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Experimental and numerical analysis to collapse of a framed structure subjected to seismic loading

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ABSTRACT

The nonlinear numerical analysis to collapse of civil structures presents several difficulties, even for mechanically well-characterized materials, such as steel. In the case of steel, where the nonlinear constitutive equation is one of the simplest and best known, in many cases there are large differences when the numerical analysis and experimental results are compared. In this paper, the results of an experimental and numerical analysis of a single degree of freedom (SDOF) steel structure are presented. The structure was subjected to near fault earthquakes that caused nonlinear behavior of their components and structural collapse. The experimental model was tested on a shaking table. Complementary tests were performed to characterize the properties of the steel employed, and thus define the parameters used in the numerical simulation. After the calibration of the nonlinear material model, a comparison is made between the experimental and numerical results obtained. Finally, a numerical study, following the modeling methodology obtained from the numerical–experimental analysis, is performed to quantify the influence of the P-Delta effect on the structural collapse.

1. Introduction

One of the main objectives of the structural engineering is to prevent the collapse of structures in order to preserve the life of the occupants. Consequently, it is important, both in the design of new structures and in the assessment and rehabilitation of existing structures, to know the safety margin against collapse.

The collapse can be defined as the loss of the ability to support vertical loads by the structure. In practice, there have been direct vertical collapses and collapses with large lateral displacements. The first of them arises when one or more structural elements lose their bearing capacity suddenly, while the second type is observed when dynamic instability is reached, with large horizontal displacements and large story drifts. This latter type of collapse can be classified as instability-type collapse, according to the typology proposed by Starossek [1].

The action of gravity loads over a laterally deformed structure causes an increase in the member forces and in the lateral deflections while it reduces the resistance to lateral loads. This process is known as P-Delta effect, and may lead to negative values of stiffness in the inelastic response of flexible structures. If the displacement demand of the seismic action is high enough the structure can reach dynamic instability and collapse [2].

At present, there are different methods to evaluate the safety of structures against the collapse produced by the seismic action. Villaverde [3] have performed a comprehensive review of these methods, and concludes that the nonlinear dynamic analysis of the entire structure, modeled using finite elements, is the most reliable method for evaluating the collapse. However this method has the disadvantage of being computationally expensive. The author also states that the following considerations should be taken into account: the model must solve the equation of motion in the deformed configuration, elements that are compatible with large deformations should be employed, the mesh should be fine enough to faithfully reproduce the structural behavior in zones that undergo inelastic strains, and finally simulations must be performed with several seismic records to obtain meaningful information about the structural collapse. In any case, the material models and numerical codes should be carefully calibrated against experimental tests.

Alternatively, concentrated plasticity models that represent phenomenologically the nonlinear behavior of structural elements have been used in recent studies [4–7]. These models take into account fundamental aspects such as the degradation of strength and stiffness, both on steel and on reinforced concrete elements, and have been calibrated through many tests of cyclic loading

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[8,9]. At the same time, complete structure models were validated with experimental test results [10,11]. The use of such models allows a large number of simulations to be performed, in which the effects on the structural collapse due to the variability of the seismic action and the properties of the structure can be studied.

The structural instability under seismic loading has been studied, both at numerical and analytical levels, by several authors [12–14]. Miranda and Akkar [15] have studied the dynamic instability in SDOF systems, with bilinear hysteretic behavior and negative post-yielding slope. In this study, nonlinear dynamic analyses to collapse were performed on structures with different fundamental periods and several negative post-yielding slopes. The results of this analysis shown that dynamic instability is reached more readily in structures with more pronounced negative post-yielding slope and lower fundamental periods.

Shafei et al. [16] conducted a statistical study on the collapse of moment resistant frame and shear wall structural systems, with diverse structural parameters, subjected to seismic excitations. From the results of this study mathematical models were obtained using multivariate regression analysis. Based on the mathematical models, collapse fragility curves can be established in order to estimate the probability of the structural collapse. This probability is calculated as a function of the dynamic properties and the non-linear properties of the structure, estimated from a pushover analysis.

Adam and Jäger [17] have proposed to evaluate the vulnerability of structures with the sign of the post-yield tangent stiffness obtained from a nonlinear static analysis. From results of incremental dynamic analysis it was observed that the structural collapse is reached more readily when the structure has a pronounced negative post-yield tangent. The authors also have defined a collapse capacity spectrum to estimate earthquake intensity that produces the collapse of a structure with a given fundamental period and a post-yield stiffness. The structure analyzed with this method must be regular to be well represented by the equivalent SDOF system, and should not have resistance or stiffness degradation.

The collapse of structures induced by earthquakes has been studied experimentally in a lesser extent [18–22]. Vian and Bruneau [23] have performed experimental tests over several SDOF structures under seismic forces, which were increased to collapse level. The structures tested had different slenderness and mass, and they show no degradation. From the results of this test, it was observed that the traditional stability factor (a measure of the importance of P-Delta effect) indicates what structures are more vulnerable to collapse. The results of these tests also showed that the higher the influence of P-Delta effect, the lower plastic strains and displacements that are achieved when dynamic instability occurs.

Lignos and Krawinkler [24] have conducted an experimental and analytical study of two four-story steel frames under seismic forces that cause collapse. Plastic strains of the structure were concentrated in hinges specially designed, which were characterized in cyclic tests. On the basis of the results obtained it is concluded that the P-Delta effect and degradation in plastic hinges are the factors that define the behavior of the structures when they are near collapse.

Lignos et al. [25] have made an analysis of the numerical models employed to reproduce the full scale test of a 4-story steel frame. The test was performed on the E-Defense shaking table in Japan in 2007 [26] as part of a contest that was aimed to assess the responses of various analytical models. These responses were ordered according to their similarity to the structural response measured experimentally. From the results of the contest, it was concluded again that in order to obtain reliable results, P-Delta effect and degradation of strength and stiffness of structural elements must be taken into account explicitly in the numerical model.

The main objectives of this paper are to evaluate the effectiveness of a numerical model to replicate the experimental collapse of a SDOF structure that does not have strength or stiffness degradation, and to provide insight on the influence of P-Delta effect in the collapse of framed steel structures subjected to near fault earthquakes. For this purpose, experimental tests were conducted on steel-frame structures using a shaking table. The paper includes a brief description of the dynamic actions employed, additional tests performed, and the experimental and numerical models of the tested structures. After this, the calibration of the numerical model is shown and the comparative results of both models are presented along with the conclusions. Finally, a numerical study, following the modeling methodology obtained from the numerical–experimental analysis, is performed to quantify the influence of the P-Delta effect on the structural collapse. It is worth mentioning that the conclusions obtained in this work are limited to flexible structures without strength or stiffness deterioration, as the structure studied in this case reaches the collapse by dynamic instability prior to suffer effects such as local buckling, lateral torsional buckling or material degradation due to fatigue phenomena.

2. Experimental model

The model employed in this work is a frame structure, in which the columns were made of steel flat bars and the beam was made of rectangular steel tube filled with lead to achieve mass values desired. The high bending stiffness of the beam produced a restriction on the rotation of the column ends, thereby forming a SDOF system. Fig. 1 shows the geometry of the model.

In the experimental tests, two models with different column heights and mass in the beam were employed, adopting the values shown in Table 1. These values were chosen in order to obtain

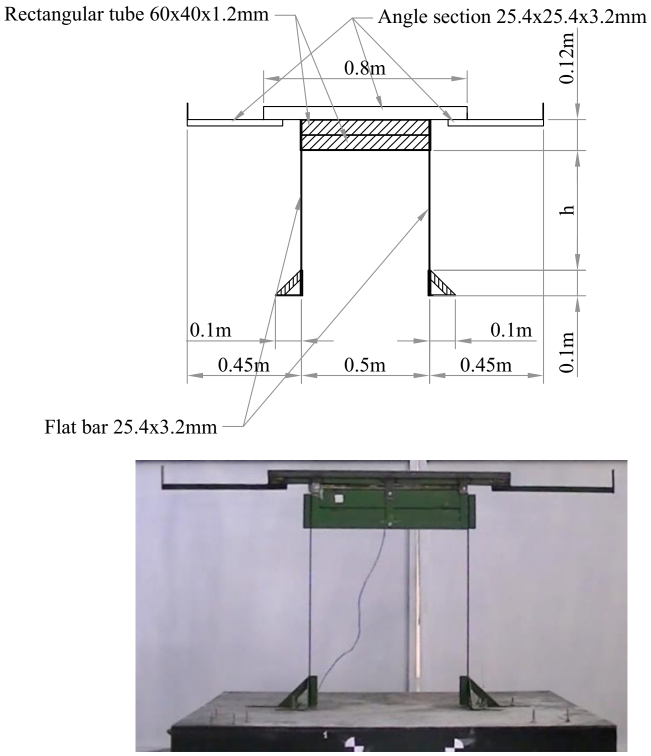

Fig. 1. Experimental model.