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Seismic capacity-based design of narrow strap-braced cold-formed steel walls

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ABSTRACT

In North America, the seismic design of strap-braced cold-formed steel shear walls is carried out using the AISI S213 Standard, which is soon to be replaced by a new seismic specific standard AISI S400. Both standards require the use of a capacity-based design procedure in which the tension-only diagonal braces are assumed to act as the inelastic fuse elements in the pin connected seismic force resisting system, while all other elements remain essentially undamaged under loading. Experimental work has shown this assumption to be valid for walls with low aspect ratios; however, the testing of high aspect ratio walls has revealed that large moments develop in the frame members, which can result in their failure prior to yielding of the braces. This paper describes a simple method with which these frame moments can be determined and accounted for in the capacity-based design procedure.

1. Introduction

In North America, the seismic design of cold-formed steel lateral framing systems is carried out following the provisions found in the American Iron and Steel Institute (AISI) S213 Standard for "Cold-Formed Steel Framing — Lateral Design" [1], which is soon to be replaced by a new seismic specific design standard, AISI S400 "North American Standard for Seismic Design of Cold-Formed Steel Structural Systems" [2]. The seismic capacity-based design procedure for diagonal strap-braced cold-formed steel (CFS) walls (Fig. 1a) in both of these standards was formulated, in part, considering the performance of full-scale wall test specimens with 1:1 to 2:1 aspect ratios [3–14]. The intent of the capacity-based design procedure is to ensure that the strap braces act as fuse elements, dissipating seismic energy while limiting the wall resistance with a controlled, ductile yielding of the cross-section along the brace length. All other elements in the seismic force resisting system (SFRS), i.e., brace connections, gusset plates, chord studs, track, anchor rods, hold-downs and shear anchors, must be designed to have a resistance higher than the forces that are associated with the expected yield strength in tension of the strap braces along with any gravity loads that are applied in combination with the earthquake loads.

At present, the Eurocode standards for seismic and cold-formed steel design [15,16] do not specifically address the lateral system design of a cold-formed steel framed wall. Nonetheless, researchers in Europe have proposed relevant design methods. Dubina [13], for example, has summarized methods to analyze and design a variety of cold-formed steel framed wall systems, including strap-braced walls. Fiorino et al. [17] did develop a design method for oriented strand board (OSB) sheathed shear walls, which was implemented in Italy; this method however, is not applicable for strap-braced walls. Macillo et al. [18] have established links with the existing Eurocode 1998-1-1 [15] for hot-rolled steel cross-braced frames and that of the cold-formed steel strap-braced walls tested by Iuorio et al. [19] and others. This Eurocode 1998-1-1 standard contains provisions for traditional hot-rolled steel concentrically braced frames with X diagonals, including tension-only configurations. However, these provisions were not originally intended for use with the specifics of a CFS framed structure. Furthermore, this work addressed low aspect ratio walls within the range 1:1 to 2:1. Note, Macillo et al. made mention that non-energy dissipating members of the wall such as beams and columns are "…evaluated by considering the interaction with the bending moment (M_{Ed}), that is generally null for the examined systems; …" [17]. Given the aspect ratio of the walls that were being studied this statement does have an element of truth, however, the development of moments in the framing occurs as the aspect ratio increases, as will be demonstrated herein. Further to this, Tian et al. [8] carried out tests on 2:1 aspect ratio walls (2.45 m in height × 1.25 m in

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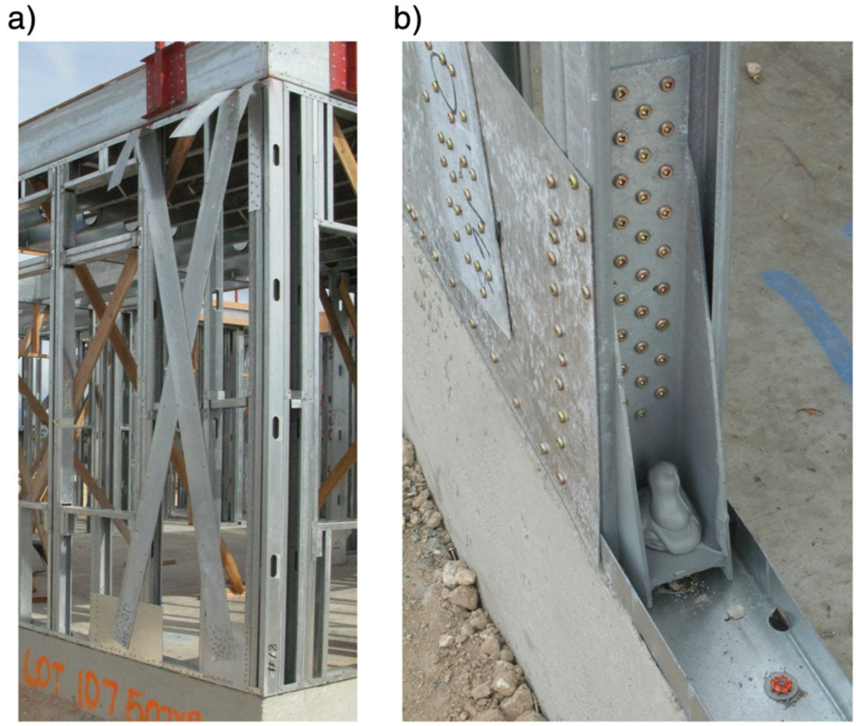

Fig. 1. a) Typical narrow diagonal strap-braced cold-formed steel wall, b) hold-down device and gusset plate.

length) for which chord stud failures were observed; the design of these studs was not done following a capacity based approach that accounted for both probable axial compression force and probable bending moment.

Research on strap-braced walls is of course not limited to North America and Europe. As an example, Moghimi and Ronagh [20] also presented a design approach of strap-braced walls in which the risk of connection and stud failure is minimized; however, this again was carried out for 1:1 aspect ratio walls (2.4 m × 2.4 m).

In the calculation of the forces that transfer through the SFRS following the North American AISI Standards, as the strap braces yield the triangulated configuration of the wall leads to the notion of pin connected truss-like behavior, which results in only axial forces being applied to the chord studs. Experimental evidence has shown that for walls with 1:1 aspect ratios the joint fixity is for the most part inconsequential [12]; however, tests on narrow 4:1 aspect ratio walls, and even 2:1 aspect ratio walls, by Comeau & Rogers [21] and Velchev & Rogers [22] have revealed that as the aspect ratio increases the joint fixity at the wall corners leads to frame-like behavior, subjecting the chord studs to combined bending moments and axial forces. The hold-down devices used to connect the chord studs to the underlying foundation (Fig. 1b), or to the braced wall located in the story above or below, and the gusset plates commonly used to attach the chord studs and track to the brace (Fig. 1b) result in flexurally stiff connections and the subsequent development of moments in the frame members. The combination of high axial compression force and bending moments may lead to the failure of the chord studs prior to strap yielding if unaccounted for in capacity design. This will result in a decrease of the ductility of the SFRS and a loss of the post-earthquake gravity load-carrying ability of the structural walls.

The objective of this paper is to describe an investigation of the response to lateral loading of high aspect ratio strap-braced walls in which both experimental and analytical evidence is provided to illustrate the development of frame bending moments. Ultimately, a proposal is made for a simple capacity-based design procedure that accounts for both the axial and flexural forces applied to the frame members of cold-formed steel strap-braced walls.

2. Current design approach

The North American approach for the design of CFS strap braced walls subjected to in-plane lateral seismic loading can be found in the AISI S213 [1] and S400 [2] Standards. The assumption of truss behavior allows for the use of simple trigonometric relations to determine axial force demands in the chord studs, for example, associated with the expected tensile force of the strap braces and any companion gravity loads. As long as the factored axial resistance of the selected chord stud is greater than this demand, the belief is that the braces will yield in tension before any damage is done to the studs. The “undamaged” chord studs would then be available to maintain their gravity load-carrying role post-earthquake.

2.1. SFRS member demand and resistance

The brace members in a cold-formed steel framed structure are initially selected in consideration of the lateral force and drift requirements imposed by the relevant building code for both wind and seismic loading. The factored tension resistance of the braces is determined using the standard approach found in AISI S100, the “North American Specification for the Design of Cold-Formed Steel Structural Members” [23], accounting for the net cross-section fracture and gross cross-section yielding failure modes. Strap braces are considered to have no resistance in compression due to their high slenderness; hence, a tension-only lateral structural system exists. The brace selection may also be contingent upon the stability requirements of the structure under gravity loading and drift limits.

Subsequent to the initial selection of the braces further seismic specific design provisions, material property requirements and detailing as per the AISI S213 [1] and AISI S400 [2] Standards must be met. Although a factored resistance of the braces has been determined in the initial selection of the members, in the event of a rare design level earthquake it is expected that the force in the braces will exceed this resistance level and will enter into the inelastic range of behavior. Energy arising from the ground motion will be dissipated due to the ability of the steel braces to carry load after yielding of the cross-section. However, to