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Fragility curves for thin-walled cold-formed steel wall frames affected by ground settlements due to land subsidence

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ABSTRACT

This report presents the results of a study on the performance of thin-walled cold-formed steel wall frames with different sheathing systems affected by angular distortions simulating ground differential settlements due to land subsidence. The wall frames are sheathed with different systems: expanded polystyrene, OSB, calcium silicate and gypsum board. Using experimental testing and numerical simulation, moment–rotation curves were calculated for the studs. A non-linear static pull-down analysis was performed producing several degrees of angular distortion simulating ground settlements. Lastly, fragility curves were calculated based on three levels of damage for wall frames with different sheathing systems.

1. Introduction

Ground failure associated with land subsidence is the primary geotechnical hazard in several cities in central Mexico that has caused enormous economic loss by damaging public and private properties, including dwellings. The damage caused by ground failures is variable and considerable, even though the local government is aware of this problem and has undertaken steps to mitigate ground failure-related damages. Active fracture zones associated with land subsidence induce displacements in buildings in the form of differential settlements, which cause damage to structural systems in dwellings, especially those based on masonry, because of their low capacity to absorb angular distortion. The most widely used structural systems are confined masonry walls with reinforced concrete beams and columns as well as internal reinforced masonry, both of which meet the requirements for structural masonry located in seismic zones. However, the problem of subsidence induces different structural distortions compared with the problems caused by dynamic lateral loads.

Cold-formed steel sections have instability problems because of the effects of certain buckling modes due to the slenderness of the section [1]. One of the principal uses for this type of material is for structural frames in the form of modules, which are most commonly assembled using elements with edge-stiffened flanges and elements with simple flanges with different dimensions and gages. One of the advantages of this type of modular system is its versatility for industrial production, which has a direct impact on manufacturing and quality control. Although these cold-formed steel frames have been used for decades, their application as principal elements that support load is relatively new, which is why the specifications and related standards associated with the application of this system and its behavior under lateral loads continue to be improved and perfected [2]. Furthermore, the majority of studies on cold-formed steel structures have been primarily focused on their performance under seismic events, e.g., the performance under lateral loads using non-linear static push-over analysis, as described in the specifications provided by the Applied Technology Center [3]. However, few studies have focused on the case of cold-formed steel structures affected by ground settlement due to land subsidence phenomenon; therefore, conducting research on this issue is a priority for zones affected by land subsidence. The primary objective of this study is to assess the structural performance of thin-walled cold-formed steel wall frames with different sheathing systems to be used in zones affected by ground settlement; because of its mechanical properties, the structural performance could allow large displacements to be absorbed without failing. Likewise, because an industrialized construction method is being used, the rehabilitation, repair and/or structural

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reinforcement costs of these structures once damaged by land subsidence will be much lower than those corresponding to systems using traditional housing construction. In this report, the results of an experimental and numerical study, with the objective of assessing the performance of thin-walled cold-formed steel wall frames under angular distortion and simulating the differential ground settlements due to land subsidence phenomenon, are presented.

1.1. Land subsidence

Over the past few decades, the land subsidence phenomenon by ground water withdrawal has extended into valleys in Mexican territory where the aquifer is formed by non-consolidated materials, such as alluvial deposits and lacustrine or sedimentary volcanoes [4–12]. The fracturing associated with subsidence has been carefully studied in several parts of the world [13–16]. The costs associated with subsidence are critical when damage occurs in densely populated cities, which is true for most cases in Mexico. However, there are no studies quantifying economic losses for the damages related to land subsidence. In these cases, the effects of ground failures related to subsidence are often detected after differential settling of the buildings has already begun, and, in certain cases, the studies do not begin until damage has already occurred, such as cracks in the walls. Subsidence and fracturing are two conditions that can consequently damage a large number of housing structures, especially houses made of masonry because of its low ductility and low capacity to absorb angular distortion.

1.2. Non-linear static push-over analysis

The design guide NEHRP (ATC-40) provides a complete description of the non-linear static push-over analysis method; it also includes certain orientations for models and the assessment of behaviors after the elements and structural components have yielded. [17]. The push-over analysis is where the model of the structure is subjected to a previously defined monotonic horizontal load, which is incremented until it reaches its maximal considered displacement or the structure fails. The goal of the push-over analysis is to assess the structural performance, estimate the strength and capacity of deformation using a static non-linear analysis and compare these capacities with the demands based on the levels of performance [18]. Although the static non-linear analysis of structures has been recently included in the design process for new building construction, the procedure itself is not new and has been used for several years in investigative and design applications. This procedure has become simpler because it allows a direct assessment of the response of structures from horizontal displacements caused by earthquakes of considerable magnitude, and it can be a good alternative in relation to other procedures that are more complex in their analysis [19]. This procedure uses non-linear simplified techniques to estimate the structural deformation. However, the non-linear dynamic procedure, commonly known as non-linear time-history analysis, requires considerable judgment and experience to perform; it can be used only inside the limits described in the specifications [20]. The push-over analysis is represented by the capacity curve of the structure, which is a load–displacement curve that represents the horizontal shear force and the displacement on top of the structure. The capacity of a structure depends on its strength and the capacity of deformation of its components.

1.3. Non-linear static pull-down analysis

The pull-down analysis of a structure can be considered when one of its supports suffers a vertical displacement, generally downwards. The results for this type of analysis are similar to the results that occur when a static non-linear push-over is used; the only difference is the direction in which the displacements are evaluated. In the push-over analysis, the horizontal displacements are assessed; in the pull-down analysis, the focus is on the vertical displacements, which can be generated by different causes. An important parameter in this type of vertical displacement (settlement) is its rate, which depends on the landslide type or other phenomenon that affects the structure. The primary difficulty in obtaining reliable results for landslides compared with other natural threats, such as earthquakes or flooding, is caused by the complexity in modeling landslides, identifying the relevant parameters of intensity and assessing the vulnerability using the quantitative method. According to Negulescu [21], there are three general methods to predict the damage in structures due to the movement and settlement of foundations:

- empirical method, which establishes a criteria for serviceability in linking the observed deformations of field measurements with damage;
- methods using the fundamentals of structural engineering;
- methods based on numerical modeling.

The methodology followed in the current case consisted of performing non-linear pull-down analysis for different types of cold-formed steel wall frames affected by vertical displacement and simulating the effect produced by land subsidence, which develops gradually in buildings over the years.

1.4. Fragility functions

Fragility functions describe the probability that a structure exceeds a determined state of damage related to a dependent parameter [22] e.g., the inter-story drift (ISD) or the peak ground acceleration (PGA) in the case of evaluating the seismic performance [23]. It can be stated that these functions are a measurement of vulnerability for a structure in probability terms. The methodology to obtain the fragility curves is governed by document ATC-58 [24], which establishes specific guidelines in developing fragility curves for a given structure or element; these procedures have to be followed to secure an adequate and reliable fragility curve development. The fragility curves are constructed using cumulative lognormal distribution functions; they are based on two fragility parameters, a median value (θ) and a dispersion value (β), which is a lognormal dispersion value of the function in relation to the (x) variable, which is the dependent parameter.

2. Methodology

2.1. Experimental methodology

Thin walled cold-formed steel wall frames with a longitude of 1600 mm and a height of 1500 mm were used (see Fig. 1); they were structured with simple channel section 350T125-33 elements (tracks) on the top and bottom parts of the frame and vertical stiffened channel section 350S162-33 elements (studs). The center to center distance between the studs was 400 mm. Used as a sheathing material, a high-density expanded polystyrene panel with a thickness of 75 mm was inserted between the studs. The connections between the studs and the tracks were made using NN° 8 flat head self-drilling screws with a longitude of 20 mm and applied to each joint; thus, four screws were used. To fasten the wall frames to the ground, "hold-down" type anchors at a right angle, constructed of steel plate A-36 of 4-mm thickness, were put in each bottom end of the frame; the anchors fastened the frame using 14 self-drilling screws N° 10 that were 38 mm in longitude, and a steel screw A-307 Gr. B with a diameter of 16 mm was used to anchor the frame to the ground. A double action hydraulic actuator with a 160 kN capacity connected to a load beam was necessary to apply the monotonic horizontal load on