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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

Land subsidence phenomenon due to ground water withdrawal is a current problem in many places around the world, particularly in the shallows of Mexico. This causes ground differential settlements that affect structures, mainly dwellings and buildings based on reinforced concrete and masonry. Eventually, these structural materials do not exhibit an adequate performance beyond a certain level of angular distortion. This work presents the results about a study regarding 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 composed by vertical (studs) and horizontal elements (tracks), with different sheathing systems: polystyrene, OSB, gypsum and calcium silicate. By means of experimental testing of wall frames subjected to monotonic lateral loads, the rotational stiffness was obtained for the wall frames with polystyrene. Likewise the rotational stiffness of the other wall frame systems was calculated based on the data provided by other author's publications. On the other hand, by means of numerical simulation, all the wall frame systems were modeled in structural analysis software, calibrating them based on the rotational stiffness. Also, the moment-rotation curves were calculated for the studs and tracks based on the

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direct strength method. A non-linear static pull down analysis was performed producing several degrees of angular distortion simulating ground settlements for all the wall frames sheathing systems. With the data acquired fragility curves were calculated according three levels of damage for the wall frames with different sheathing system.

Introduction

The majority of studies on cold-formed steel structures have been centered mainly in behaviors under seismic action. For example, the behavior of lateral loads realized with non-linear static push-over analysis, described in the specifications of Applied Technology Center [ATC 40, 1996]. Nonetheless, the case of cold-formed steel structures affected by ground settlement and, above all, for the land subsidence phenomenon, has been the subject of very few studies.

In this paper, the results of an experimental and numerical study, with the goal of assessing the performance of thin-walled cold-formed steel wall frames under angular distortion simulating differential ground settlements due to land subsidence phenomenon is presented.

The land subsidence phenomenon by ground water withdrawal has been extended in the past decades over the Mexican territory in valleys where the aquifer is formed by non-consolidated materials such as alluvial deposits, lacustrin or sedimentary volcanoes geologically recent [Figueroa, 1994; Aguirre et al., 2000; Garduño et al., 2001; CENAPRED, 2001; Arroyo et al., 2003; Arroyo et al., 2004; Rojas et al., 2002; Pacheco et al., 2006; Zermeño et al., 2004]. The fracturing associated with subsidence has been carefully studied in many parts of the world [Poland, 1984; Borchers, 1998; Prince et al., 1995; Zhang et al., 2005]. Subsidence and fracturing are two conditions that have as a consequence the damaging of a huge quantity of housing, especially houses made of mud pieces and/or concrete blocks masonry, due to a low ductility and low capacity to absorb angular distortion.

The design guides NEHRP [ATC-40, 1996], show a complete description of the method of non-linear static push-over analysis, it also includes some orientation about models and assessing of behaviors after the yield of elements and structural components [Hazus, 2011]. The push-over analysis is the one that the model of the structure is subjected to a monotonic horizontal load , previously defined, which is incremented until it reaches its maximal considered displacement or until the structure fails. The goal of the push-over analysis is to assess the structural performance, estimating the strength and capacity of deformation using a static non-linear analysis and comparing these capacities with the demands according to the levels of performance [Kalavagunta et al., 2012]. Even if static non-linear analysis of structures has been recently included in design supplies for new buildings construction, the procedure itself is not new and has been used for many years in investigation and design applications. It became a simpler method since it gives direct assessing of the response of structures in front of horizontal displacement due to earthquakes of considerable magnitude and it can be a good alternative in relation to other procedures more complex in their analysis [FEMA 450-1, 2003].

This procedure uses non-linear simplified techniques to estimate the structural deformation. On the opposite side, the non-linear dynamic procedure, commonly known as non-linear time-history analysis, requires considerable judgement and experience to carry out; it can be used only inside the limits described in specifications [FEMA 356, 2000]. 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 the components.

The pull-down analysis in a structure can be considered when one of the supports suffers a vertical displacement, generally going downward. This type of analysis results similar to the one that occurs when a static non-linear push-over is realized, the only difference being the direction in which the displacements are evaluated. While in the push-over analysis, the horizontal displacements are being assessed, in the pull-down analysis, the focus is on the vertical ones, 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 major difficulty to obtain reliable results for landslide compare to other natural threats, like earthquakes or flooding, is caused by the complexity of modelling of landslides, identifying the relevant parameters of intensity and assessing the vulnerability using quantitative method. According to [Negulescu, 2010], there are three general methods to predict damage in structures due to movement and settlement of foundations: empirical method, which establishes criteria of serviceability in linking the observed deformations of field measurements with damage, methods using the fundamentals of structural engineering and methods based on numerical modelling.

The methodology followed in the present case consisted in carry out non-linear pull-down analysis of different types of cold-formed steel wall frames, affected by vertical displacement, simulating the effect produced by land subsidence, which is developed slowly as the years pass by.

Fragility functions describe the probability that a structure exceeds a determined state of damage related to a dependent parameter [Shinozuka, 1998]. For example, the inter-story drift (ISD) or peak ground acceleration (PGA) for the case of evaluating the seismic performance [Jeong et al., 2012]. It could be said that these functions are a measurement of vulnerability of a structure in probability terms.

The methodology to obtain the fragility curves are governed by document [ATC-58, 2009], 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 with cumulative distribution functions of lognormal type; 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.

Methodology

Thin walled cold-formed steel wall frames with a 1600 mm longitude and 1500 mm height were used (see Figure 1), they were structured with elements of simple channel section 350T125-33 (tracks) on the top and bottom parts of the frame, and also with vertical elements of stiffened channel sections 350S162-33 (studs).

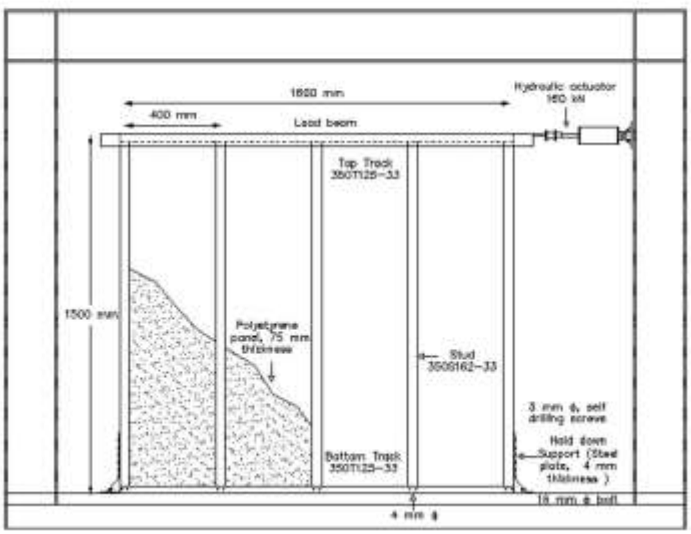

Figure 1.- Layout of the experimental test

The distance between the studs was 400 mm center to center. As sheathing material, high-density expanded polystyrene panel of 75 mm thickness, inserted between the studs was used. The connections between studs and tracks were made by N° 8 flat head self drilling screws with 20 mm longitude; they were applied in every joint, so 4 screws in total were used. To fasten the wall frames to the ground, two anchors type “hold-down” at right angle, made with steel plate A-36 of 4 mm thickness, were put in every bottom end of the frame; they fastened the frame using 14 self drilling screws N° 10 of 38 mm longitude and to anchor to the ground a steel screw A-307Gr. B of 16 mm diameter was used.

A double action hydraulic actuator of 160 kN capacity connected to a load beam was necessary to apply monotonic horizontal load on the top end of the frame, which was gradually increased to reach a 151 mm target displacement. Measuring instruments were put on the points of interest to evaluate the displacements for a total of 20 points distributed uniformly on the area of the frame. The average rate of load application was 8 mm/min.

The values of elastic rotational stiffness of the wall frame that served in the calibration of the numerical simulation models were determined by tests where the frames described previously were subjected to lateral loads. Wall frames with and without expanded polystyrene sheathing of 75 mm thickness was tested. The expanded polystyrene is basically used as an isolating thermo acoustic element; nevertheless in the present study the contribution of this material in the structural behavior of the system was evaluated.

As the first step in the numerical methodology, were taken as reference experimental results of lateral load-displacement of different models of wall frames of cold-formed steel sections with different sections, gages, dimensions, separations and sheathing materials such as wood OSB, calcium silicate and gypsum board panels, carried out and published by different authors [Xuhong and Yu, 2006; Pan and Shan, 2011; Baran and Alica, 2012; Nithyadharan and Kalyanaraman, 2012]; the load-displacement curves are shown in Figure 2, including our own expanded polystyrene system.

The aim was to simulate numerically the behavior of all these structures by means of a non-linear analysis software (SAP, 2000) in order to reproduce the load-displacement curves. By means of the lateral load-displacement curves of each model, the elastic rotational stiffness values were obtained in order to calibrate the models. Likewise, the values of the modulus of elasticity and the shear modulus were utilized as calibration parameter depending on each sheathing material. In total, 27 models of different thickness, gauges and sheathing materials were generated.

The numerical models utilized for these simulations were assembled using bar type elements for studs and tracks and area type elements for sheathing. The area type elements were discretized in 10 cm size maximum, the connectivity of the bar type elements were considered semi-rigid and a spring with rotational stiffness was assigned, which value was found from experimental testing.

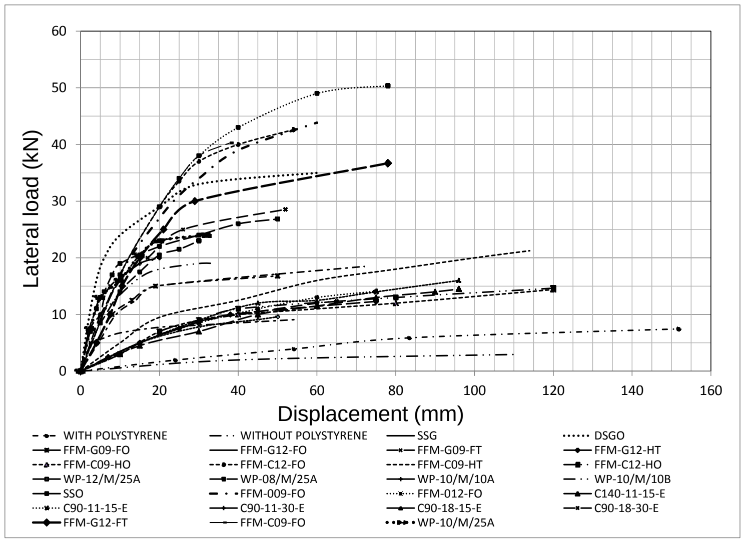

Figure 2.- Load-displacement curves for cold-formed steel wall frames with different sheathing materials

Due to the fact that the moment-rotation response of cold-formed steel elements results to be highly sensible to slenderness of the transversal section and also offers a good response of mechanical behavior of the element, this parameter was used to assess the development of every one of the analyzed models and to compare the results. Taking the obtained information as a start, moment-rotation curves were constructed from each model with its matching sheathing material including the expanded polystyrene wall frame.

The specifications propose approximated methods to consider the reduction of stiffness due to local buckling, using variations of the effective width method. Except that, these stiffness reductions are valid until a maximum strength range of the element and that means that they are not suitable to determine the stiffness beyond the maximum strength, that is why it is necessary to assess the behavior of elements beyond maximum strength, in order to get a more realistic analysis.

Based on above mentioned and to carry out a non-linear analysis, it was necessary to plot the moment-rotation curves for each of the sections used as studs, knowing that these curves describe its mechanical behavior in zones where plastic hinges tent to form.

The curves utilised in the present study were calculated and adapted taking reference on the analytic procedure proposal for [Ayhan and Schafer, 2012], which took as a reference the moment-rotation curves proposed by [ASCE/SEI 46-06, 2007]. According to these authors, the type 1 curve (ASCE 41) includes as well as the pre-peak loss of stiffness, the degradation characteristics of the post-peak regime, so it is considered the most suitable to represent the mechanical behavior of thin walled cold-formed steel sections. Following the calculation sequence proposed and based on the geometrical properties of all the sections (studs) of all the analysed models, the moment-rotation curves for local buckling as well as for distortional buckling of these structural elements could be plotted (Figures 3 and 4, respectively).

Once built the numerical models on the non-linear analysis software SAP 2000, the models were able to be calibrated, depending on the mechanical parameters obtained experimentally: elastic rotational stiffness, modulus of elasticity and shear modulus of sheathing material, as previously mentioned. Subsequently, the pull-down analysis was carried out on all the virtual structural models, using a vertical monotonic incremental displacement step by step on the right end support (control joint), simulating a differential settlement of the ground due to the land subsidence phenomenon, as shown on Figure 5. The angular distortion is the ratio between displacement and longitude of the structural frame analysed.

The behavior of all the virtual models was assessed by obtaining the values of the moment depending on angular distortion for each step in the application of incremental displacement beyond linear regime, adopting the following methodology:

1. Building of the virtual models of cold-formed steel wall frames without any type of sheathing in the software of non-linear analysis SAP 2000, according to geometry and number of elements (studs and tracks).
2. Assignation of properties: mechanical parameters of materials (steel and sheathing), geometrical properties of transversal section of cold-formed steel elements, loads applied and states of load.
3. Calibration of virtual models to reproduce the wall frames behavior with lateral loads in accordance with experimental tests carried out for expanded polystyrene system and using the load-displacement curves obtained from different authors, according to elastic rotational stiffness values and elasticity as well as shear modulus.
4. Assignation of moment-rotation curves for local and distortional buckling on the ends of each one of the studs to simulate plastic hinges.
5. Configuration of parameters for static non-linear pull-down analysis: maximum displacement, control joint and number of steps.
6. Running the non-linear analysis on each one of the virtual models and process the results.

From the non-linear analysis results the moment values in each one of the studs for each vertical displacement (or angular distortion) were obtained for each and every one of the virtual models analysed. The results were grouped together depending on the sheathing material utilized and the moment maximal values of the whole model for each level of distortion was filtered (which would not necessarily correspond to the same stud), expressing it relatively taking as a reference the plastic moment, Mp.

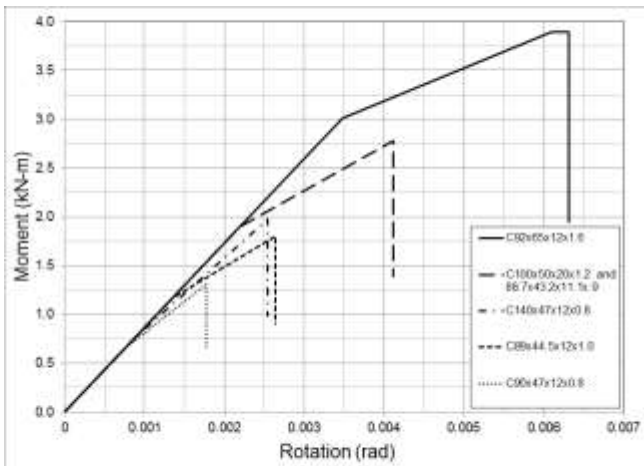

Figure 3.- Moment-rotation curves for local buckling

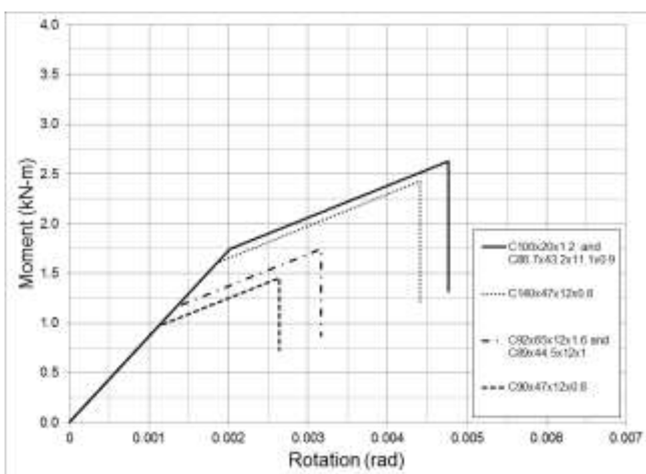

Figure 4.- Moment-rotation curves for distortional buckling

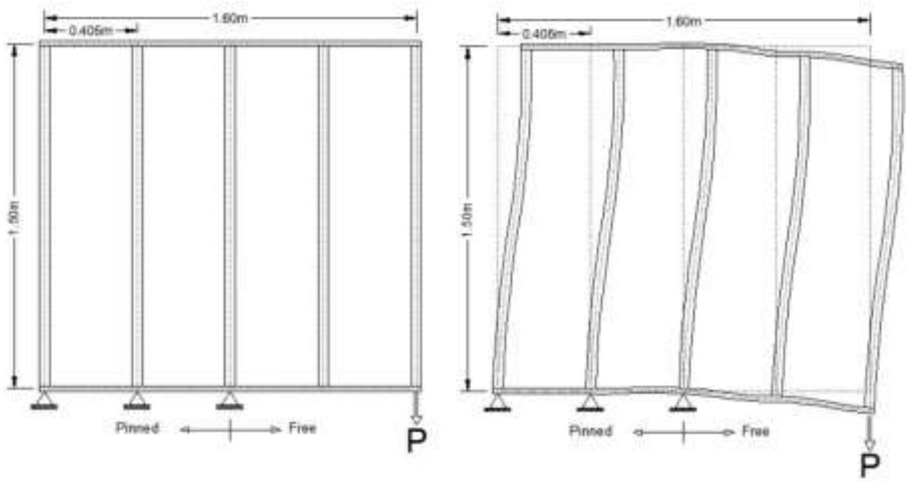

Figure 5.- Static non-linear pull-down analysis procedure

Results and analysis

In Figure 6, the results corresponding to lateral load-displacement for the cold-formed steel wall frames with and without expanded polystyrene sheathing are presented, subjected to a lateral monotonic load.

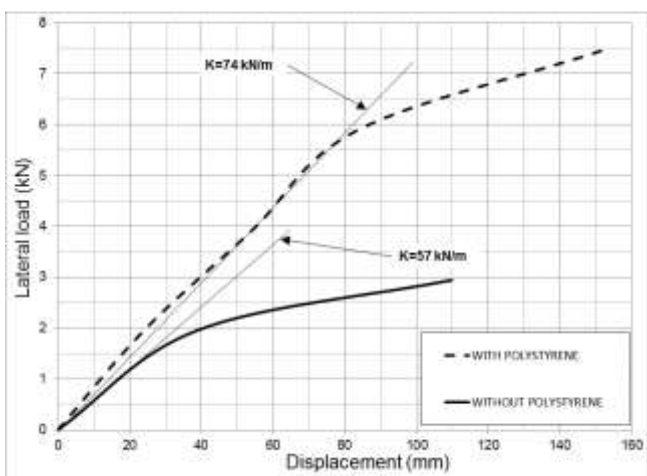

Figure 6.- Load-displacement curve for cold-formed steel wall frames with and without polystyrene sheathing

In the previous graphic, it can be seen that the elastic rotational stiffness is major for the case when the frame includes the expanded polystyrene sheathing within the studs; in this way it can be appreciated that the contribution of polystyrene to the frame stiffness is approximately 30%, since the stiffness of the wall frame without polystyrene sheathing is 57 kN/m and with polystyrene is 74 kN/m. The second phase of the curves where the slope is reduced corresponds to the wall frame behavior in the non-linear regime, once that the loss of stiffness is generated by failure of sheathing and/or yielding of the connexions when plastic hinges are formed on the stud-track joint, either by local or distortional buckling. In Figure 7 the results corresponding to relative moments of all the analysed virtual models are presented, that is to say, the relation between the moment and the plastic moment (M/Mp), as a function of the angular distortion, defined as the ratio between the vertical settlement and longitude of the cold-formed steel wall frame.

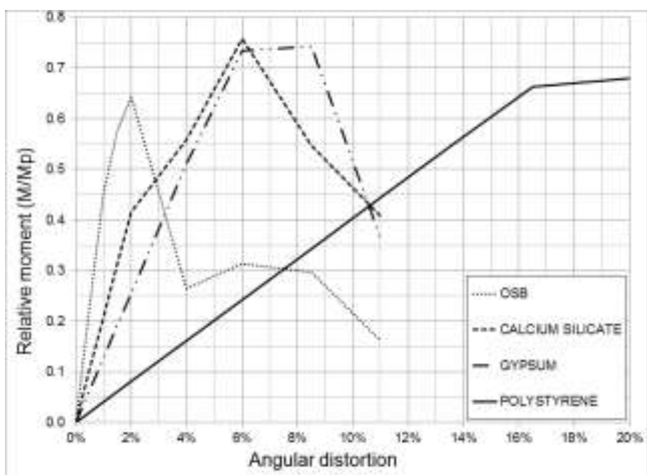

Figure 7.- Relative moment–angular distortion curves for wall frames with different sheathing materials

In the previous graphic, it can be observed that the cold-formed steel wall frame covered with OSB offers the greatest stiffness of all systems, being greater in more than one order of magnitude in relation to the expanded polystyrene frame, which presents the minor stiffness as a structural system. However, the previous could be against the OSB system if what is looked for in this case is a structure that “absorbs” ground differential settlements without failing, and in the foretold case, the system fails when occurs an angular distortion below 2%.

On the other hand, it can be seen that all the systems present a behavior characterized by a linear regime until the maximum peak and they later enter to a non-linear regime with a residual post-peak strength, with the exception of the panel with calcium silicate sheathing system, which presents a bi-linear behavior with a degradation on the slope after 40% of the Mp and an angular distortion corresponding to 2%, to finally reach a maximum strength of 75% of the Mp for an angular distortion up to 6% and later a residual post-peak non-linear strength; in every case the studs will work up to at least 65% of the Mp, approximately. It is noteworthy that for none of the structural systems, the studs present a failure corresponding to a full plastification of section, meaning that they never reach the Mp value, because they first present failures due to distortional buckling of the section.

In summary, based on previously analysed results, it is possible to affirm that the cold-formed steel frame with polystyrene sheathing is the one that presents a greater ductility; since it admits big displacements (vertical settlement expressed as angular distortion) without suffering excessive damage in comparison with other systems.

Fragility analysis

Fragility curves were developed using the equation given at (ATC-58, 1996). In this work, fragility curves for thin-walled cold-formed steel wall frames affected by differential ground settlements due to land subsidence were developed. A peculiarity of land subsidence phenomenon is that ground settlements take a long time to be accomplished. The construction of fragility curves requires owning a clear idea of the damages generated in the elements of the structure, in order to be able to characterize or identify them as boundary zones of degradation of the structure. Particularly in this case, it is necessary to identify the states of damage when the structure is subjected to vertical displacement simulating the effects of ground settlements by land subsidence.

On the other hand, there are different existing methods to generate fragility curves and matrix of damage probability, for example: methods based on field observation, experimental methods, methods based on experts opinions and analytical methods, which are classified as determinist and probabilistic methods. For this investigation the Plastic Moment (Mp) directly associated to angular distortion was applied as a reference parameter; three damage states related to this parameter were defined, 0.5 Mp for light damage, 0.65Mp for moderate damage and Mmax for complete damage.

Through statistical analysis of the results, median values and dispersion values were obtained by applying the pull-down procedure to each of the frames in study. Fragility curves for each state of damage and type of sheathing were generated applying fragility functions.

These curves are presented in the Figures 8a, 8b, 8c and 8d for expanded polystyrene, OSB, calcium silicate and gypsum board wall frames, respectively.

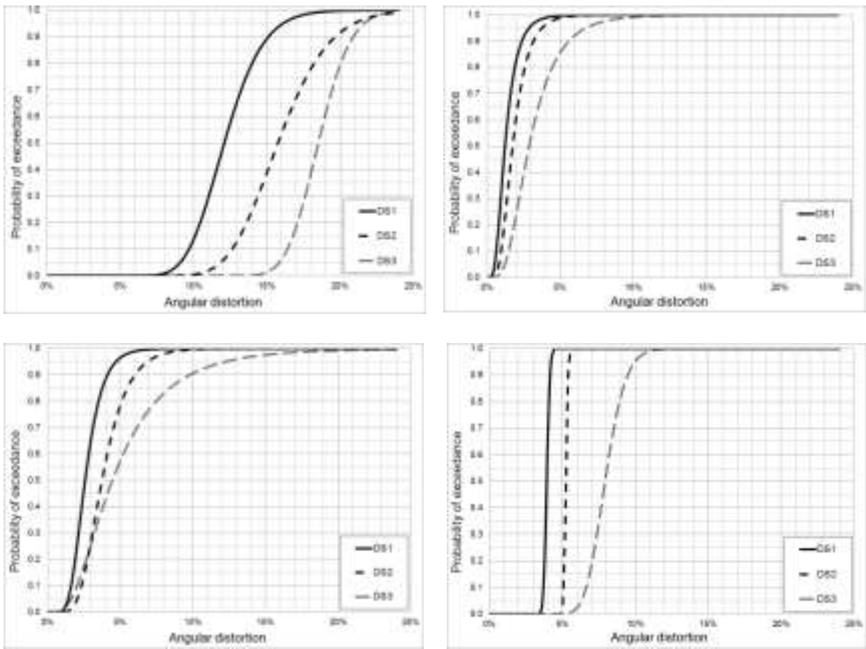

Figure 8.- Fragility curves for land subsidence of cold-formed steel wall frames with different sheathing materials

It can be observed that in relation to the expanded polystyrene wall frame, for an angular distortion of 10% the structure practically stays without damage, presenting only 15% of probability approximately that it will reach a low state of damage, while other sheathing material, for this level of distortion, present a high probability of reaching a complete state of damage.

For the case of the gypsum board wall frame it can be seen that it has a high probability of presenting low and moderate damage with only 5% of angular distortion.

The behavior of the calcium silicate wall frame results more favorable than the OSB and gypsum, since it bears a greater angular distortion, having the same levels of structural damage.

According to the fragility curves obtained for the cold-formed steel wall frame with expanded polystyrene, in general terms this structural system presents the best performance before differential ground settlements, since for an angular distortion of 19% there is a probability of 50% that a complete damage occurs, a 80% probability that it presents moderate damage and a 98% probability that it would only present a low level damage in the structure.

Conclusions

According to the experimental results it can be observed that for the wall frame sheathed with expanded polystyrene, it gives enough elastic rotational stiffness to the system, with approximately 30%.

The OSB wall frame offers the greatest stiffness of all the systems, being greater in more than one order of magnitude compared to the expanded polystyrene wall frame tested experimentally, which present the lowest stiffness as a structural system, by comparing the relative moment (M/Mp) related to angular distortion.

For none of the structural systems, the studs present a failure corresponding to a full plastification of section, meaning that they never reach the Mp value, because they first present failures due to distortional buckling.

The cold-formed steel wall frame with polystyrene sheathing is the one that presents a greater ductility; since it admits great displacements (vertical settlement expressed as angular distortion) without suffering excessive damage in comparison with other systems; this has been verified from a numerical point of view by determination of the relative moment, as well as a probabilistic point of view by calculating the fragility curves.

Even if in experimental testing to lateral load the wall frame sheathed with expanded polystyrene presented a minor lateral strength in comparison with the results of other researchers, regarding ductility, this system had the best behavior.

Finally, the use of structures based on cold-formed steel wall frames with polystyrene sheathing would be very suitable in order to reduce damages and guarantee structural safety in housing constructed in zones affected by ground settlement due to land subsidence.

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