loads to ensure capacity design of SPSWs combines a linear elastic beam model and plastic analysis. A model of the VBE on elastic supports is used to determine the axial forces in the HBEs and a plastic collapse mechanism is assumed to estimate the lateral seismic loads that cause full web plate yielding and plastic hinging of HBEs at their ends. A simple VBE free body diagram is then used to determine the design VBE axial forces and moments. For use in design, iteration may be necessary as certain parameters are assumed at the beginning of the process that may need revision as the design progresses.

2.1. Plastic Collapse Mechanisms

Plastic collapse mechanisms for SPSWs subject to lateral loads have been proposed by Berman and Bruneau (2003) and have been shown to agree well with experimental results for ultimate capacity of single and multistory SPSWs. They examined two types of plastic mechanisms for multistory SPSW, namely, a uniform collapse mechanism and a soft-story collapse mechanism which are shown schematically in Figures 1a and 1b respectively. For the purpose of capacity design of VBEs, it is conservative to use the uniform plastic collapse mechanism as it will result in larger base shear forces and larger VBE demands. Furthermore, if a soft-story mechanism is found to be likely, it is recommended that the SPSW be redesigned to develop more uniform yielding of the web plates over the height. This can be achieved, even for web plates of equal thickness over the height, by adjusting the sizes and moments of inertia of the surrounding HBEs and VBEs. Therefore, the uniform collapse mechanism shown in Figure 1a will be used in the proposed procedure for determination of capacity design loads for SPSW VBEs.

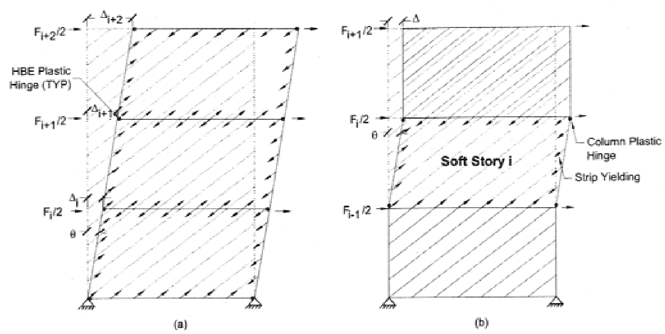


Figure 1. SPSW Collapse Mechanisms

2.2. Free body diagrams of VBEs

Assuming that the web plates and HBEs of a SPSW have been designed according to The Provisions to resist the factored loads (or, for the case of HBE design the maximum of the factored loads or web plate yielding), the required capacity of VBEs may be found from VBE free body diagrams such as those shown in Figure 2 for a generic 4-story SPSW. Those free body diagrams include distributed loads representing the web plate yielding at story *i*, ω_{xci} and ω_{yci}, moments from plastic hinging of HBEs, M_{prli} and M_{prri}, axial forces from HBEs, P_{bli} and P_{bri}, applied lateral seismic loads, found from consideration of the plastic collapse mechanism, F_i, and base reactions for those lateral seismic loads, R_{yl}, R_{xl}, R_{yr}, and R_{xr}. The following describes how the components of the VBE free body diagrams are determined. Note that for the purpose of this discussion lateral forces are assumed to be acting from left to right on the SPSW of Figure 2.

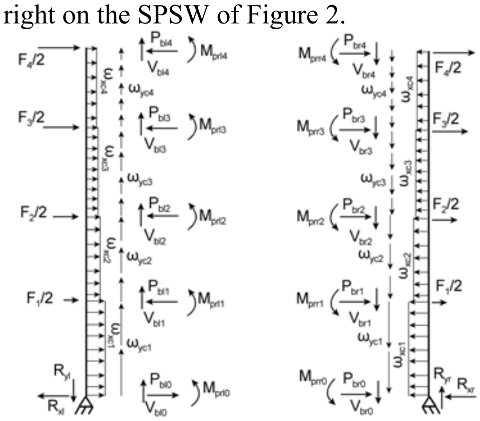


Figure 2. VBE Free-Body Diagrams

2.3. Forces from Plate Yielding

The distributed loads to be applied to the VBEs (ω_{yci} and ω_{xci}) and HBEs (ω_{ybi} and ω_{xbi}) from plate yielding on each story i may be determined as:

$$\omega_{yci} = (1/2) F_{yp} t_{wi} \sin 2\alpha \qquad \omega_{xci} = F_{yp} t_{wi} (\sin\alpha)^2 \tag{2.1}$$

$$\omega_{ybi} = F_{yp} t_{wi} (\cos\alpha)^2 \qquad \omega_{xbi} = (1/2) F_{yp} t_{wi} \sin 2\alpha \tag{2.2}$$

where F_{yp} is the yield stress of the web plate and t_{wi} is the plate thickness. These are found from resolving the plate yielding force, occurring at an angle α from the vertical, into horizontal and vertical components acting along the VBEs and HBEs. Note that the inclination angle, as determined per *The Provisions*, depends on the VBE cross-sectional area and moment of inertia and will have to be assumed at the beginning of a design procedure and then revised once VBEs have been selected. An initial assumption of 45° is suggested.

2.4. HBE Axial Forces

As part of estimating the axial load in the HBEs, an elastic model of the VBE is developed. The model consists of a continuous beam element representing the VBE which is pin-supported at the base and supported by elastic springs at the intermediate and top HBE locations. HBE spring stiffnesses at each story i, k_{bi}, can be taken as the axial stiffness of the HBEs considering ½ the bay width (or HBE length for considerably deep VBEs), i.e.:

$$k_{bi} = \frac{A_{bi} E}{L/2} \tag{2.3}$$

where A_{bi} is the HBE cross-sectional area, L is the bay width, and E is the modulus of elasticity. This VBE model is then loaded with the horizontal component of the forces from the web plates yielding over each story, namely, ω_{xci}. An initial VBE size will have to be assumed for use in this model and some iteration may be required once that VBE size is revised. It is reasonable to neglect the rotational restraint provided by the HBEs and this assumption has been observed to have a negligible impact on the resulting spring forces, P_{si}. Note that these spring forces correspond to compression forces in the HBE, and can be of significant magnitude. Physically, one can envision the SPSW VBEs as being pulled toward each other by the uniformly distributed forces applied by the yielding webs, and the HBEs acting as regularly spaced "shoring" to keep the VBEs apart.

The axial force component in the intermediate and top HBEs resulting from the horizontal component of the plate yield forces on the HBEs, ω_{xbi}, is assumed to be distributed as shown in Figure 3a. Note that for the bottom HBE, this distribution is the reverse of that in the top beam. These axial force components are then combined with the spring forces from the linear VBE model, resulting in the following equations for the axial force at the left and right sides of the intermediate and top HBEs (P_{bli} and P_{bri} respectively):

$$P_{bli} = -(\omega_{xbi} - \omega_{xbi+1}) \frac{L}{2} + P_{si} \tag{2.5}$$

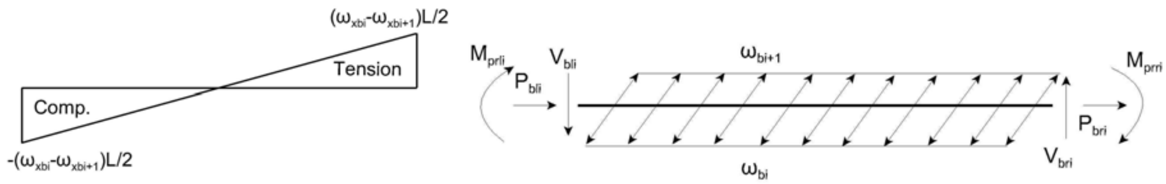
$$P_{bri} = (\omega_{xbi} - \omega_{xbi+1}) \frac{L}{2} + P_{si} \tag{2.6}$$

where the spring forces should be negative indicating that they are adding to the compression in HBEs. As mentioned above, the axial forces from ω_{xbi} and ω_{xbi+1} in the bottom HBE may be taken as the mirror image of those shown in Figure 3a, where ω_{xbi} is zero in that case as there is no web below the bottom HBE. Furthermore, there are no spring forces to consider at the bottom HBE location as the horizontal component of force from web plate yielding on the lower portion of the bottom VBE is added to the base reaction determined as part of the plastic collapse mechanism analysis, as described below. Therefore, the bottom HBE axial forces on the right and left hand sides, P_{bl0} and P_{br0} are:

$$P_{bl0} = \omega_{xb1} \frac{L}{2} \quad \text{and} \quad P_{br0} = -\omega_{xb1} \frac{L}{2} \tag{2.7}$$

2.5. HBE Reduced Plastic Moments and Corresponding Shear Forces

Once the HBE axial forces have been estimated it is possible to determine the plastic moment that will develop at the HBE ends for the assumed collapse mechanism, reduced for the presence of axial load. Note that it is conservative to assume that this reduction is negligible; however, since substantial axial loads may develop in the HBEs, resulting in significantly reduced plastic moment capacities, it can be advantageous to account for the reduced plastic moments at the left and right HBE ends, M_{prl} and M_{prr}, respectively.



(a) (b)

Figure 3. (a) HBE Axial Force Diagram (plate forces only) (b) HBE Free-Body Diagram

The intermediate and top HBEs will have free body diagrams similar to that shown in Figure 3b, except that there will be no plate forces acting above the top HBE. For the bottom HBE, the axial forces at the HBE ends will be in the opposite direction to those shown in Figure 3b and there will be no plate forces acting below the HBE. The reduced plastic moment capacity at the HBE ends can be approximated by (Bruneau et al, 1998):

$$M_{prli} \;\; or \;\; M_{prli} = \begin{cases} 1.18\left(1-\dfrac{|P_{bli}|}{F_{yb}A_{bi}}\right)Z_{xbi}F_{yb} & if \quad 1.18\left(1-\dfrac{|P_{bli}|}{F_{yb}A_{bi}}\right)\le 1.0 \\ Z_{xbi}F_{yb} & if \quad 1.18\left(1-\dfrac{|P_{bli}|}{F_{yb}A_{bi}}\right)>1.0 \end{cases} \tag{2.8}$$

where F_{yb} is the HBE yield strength, A_{bi} is the HBE cross-sectional area for story i, and Z_{xbi} is the HBE plastic modulus for story i.

Using the reduced plastic moment capacities and the HBE free body diagram shown in Figure 3b, the shear forces at the left and right ends of all HBEs, V_{bl} and V_{br} can be found from:

$$V_{bri} = \frac{M_{prri}+M_{prli}}{L} + \left(\omega_{ybi}-\omega_{ybi+1}\right)\frac{L}{2} \tag{2.9}$$

$$V_{bli} = V_{bri} - \left(\omega_{ybi}-\omega_{ybi+1}\right)L \tag{2.10}$$

2.6. Applied Lateral Loads

The final forces necessary to complete the free body diagram of the VBE are the applied lateral loads corresponding to the assumed collapse mechanism for the SPSW (Figure 1a). Following the derivation in Berman and Bruneau (2003) the governing equation for that collapse mechanism is:

$$\sum_{i=1}^{n_s} F_i H_i = \sum_{i=0}^{n_s} M_{prli} + \sum_{i=0}^{n_s} M_{prri} + \sum_{i=1}^{n_s} \frac{1}{2}\left(t_{wi}-t_{wi+1}\right)F_{yp} L H_i \sin\left(2\alpha_i\right) \tag{2.11}$$

Where F_i is the applied lateral load at each story to cause the mechanism, H_i is the height from the base to each story, and other terms are as previously defined. Note that the indices for the HBE plastic moment summations begin at zero so that the bottom HBE (denoted HBE_0) is included.

To employ Eq. 2.11 in calculating the applied lateral loads that cause this mechanism to form, it is necessary to assume some distribution of those loads over the height of the structure, i.e., a relationship between F_1, F_2, etc. For this purpose, a pattern equal to that of the design lateral seismic loads from the appropriate building code may be used. This is an approximation that is simple and that has been observed to provide reasonable results for SPSW. It would also be appropriate to use the deformation pattern of the first mode of vibration of the structure for this purpose (obtained from a modal analysis), but this more sophisticated approach is unnecessary given that the code specified distribution of lateral seismic forces vertically on a lateral force resisting system is meant to simulate first mode characteristics. Once a load pattern is assumed and a relationship between the applied collapse loads at each story is determined, Eq. 2.11 may be used to solve for those collapse loads.

The base shear force, V, for the collapse loading is found by summing the applied lateral loads. Horizontal reactions at the column bases, R_{xL} and R_{xR}, are then determined by dividing the collapse base shear by 2 and adding the pin-support reaction from the VBE model, R_{bs}, to the reaction under the left VBE and subtracting it off the reaction under the right VBE. Vertical base reactions can be estimated from overturning calculations using the collapse loads as:

$$R_{yl} = \frac{\sum_{i=1}^{n_s} F_i H_i}{L} \qquad \textit{and} \qquad R_{yr} = -R_{yl} \tag{2.12}$$

2.7. Determination of VBE Design Loads

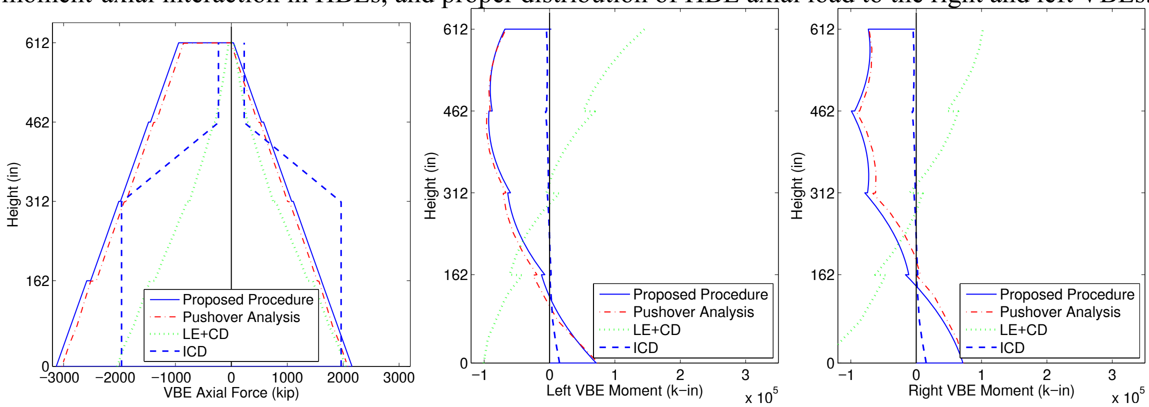
The moment, axial, and shear force diagrams for the VBEs are established once all the components of the VBE free body diagrams are estimated. The diagrams give minimum design actions for those VBEs such they can resist full web plate yielding and HBE hinging.

2.8. Additional Considerations

Though not explicitly considered in the above formulations, use of the ratio of expected to nominal yield stress, R_y, may be incorporated into the procedure when determining the distributed loads from plate yielding and when determining HBE plastic moment capacity. Additionally, when deep VBEs are used, the length between VBE flanges, L_{cf}, may be substituted for the column centerline bay width, L, when applying the plate yielding loads to the HBEs. Furthermore, using the schematic structure shown in Figure 3 for which structural members have no width, the HBE plastic hinges are assumed to form at the VBE centerlines, which is not the actual case. HBE hinges will typically form $d_b/2$ from the column face, where d_b is the HBE depth. This can be accounted for by either including in the VBE free body diagrams the distance from the column centerlines to the HBE hinge locations or by calculating the projected column centerline moment as is done for moment frames. This calculation is not included here for simplicity and because the increase in moment applied to the VBE is generally small relative to the magnitude of the moments generated by web plate yielding and HBE hinging. Gravity loads are another consideration that has not been included; however, they can easily be added to the vertical components of the web plate yield forces that are applied to the HBEs in Figure 3b. They will then be accounted for in the resulting HBE shear forces and VBE axial forces. Finally, this procedure will provide reasonable VBE design forces for SPSWs that can be expected to yield over their entire height, typically shorter SPSWs. This procedure will likely be overly conservative for tall SPSWs where nonlinear time history analysis indicates that simultaneous yielding of the web plates over the entire SPSW height is unlikely. In those situations it may be acceptable to reduce the VBE axial forces obtained from this proposed procedure (following a procedure similar to that proposed by Redwood and Channagiri 1991) to account for some web plates remaining partially elastic while others yield. However, at each story the VBEs should be designed to resist the moments generated by yielding of the web plates at that level and the corresponding frame moments.

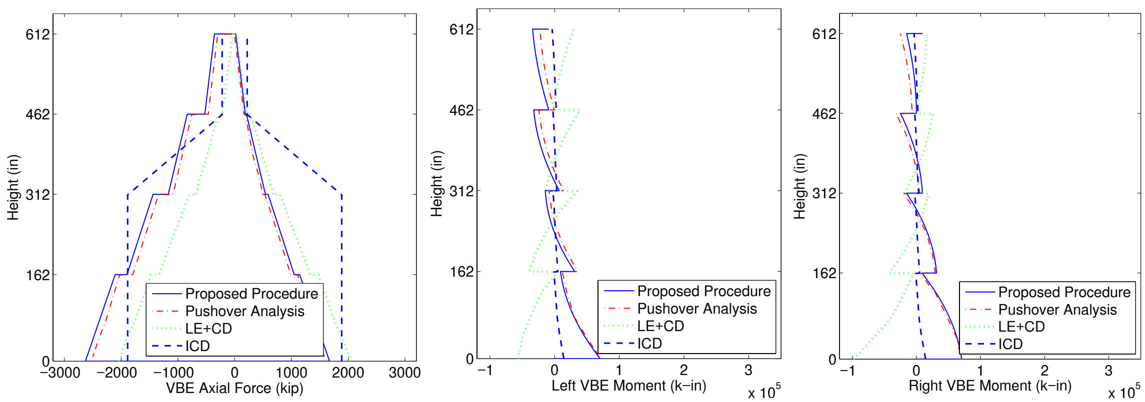
3. COMPARISON WITH PUSHOVER ANALYSIS RESUTLS

Figures 4 and 5 compare axial loads and moments from the three procedures for approximating VBE design loads with those from pushover analysis for both SPSW-C and SPSW-V, which are described in Berman and Bruneau (2008). These SPSWs are both 4-stories with constant and variable web plate thicknesses for SPSW-C and SPSW-V respectively. The three procedures are the two currently present in the Commentary of *The Provisions* (the combined linear elastic computer programs and capacity design concept (LE+CD); the indirect capacity design approach (ICD)) and the procedure proposed here. As shown, the proposed procedure agrees well with pushover results in terms of both VBE axial force and moment. Furthermore, the proposed procedure is able to capture the important aspects of SPSW behavior that effect the VBE force diagrams, such as moment-axial interaction in HBEs, and proper distribution of HBE axial load to the right and left VBEs.



(a) (b) (c)

Figure 4 Design Actions for SPSW-C VBEs (a) Axial Force (b) Left VBE Moment (c) Right VBE Moment



(a) (b) (c)

Figure 5 Design Actions for SPSW-V VBEs (a) Axial Force (b) Left VBE Moment (c) Right VBE Moment

The LE+CD procedure agrees well with pushover analysis for VBE axial force as shown in Figures 4a and 5a. However, because the procedure neglects the application of the lateral loads to cause web plate yielding when evaluating the VBE moments, the moment diagrams in Figures 4b, 4c, 5b, and 5c are not in agreement. Neglecting the applied loads to cause infill yielding, results in moment diagrams that do not include the significant contributions of frame action under those loads, which in these cases are actually large enough to not only change the magnitude but also the sign of the moment VBE moments. Although it appears the VBE moment diagrams from the LE+CD for the VBEs from SPSW-V may simply be reversed, that is not the case, and those for SPSW-C would not agree even if they were converted into their mirror image.

Finally, the ICD approach reasonably estimates the VBE axial forces; however, because the overstrength is very large for these SPSWs, it is not able to adequately estimate the VBE moments. As shown in Figures 4b, 4c, 5b, and 5c the ICD results in VBE moment diagrams that have similar shape to those from pushover analyses but significantly underestimates the values. Therefore, the proposed procedure is the only one of the three methods available for estimating design loads for VBEs that ensures web plate yielding is able to fully develop prior to hinging in VBEs.

4. CONCLUSIONS

A procedure for estimating the design loads for VBEs of SPSWs has been proposed. The procedure does not involve nonlinear analysis and is based on an assumed plastic collapse mechanism and linear model of one of the vertical boundary elements. Moment and axial force diagrams from the proposed procedure were shown to agree well with results from pushover analyses of two example steel plate shear walls.

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