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Computational study of elastic and inelastic ring shaped – steel plate shear wall behavior

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ABSTRACT

Ring shaped – steel plate shear walls (RS-SPSWs) are a new type of steel plate shear wall (SPSW) system that utilize strategic cutouts in a solid plate to mitigate shear buckling and encourage full hysteretic behavior and thus large energy dissipation. Previous experiments have demonstrated that the RS-SPSW concept can significantly reduce buckling and dissipate more energy than solid web plate SPSWs with similar strength. However, because of limitations in the number of tests and associated instrumentation, the experimental results did not provide enough data to thoroughly investigate several facets of RS-SPSW behavior, such as the distribution of shear deformation along the web plate height, web plate forces on the boundary elements, and web plate slenderness effects on buckling resistance.

This paper details three computational studies that build upon the experimental test results to develop and validate useful design equations for RS-SPSWs. The paper starts with a description of the RS-SPSW nonlinear finite element models that utilize shell elements for the web plate. Then, the model is validated against experimental specimens by comparing the load-deformation behavior and the evolution of cumulative energy dissipation. Next, the computational models are utilized to explore the uneven shear deformation distribution along the height of the web plate allowing derived prediction equations to be validated. The computational models are also used to determine boundary element demands and to validate a proposed distribution of web plate forces for use in design. Lastly, the modeling approach is utilized to better understand shear buckling of the web plates in terms of non-dimensional web plate parameters.

1. Introduction

Steel plate shear walls (SPSW) can be a desirable seismic force resisting system (SFRS) due to their high ductility, thinner width than equivalent concrete shear walls, and quick construction [1]. In North America, SPSWs are typically constructed using a thin, unstiffened steel web plate that is surrounded by a moment resisting frame [2]. While SPSW's have advantages, they also have several challenges associated with the thin web plate. For example, the web plates are prone to shear buckling at small lateral loads which results in pinched hysteretic behavior, low energy dissipation and small stiffness during load reversal.

Alternatively, Fig. 1 shows the ring shaped – steel plate shear wall (RS-SPSW) that consists of a flat steel web plate cut to have a pattern of circular rings that are interconnected by diagonal links. The horizontal boundary element (HBE) to vertical boundary element (VBE) connections are simple shear connections, unlike current SPSW design which requires seismic moment connections [2]. As shown in Fig. 1, the geometry can vary between floors depending on the desired behavior and intermediate stiffeners may be used to help resist shear buckling. The intermediate stiffeners are made with steel shapes (e.g. angles or channels) bolted together, but not attached to the beams or foundation to prevent putting additional demands on the HBE and VBE [3].

As compared to a solid plate, the ring shape modifies the web plate plastic mechanism and utilizes the intrinsic geometric properties of a ring to resist buckling (described in more detail later) [4]. Since RS-SPSWs resist buckling, many of the previously mentioned challenges of conventional SPSWs are mitigated. Experiments have shown that RS-SPSWs display full hysteretic behavior, large stiffness during load reversals, and high energy dissipation [3]. With these improvements in web plate behavior as compared to conventional SPSW, the seismic moment connections between the beams and columns are no longer necessary which offsets some of the costs associated with cutting the plate and increases speed of erection [4]. A limited economic comparison examined the cost difference between seismic qualified

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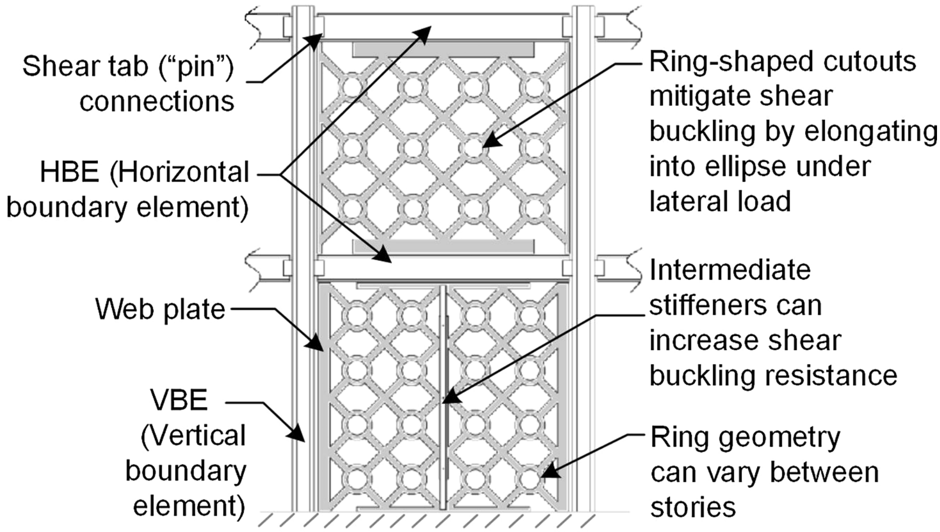

Fig. 1. Rendering of RS-SPSW in building.

complete joint penetration (CJP) welds and waterjet fabrication of RS-SPSW web plates. A quote for field CJP welds at both ends of a W18x86 beam, with required field inspection, was obtained in southwestern Virginia to be $3700; but that quote would likely increase for HBE's with flanges thicker than a W18x86 and is subject to regional variation [4]. Waterjet cutting cost for RS-SPSW web plates was estimated to range between $4000 and $7000 depending on plate thickness, waterjet quality level, and geometry complexity [4]. Additionally, assuming steel material cost of 0.50 $/lb., the thicker RS-SPSW web plate would add approximately $3000 per web plate in raw material cost compared to the thin conventional SPSW web plates.

An experimental study on five large-scale specimens evaluated the application and detailing of RS-SPSW in realistic building scale configurations [3]. However, it was deemed impossible to provide enough instrumentation on these specimens to fully capture the stress and strain distributions throughout the web plate and the distribution of web plate forces applied to the boundary elements. Furthermore, there were an insufficient number of specimens to evaluate shear buckling resistance and the proposed limits on web plate geometry to control buckling [5].

This paper builds on the large-scale experimental program results by using validated finite element (FE) models to better understand the behavior of tested RS-SPSW configurations and then examines a larger set of configurations to develop methods for controlling web plate buckling. To provide context, this paper begins with a review of computational methods previously used to predict SPSW behavior, followed by a description of RS-SPSW mechanics and the large-scale experiments. The finite element modeling approach is presented and several aspects of model behavior are validated against the experimental results. The models of the specimens are then used to explore features of the specimen behavior not observable from experiment instrumentation. Lastly, the FE modeling approach is used to examine shear buckling with 42 unique configurations of RS-SPSW web plates. The results of the analyses lead to equations that describe the relationship between RS-SPSW geometric parameters and the distribution of shear deformation over the web plate height, the web plate forces applied to the boundary elements, and the elastic shear buckling resistance, which can all be used in design.

2. Background

2.1. Computational methods for modeling SPSW

Early research on unstiffened steel plate shear walls was pioneered by Thorburn et al. [6] in the early 1980′s. In conjunction with significant experimental testing, several investigations were conducted on the effective analytical modeling of SPSWs. The earliest SPSW computational models were developed by Mimura and Akiyama [7] and utilized an Euler plate buckling algorithm to solve for the web plate shear buckling load assuming a pinned boundary condition. After the shear buckling load was surpassed, the plate was assumed to resist shear by diagonal tension field action. Thorburn et al. [6] developed the strip model and single equivalent diagonal brace model to capture SPSW web plate behavior. The strip model assumes the shear buckling strength of the web plate is negligible and that lateral loads are only resisted through tension field action of the web plate. The web plate is modeled as a series of diagonal, tension-only pin-ended strips, usually using truss elements, oriented at the approximate angle of the tension field [6]. The strip model, and its variations, has been shown to predict the monotonic push-over and cyclic behavior of SPSWs reasonably well compared to experimental tests [6,8–10]. For the strip model to be utilized for cyclic loading analyses, strips need to be oriented in both tension field directions.

In addition to the strip model, simplified orthotropic membrane models have been used to model SPSW behavior [11,12] wherein the steel modulus of elasticity is assigned in the membrane's diagonal tension field direction and near zero modulus of elasticity is assigned in the orthogonal direction. Elastic orthotropic membrane models are significantly less computationally expensive than nonlinear finite element models although modern advancements in computing have diminished the importance of computational cost. For research projects and design of larger buildings, nonlinear finite element analysis is more common.

Finite element (FE) models of SPSWs typically use four-node shell elements for the web plate and either beam elements or shell elements for the boundary members. Geometric nonlinearity is included to capture plate buckling and material nonlinearity is often modeled using kinematic strain hardening [e.g. 13]. Many researchers have shown that FE models can accurately predict cyclic SPSW behavior, buckling mode shape, out-of-plane web plate displacements, stress distribution, and web plate forces applied to the boundary elements [e.g. see 10,13,14,15,16,17,18].

2.2. Ring shaped – steel plate shear wall concepts

The ring shaped – steel plate shear wall (RS-SPSW) concept capitalizes on the intrinsic geometric property of a ring to resist buckling during elongation. Fig. 2 describes the concept of how a ring shape