Thin-Walled Structures 106 (2016) 244–257

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Development of a new deteriorating hysteresis model for seismic collapse assessment of thin steel plate shear walls

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ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form
30 April 2016
Accepted 13 May 2016

Keywords:
Steel plate shear wall
Deteriorating hysteresis model
Probabilistic seismic collapse assessment
Sensitivity assessment

ABSTRACT

A new hysteresis model is developed for thin Steel Plate Shear Wall (SPSW) systems which incorporates cyclic and in-cycle deteriorations. The model is implemented into the OpenSees software and is validated against a number of experimental evidences. Seismic response sensitivity of SPSW system to the hysteretic model characteristics is evaluated, afterwards, using three code-conforming SPSWs with different heights. The 15 variant models developed for each frame using different combinations of deterioration parameters are subjected to incremental dynamic analysis. The sensitivity of the derived median collapse capacities, expressed in $S_a(T_1)$ terms, to the "cyclic" and "in-cycle" deterioration parameters are finally assessed.

1. Introduction

Steel plate shear wall (SPSW) system is a lateral load resisting system composed of vertical and horizontal boundary elements (HBEs and VBEs) interconnected through infill plates (Fig. 1a). The infill plates play an important role in providing stiffness, energy absorbance, and ductility for the system and are used in two stiffened and unstiffened (thin) forms. Various experimental researches have been performed on the behavior of thin SPSW systems under monotonic and cyclic loadings (e.g. [1–6]). These studies have proven the system to possess a stable hysteretic behavior dominated by the diagonal tension fields forming after compressional buckling of the thin plate (Fig. 1b).

Despite the SPSW system's advantages in providing lateral stiffness, energy absorption capacity, and a high degree of indeterminacy leading to more reliable resistance against seismic forces, wider utilization of the system is hindered by current conservative design approaches [7,8]. To release some of this conservatism, performing systematic performance evaluations of SPSW system that consider varied geometric configurations and account for uncertainties is necessary [9]. Such analyses can be efficiently performed only using macroscopic finite element methods that combine experimentally established empirical relations with plasticity theory and account for component deterioration resulting from accumulative member damages.

Macroscopic FE methods remarkably enhance the efficiency of numerical analyses by eliminating the need for establishing finely detailed plasticity-governed shell and solid meshes. Distributed plasticity beam-columns that account for partial nonlinearity in member's cross section and consider the axial-flexural interaction (through fiber concept) can be named as instances of macroscopic FE methods [10]. The macroscopic FE approach was first used in "strip model" concept by Thorburn et al., [2] for modeling steel infill plates. Strip model uses diagonal truss members that mimic formation of tension fields within a thin infill plate. Equations addressing cross areas and inclination angles of the strips (trusses) have been analytically provided by Timler and Kulak [1]. For cyclically loaded specimens, Timler and Kulak [1] proposed the strips to be used in two opposite diagonal directions (as illustrated later in Section 3.1) while their compressional behavior was simply represented by an elastic zero-stiffness model. This model is called "original strip model" from now on throughout this article. A few more advanced hysteresis models have also been proposed by recent researches that include, mainly, the Choi-Park [11] and Purba-Bruneau [12] hysteresis models.

In the coming parts of this article, the original strip model and the two more recently developed models are, initially, evaluated for satisfying the required hysteresis models characteristics. The predictions provided by these models for a few experimentally tested specimens are regarded for this purpose. Subsequent to identifying the shortcomings of available models, a new hysteresis model is developed that addresses these drawbacks. This model is implemented in OpenSees software [13] as a new uniaxial-material object. This material, when assigned to diagonal truss elements, represents the infill plate via the strip method. Validation

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http://dx.doi.org/10.1016/j.tws.2016.05.008
0263-8231/

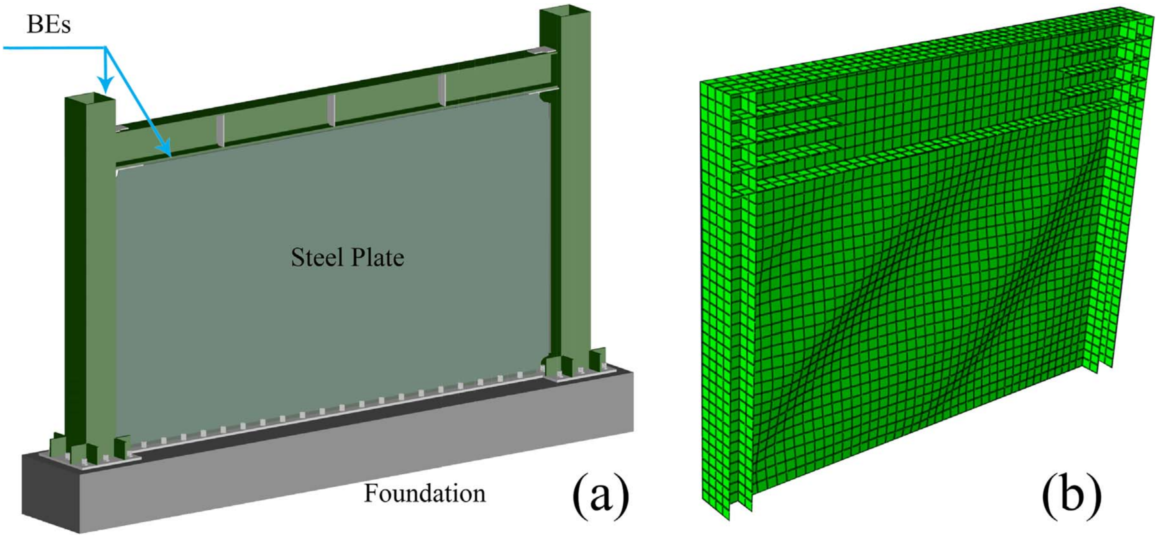

Fig. 1. A one-story thin SPSW: (a) system's configuration and (b) tension field formation shown by finite element analysis after compressional buckling under lateral loading.

of the model versus a number of experimental evidences having different geometric characteristics is the subject of the next part of this study.

Presenting regression equations that propose appropriate values for parameters of the developed model is supposed to be the next study step. This step was, however, not affordable at the current state due to the unavailability of required experimental data. That is, the limited experimental observations available for thin SPSWs provide a combined behavior of infill plates (sometimes in a multi-story configuration) with those of the surrounding members and the connections. The infill plate deterioration, which is the focus of the developed model, is not, therefore, extractable from the hysteretic response of the experimental specimen in which plate tearing has concurred with members' local buckling. For calibration of the developed model, hysteretic response of the infill plate is best extracted using a pure shear specimen in which a single plate is surrounded by rigid pin-connected rods and is diagonally tensioned in a cyclic fashion. A number of such experiments have been previously conducted by [4] which are too few for a calibration study to be based on. A variety of such experiments with different plate properties would be required for a complete calibration of the developed model. In lack of these experiments, finite element models can be utilized which are fine-tuned against experimental observations. Repeating such analyses, similar to that performed by [11], can provide an early and affordable substitute for the described experiments. At the present situation, providing intuition regarding the effectiveness of different deterioration parameters is assumed to facilitate a later calibration study and is attempted in this study.

In this regard, seismic response sensitivity of SPSW system to the numerical values of the implemented model is assessed in the second section of this article. As stated above, the objectives behind this assessment are: 1) to provide intuition regarding the degree to which various hysteretic deterioration modes would affect probabilistic seismic performance of SPSW system; and 2) to identify the most prominent hysteresis parameters for the later model calibration program to concentrate on. For achieving this purpose, a number of 3-, 10-, and 17-story SPSW configurations are designed regarding the latest guidelines. These structures are intended to reflect various lateral load resisting mechanisms respecting the domination of flexure or shear modes. Different variants of each structure are, then, numerically modeled in OpenSees software using the developed hysteresis model (named as SPSW02 uniaxial-material object) that incorporate different levels of in-cycle and cyclic deteriorations (see Section 2). The resulting 45 SPSW models are then subjected to static push-over and incremental dynamic analysis (IDA) [14] methods. The IDA procedure has been used within the probabilistic seismic performance assessment procedure proposed by Pacific Earthquake Engineering Research (PEER) Center [15]. Quantified probabilistic performances extracted for different models are, then, regarded for evaluating the effect of various hysteresis parameters.

2. Deterioration modeling requirements

A comprehensive review of hysteresis model types is provided by FEMA P440A [16] along with accurate methods for numerical representation of experimentally observed deteriorations. As described in [16] and also by earlier researchers such as [17], two causes can be named for deterioration of a component behavior, namely excessive deformation and repetition of the load reversals. The former being called "in-cycle" deterioration can be captured, experimentally, through a monotonic testing and is represented, numerically, via introduction of a softening post-cap branch to the backbone curve (or the "force-displacement capacity boundary" as denoted by [16]). The latter so-called "cyclic" deterioration is observed in cyclic experiments whose data can be regarded for correlating the deterioration extent to properties of the observed hysteretic load-displacement path [17]. Various formulations, such as Rahnama-Krawinkler [18], Kratzig [19] and Park-Ang [20], have been provided, so far, for such correlation.

As far as the "in-cycle" deterioration is regarded, definition of the post-cap softening branch is done using a cap deformation, δ_c, and a negative slope, K_{pc}. These parameters are commonly normalized as δ_c/δ_y and $\alpha_c=K_{pc}/K_e$ with δ_y and K_e representing, respectively, the yield deformation and initial stiffness of the component (Fig. 2). The δ_c/δ_y parameter is occasionally (as in [17] and also this paper) called the "ductility capacity". On the other hand, the cyclic deterioration type is represented, numerically, through introduction of a cyclic damage index, β, which is computed at the end of each cycle (excursion) and can be used to deteriorate various characteristics of the backbone curve, e.g. yield strength and loading/unloading stiffness, at the new cycle.

A complete definition of a hysteresis model requires a "cyclic rule" to be determined in addition to the backbone curve (which also includes definition of the in-cycle deterioration) and cyclic deterioration. Cyclic rules determine how the hysteresis curve transitions between the two backbones defining the positive and