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Equivalent constitutive model of steel plate shear wall structures

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ABSTRACT

To accurately and efficiently predict seismic responses of steel plate shear wall structures using simplified strip element models, an improved uniaxial equivalent constitutive model was proposed. Skeleton curves were employed, respectively, to quantify the effect of appreciable cyclic hardening characteristics of different steel materials and to take into account the influence of compressive residual stress. Simplified hysteretic criteria were suggested to capture pinching phenomena, reloading process and unloading process in details. Then, the proposed model was incorporated into the general finite element software ABAQUS as a user defined material (UMAT). Together, the model was validated against a series of typical experimental results. Finally, parametric analyses of the prototypes with a wide range of width-to-thickness ratios and loading patterns were conducted, with focus on the feasibility and applicability of the proposed model. These analyses demonstrated that: the proposed model could better evaluate the hysteretic behavior of steel plate shear wall structures with a wide range of width-to-thickness ratios and different steel materials. Meanwhile, it guarantees both the computational accuracy and efficiency, providing a valuable tool for nonlinear analysis of overall steel plate shear wall structures.

1. Introduction

Due to increasing applications of high-rise buildings and frequent occurrences of rare earthquakes, steel plate shear wall structures become more and more widely used, which have robust seismic behavior and excellent lateral load-carrying capacities. A typical steel plate shear wall system comprises infill plates and a boundary frame, as shown in Fig. 1. The current design philosophy of this kind of structure is to utilize the post-buckling strength of infill plates adequately. After the occurrence of buckling, strong tension fields are formed stepwise along with large out-of-plane deformation, which assist the structure in withstanding increasing lateral loads continuously [1–3].

In order to explore the behavior of steel plate shear wall structure, both of experimental study and numerical simulation are effective methods. However, because of high costs and limited conditions of full-scale structural tests, the numerical approach is typically utilized as an effective alternative to predict the ultimate limit state of structures. When a thin steel plate shear wall is subjected to cyclic loads, strong nonlinear phenomena should be captured, such as apparent buckling and large out-of-plane deformation of infill plate, and abrupt changes of tension-field directions. For this reason, it is complex and time-consuming to simulate a full-scale structure with three-dimensional solid or shell element models, and also difficult to achieve convergence. Though the multi-scale model is more efficient, the problems of substantial computations and high storage costs are still not overcome. Based on aforementioned difficulties, currently, the line element model with beam element or truss element is most widely employed in nonlinear dynamic analyses of overall steel structure, as presented in Fig. 1. Therefore, it is critical to obtain an accurate line element approach to substitute the complicated solid or shell element method, which could achieve a balance of calculation accuracy and efficiency.

Based on this demand, various line element methods and strategies to simulate the behavior of steel plate shear wall structures have been studied in prior researches. For instance, Mimura and Akiyama [4] proposed a macroscopic hysteretic model of steel plate shear wall structure according to test results, which captured the pinching and cyclic characteristics from load-displacement curves. Thorburn et al. [5] firstly suggested a tension strip model (TSM) and an equivalent brace model (EBM) of steel plate shear wall, as illustrated in Fig. 2(a) and Fig. 2(b). Besides, the calculation method for the inclination angle between strips and vertical members was given, which was further modified to consider the contribution of stiffness of vertical boundary members by Timler and Kulak [6]. These two models were recommended in Canadian Standards [1] and American Seismic provisions [2]. They could well predict the load-carrying capacity of unstiffened steel plate shear wall structures with relatively large width-to-thickness ratios, because these two models ignored the contribution of compressive stress, and only considered the tensile behavior of each

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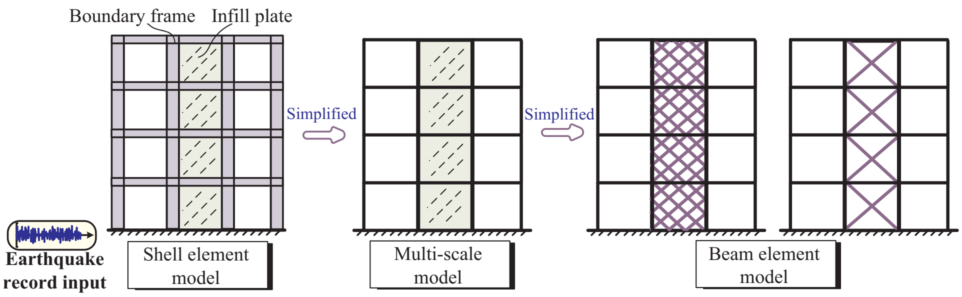

Fig. 1. Numerical simulation methods of steel plate shear wall structures.

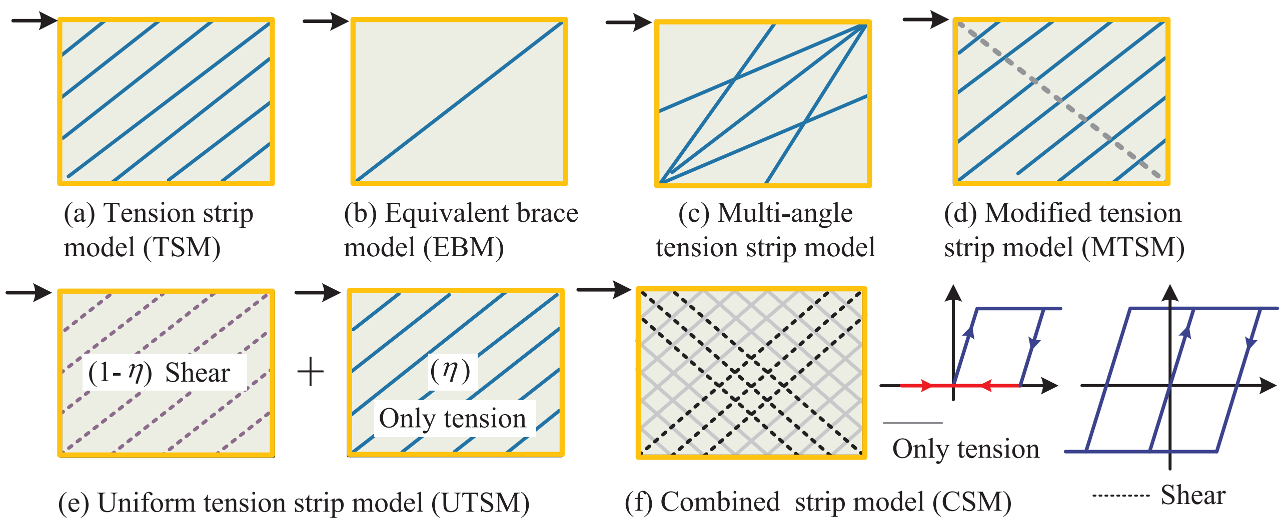

Fig. 2. Existing models of steel plate shear wall structure.

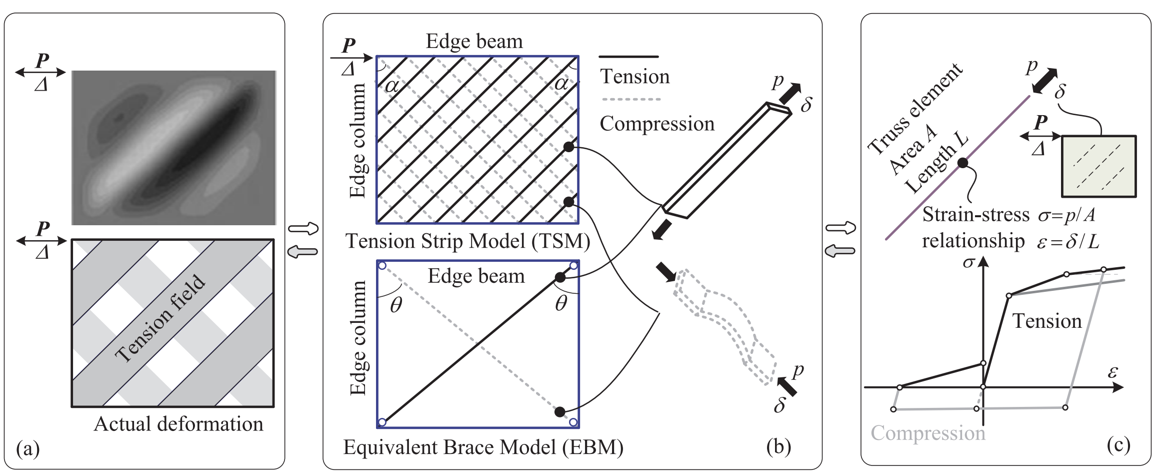

Fig. 3. Illustration of equivalent constitutive model.

strip. Elgaaly et al. [7] have developed an analytical tri-linear constitutive model of cold-rolled steel web plates for only-tension strips. The essential parameters of this model, with a certain application range (the ratio of shear critical stress and shear yield stress $\tau_{cr}/\tau_y \le 0.123$), were calibrated from test data of three experimental specimens in reference [8]. A macroscopic nonlinear hysteretic model of steel plate shear wall was proposed by Driver et al. [9], which isolated the contributions of infill plates and the surrounding frame. Rezai [10] has suggested a discrete strip model to increase the calculation accuracy of nonlinear time history analysis, as demonstrated in Fig. 2(c), which agreed with experimental results better than the conventional strip model. Berman and Bruneau [11] have found that EBM would overestimate the load-carrying capacity of steel plate shear wall structure when the width-to-height ratio was not equal to 1.0, so a correction factor was proposed to guarantee the calculation precision of EBM [5]. Shishkin et al. [12] improved the TSM by adding a compressive brace and damaged hinges, as presented in Fig. 2(d), to consider the contribution of compression and deterioration behavior caused by the tearing of infill plates. Zhou [13] reported a unified strip model, based on comprehensively considering tension fields and shear yield behavior, as shown in Fig. 2(e). This improved model comprised complete shear component and complete tension component, and made use of a parameter to control the proportion of two parts. Therefore, this model can also be used for stocky steel plate shear wall structure. Choi and