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Behavioral Characteristics of Steel Shear Panels with Different Materials and Slenderness Ratios

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ABSTRACT: In the present study, the effect of material properties and slenderness ratios on the nonlinear behavior characteristics and energy dissipation behavior of steel plates under shear loading is studied using FEM. First, the steel shear plates with respect to their slenderness ratio and nonlinear behavior are qualitatively and quantitatively classified into very slender, slender, moderate, stockyو and very stocky. To quantitatively determine the slenderness classes for each steel material, modified theoretical relationships are presented separately using statistical analyses of the obtained results for various steel plates. Also, new relationships for assessment of inelastic and plastic buckling loads are proposed, that can estimate buckling loads for moderate and stocky plates more accurately compared to the available theoretical relationships in AASHTO. In general, with increasing slenderness ratio, the capability of steel plates for energy dissipation, due to the occurrence of buckling and the resulted pinching in the hysteresis loops, is gradually decreased. In the case of very stocky plates, the capability of plates for energy dissipation is only dependent on the material yield stress, while in the class of slender, moderate, and stocky plates, it is dependent on both the slenderness ratio and material yield stress. In the case of very slender steel plates, the capability of different steel plates for energy dissipation, disregarding the material yield stress and the plate slenderness ratio, seems to be similar, less or more, for various steel materials.

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1. Introduction

Shear panels are widely used civil engineering structural members. Steel plate shear wall, box girders/plate girders of steel structures and bridges, slabs, link beam in eccentrically bracing systems, metallic yield dampers, and liquid/gas containment structures are only some of the examples of engineering elements that according to their applications use various thickness plates [1, 2]. In general, the behavior of a plate can be very complex depending on the occurrence of buckling and yielding. In turn, the occurrence of buckling and yielding depends on boundary conditions, material characteristics, aspect ratio, and slenderness ratio.

During recent decades, many research works have been carried out to investigate the strength and post-buckling capacity of slender metal (aluminum and mainly steel) plates under shear loading [3-11]. The study of the elastic buckling capacity of unstiffened flat plates was studied first by Bryan [12]. Timoshenko used the energy method to study the buckling behavior of rectangular plates under in-plane shear stresses and only for symmetric buckling modes [13], while stein investigated the shear buckling behavior of rectangular flat plates with simply supported boundaries, considering both symmetrical and asymmetrical buckling modes [14]. However, the studies on the behavior of stocky/relatively stocky plates, especially under shear loading, are relatively limited [1, 15-20].

The present study investigates the behavior characteristics of shear steel panels using the finite element method. The aspects of linear/nonlinear/energy dissipation behaviors of steel shear plates, including three types of conventional steel materials (structural mild steel, low yield point steel, and stainless steel), are investigated for a wide range of slenderness ratios, assuming simply supported boundary conditions.

2. Methodology

In this study, more than 120 steel plates with different slenderness ratios and materials, but constant aspect ratios, are numerically analyzed under shear loading using Eigen buckling/nonlinear static/quasi-static cyclic analyses [21]. As mentioned before, studies are done for three different steel materials and a wide range of slenderness, while the boundary conditions are assumed to be simply for different steel plates.

3. Discussion and Results

In very slender plates, buckling happens with out-of-plane displacements at the initial stage of loading. The plate shows significant post-buckling capacity, until the occurrence

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of its first yielding which is followed by the sudden loss of stiffness. In contrast, slender plates have relatively higher buckling capacity and so, limited post-buckling capacity. In this category, generally, with the increase of slenderness ratio, due to the decrease in the buckling capacity, the elastic portion of behavior is gradually reduced. With the occurrence of buckling, the behavior of the plate becomes geometrically nonlinear

The occurrence of buckling and yielding phenomena in the moderate plates is almost simultaneously. With the occurrence of these two phenomena, the plate reaches its maximum capacity and then enters the softening stage of its behavior. Hence, the plate behaves almost elastic before reaching its ultimate strength.

A Stocky plate experiences almost full yielding at a load equivalent to its nominal shear yielding capacity. After that, the plate shows a small loading capacity until the occurrence of plastic buckling. After the occurrence of the plastic buckling, the plate reaches its ultimate strength. As a result, in this category, the plate does not experience geometrical nonlinear behavior, before reaching its ultimate strength.

In very stocky plates, the entire plate yields simultaneously at a load equivalent to its nominal shear yielding capacity. Then, the plate shows a limited loading capacity before reaching its ultimate strength. In this category, the plate does no buckle, so it's out-of-plane displacement is very limited. Depending on the material properties and disregarding the slenderness ratio, an important portion of the loading capacity is provided by the plate in the elastic range of behavior.

Also, according to the nonlinear static analysis results, new relationships for moderate and stocky plates are proposed, which can predict the respective buckling load of each category more accurately than those of AASHTO [22]. (Eqs. 1 and 2, respectively)

$$\tau_{cr} = \left[0.592 \times \left(EK\sigma_y\right)^{0.50}\right] \div \lambda \tag{1}$$

$$\tau_{cr} = 0.827 \times \sigma_y \times \left(\frac{K \times E_t}{\lambda \times E}\right)^{0.047} \tag{2}$$

Based on the cyclic analysis results, for different steel materials, with an increase of slenderness ratio, due to the increased effect of buckling and the resulted the pinching phenomenon in the hysteresis curves, the energy absorption capacity of the plate always decreases. Very stocky plates do not buckle. As a result, the capability of this category in energy dissipation is only dependent on the material yield stress and thus, does not change with the slenderness ratio. However, in the cases of stocky/moderate/slender plates, the energy dissipation capability of plates is dependent on both the material yield stress and especially, plate slenderness ratio. Also, in the case of very slender plates, it seems that the energy dissipation of plates is mainly dependent on the material modulus of elasticity (and not the material yield stress and plate slenderness ratio). Hence, it remains almost the same for different steel materials.

4. Conclusions

Very slender plates buckle at the initial stages of loading. At the ultimate strength, the stress level within most of the plate is relatively low, and only a very small area of the plate at the tension corners experiences yield stress level. Compared to very slender plates, slender plates depending on their slenderness ratio have higher buckling capacity, and at the ultimate strength, yielding occurs only in a narrow region along with the tension diagonal. In moderate plates, first yielding and buckling happen almost simultaneously. At the ultimate strength, similar to slender plates, the yield zones occur in a region along with the tension diagonal, but in a larger area. On the contrary, stocky plates yield almost entirely at a load equivalent to their nominal shear yielding capacity. Similarly, the whole surface area of very stocky plates yields simultaneously at a load equivalent to their nominal shear yielding capacity. Plates of this category do not buckle and therefore, they have negligible out-of-plane deformations. Modified mathematical relationships for the classification of different steel materials regarding their slenderness ratio were proposed and compared with those of AASHTO. Also, using the statistical analyses of the finite element results, new mathematical relationships for the assessment of buckling capacity of moderate/stocky plates were proposed. In general, the energy dissipation capability of plates decreases gradually with the increase of slenderness ratio, mainly due to the occurrence of buckling and the resulted pinching phenomenon in the hysteresis curves. The energy absorption capacity of very stocky plates is only dependent on the material yield stress, while that of stocky/moderate/slender plates is dependent on both the material yield stress and plate slenderness ratio.

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