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Influence of the gravity framing system on the collapse performance of special steel moment frames

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ABSTRACT

This paper investigates the influence of the gravity framing system on the seismic performance of special steel moment frames (SMFs). The buildings used in this study were taken from one of the examples that form part of the ATC-76-1 project, which used the FEMA P-695 methodology to assess the collapse probability of SMF systems. Two, four and eight story SMFs were analyzed with and without the gravity frame to quantify their collapse performance. Aspects of the gravity frame that were investigated include the contribution of stiffness and strength of beam to column connections, and the location of splices in the gravity columns. Moreover, this research investigates the potential for the development of inelastic deformations in the gravity columns, and the effect of such deformations on structural response. The results show that gravity connections and gravity column continuity profoundly affect the computed response and collapse probability. The inelastic behavior in gravity columns has a less important effect but should be included in the analysis.

1. Introduction

The seismic performance of special steel moment frames (SMFs) has been assessed analytically, experimentally, and through observation of performance during previous earthquakes. These different perspectives provide valuable insight into the likely behavior of SMF systems. Additional insight into behavior has recently been provided by Zareian et al. [1] through collapse analysis carried out using the FEMA P-695 methodology [2]. The buildings used in the study ranged from 1 to 20 stories in height and were designed using ASCE 7-05 [3] and AISC 341-05 [4]. The strength and stiffness of the gravity system were not included in the Zareian et al. study because the P-695 methodology specifies that it not be included when assessing the collapse probability of "performance groups" of similar generic archetypes.

It is typical to ignore the strength and stiffness of a gravity system during structural analysis. However, as part of the experience gained from past earthquakes, the gravity system can profoundly influence response. For example, during the Northridge earthquake in 1994, many steel frames suffered brittle failures of critical beam-to-column connections, but the structures did not collapse. The most likely reason that the buildings remained standing is that the gravity framing acted as a "backup system," preventing structural collapse subsequent to the failure of the connections [5]. Presently, there are no published studies where the gravity system is explicitly modeled and a complete P-695 methodology has been performed to determine its influence on collapse probability.

Gupta and Krawinkler [6] addressed the response of SMFs at various seismic hazard levels. In this study, nonlinear static and dynamic analyses were performed on a variety of different models. The first model was a basic centerline model, and the second model explicitly included the strength and stiffness of the panel zone. There were two additional models that included the gravity system. Model 3 had simple composite connections with strength capacity equal to forty percent the plastic moment capacity of the beam ($0.4M_p$) for positive bending (top in compression) and strength of twenty percent the plastic moment capacity of the beam ($0.2M_p$) for negative bending. Model 4 had half of the connection strength of model 3. The gravity connections were defined with a simple rotational spring in which the maximum strength was achieved at a rotation equal to 0.02 rad for positive bending and 0.01 rad for negative bending. The authors state from this study that significant response improvements might be achieved at large drifts when gravity frames are included. The potential for improvement depends on the number of gravity frames present, the properties of the gravity connections, the orientation of the columns, the column boundary conditions, and the magnitude of drift demand. However, among all of the members and connections in the gravity system, the contribution of the gravity column continuity appeared to be the most important, with the gravity connections playing a much less significant role. The main conclusion from the Gupta and Krawinkler investigation was that the gravity system can significantly increase the post-yield stiffness

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of the system, which in turn reduces the influence of P-Delta effects under high intensity ground motion.

Lee and Foutch [7] performed an analysis using post-Northridge special steel moment frames including the gravity system. The objective of this study was to compute a confidence factor, λ, which indicates if the structure satisfies the collapse prevention (CP) limit state criteria at the Maximum Considered Earthquake (MCE) (with a 2% in 50-year probability of exceedance). The way this factor is computed is conceptually similar to, but predates that used in the P-695 methodology. The capacity of the structure, which is the ultimate building capacity against total collapse, is determined using Incremental Dynamic Analysis [8], while the demand of the structure is determined with ground motions representing the 2% in 50-year hazard level. The capacity is modified by uncertainties while the demand is adjusted by a resistance factor. Then, the confidence level is obtained by the ratio of capacity to demand. The results of the analysis showed that the designed buildings would perform well at the MCE hazard level. Even though this study included the gravity system, a comparison between the performances of the structure considering only the SMF with the one that includes the gravity system was not provided.

An example of a nonlinear static pushover analysis of special SMF performance including the strength and stiffness of the gravity system was reported by NIST [9]. The analyzed structures were the same used by Zareian et al. [1], and the gravity system connections were modeled using a simple elasto-plastic model. The conclusions from this study were that the benefits of incorporating the gravity system depend strongly on the structural configuration, but it could decrease drift demands and increase collapse capacity. Additionally, it is concluded that the gravity system could be effective in delaying or preventing dynamic instability if the gravity framing increases the post-yield tangent stiffness [10].

The studies described above give an insight of the influence of the gravity system. However, none of them specifically investigated the influence of the gravity system on the collapse performance. Gupta and Krawinkler [6] used a very simple model to quantify the simple connections, Lee and Foutch [7] did not differentiate the influence between the lateral resistant system acting alone and then with the gravity system included, and in the NIST study [9] a P-695 collapse analysis was not performed.

MacRae et al. [11] revealed that continuous stiffness (no splices or splices providing full continuity) given by gravity columns can reduce story drift concentrations and prevent weak story failures in braced frames. This effect was also pointed out by Gupta and Krawinkler [6]. The effect of continuous stiffness in columns is studied in braced frames by Ji et al. [12] and in reinforced concrete structures by Qu et al. [13]. Tagawa [14] studied steel moment frames and the results of his investigation showed that continuous gravity columns improve stability and prevent plastic mechanisms.

2. Revised analysis of SMF including gravity systems

To add to the knowledge base on the influence of gravity framing on the collapse performance of SMF, the P-695 study performed by Zareian et al. [1], and analyzed further in NIST [9], has been extended to explicitly include the gravity framing. The first step in the new analysis was to validate the original analysis for the bare SMFs. This was followed by the new analysis in which the beams, columns, and connections of the gravity system are modeled explicitly. Beam-to-column connections are assumed to be partially restrained (PR). In addition, a variety of assumptions are explored to determine the influence of column continuity and splice locations in the gravity columns. The comparison is made by means of pushover curves and by performing a P-695 collapse analysis.

2.1. Evaluation and model validation

The ATC-76-1 project [15] is a continuation of the P-695 report where examples of the methodology are described. SMFs analyzed by Zareian et al. [1] form part of the examples illustrated in the report. In this study, buildings of 1, 2, 4, 8, 12 and 20 stories were designed following ASCE/SEI 7-05 [3] requirements with the exception that the deflection amplifier C_d was taken equal to the response modification factor, R, as specified in FEMA P-695.

For the analyzed buildings, the strength and stiffness of the gravity frames were not considered, because as pointed out in the P-695 report, the configuration of gravity columns is highly variable and cannot be predefined when analyzing generic archetypes. It is noted, however, that several guidelines for performance based seismic design establish that the gravity system may be or must be included. The PEER/ATC 72-1 [16] report states that the gravity system can provide significant benefits for lateral stability at large displacements and it can be included if desired. ASCE 41-13 [17] requires the incorporation of secondary components (gravity system) when performing nonlinear static or nonlinear dynamic analysis. Appendix F of FEMA P-695, which is used to assess the collapse performance of an actual building with a known gravity system (instead of an archetype without a defined gravity system) leaves the incorporation of the gravity system to the discretion of the user.

All these procedures that allow the gravity frame to be included are applied to a specific building, so the gravity system is known and its strength and stiffness can be quantified. On the other hand, the P-695 methodology is used to compute the seismic response factors of a specific structural system. In this case, the gravity system is not known. Therefore, more research is necessary to determine a generic way to include the gravity system to be part of a lateral resisting system.

In the work presented herein, a subset of the buildings analyzed as examples for the ATC-76-1 project are reanalyzed including the gravity system. The chosen SMFs are the 2, 4 and 8 story buildings. These structures were designed using the Response Spectrum Analysis (RSA) method for a seismic design category D_{max} ($S_s = 1.5$ g, $S_1 = 0.6$ g), and for a typical gravity load. The nomenclature that identifies these structures in ATC 76-1 is 2RSA (2 story), 3RSA (4 story) and 4RSA (8 story).

All the structural analyses for assessing the performance of the systems with and without gravity framing were performed in OpenSees [18] through NEEShub [19]. The approach used to characterize the nonlinear behavior of the main lateral load resisting structure is the same as that used in the ATC-76-1 project. The method used for including the gravity system is described later in this paper. However, before a complete evaluation of the structures including the gravity system was performed, the structures without gravity framing were reanalyzed to validate the published results [15] and to form the basis for comparison of the systems with the gravity framing included.

2.2. Building overview

The 2, 4, and 8 story buildings have the same plan view and seismic design category (D_{max}) and were designed using the same approach (RSA). Connections at the base of the columns are considered fixed for the 4 and 8-story models and pinned for the 2-story model. The seismic force resistance of the buildings is provided by a three-bay special SMF with prequalified reduced beam section (RBS) connections located on the perimeter of each side of the building. These SMFs provide lateral resistance to seismic forces and stability against P-Delta shears. Fig. 1 shows the plan layout for all the buildings analyzed. In the figure the main lateral load resisting system is shown, as is the gravity framing that is considered in further analysis. Note that two of the SMF columns that form part of the gravity frame are oriented on the weak axis. To be conservative and in order to evaluate just the effect of gravity columns, the lateral strength provided by the SMF columns oriented on the weak axis is not considered. The shaded area in the figure represents the tributary area for gravity loading on the individual SMF.

The bay width (center line dimensions) between columns of each SMF is 6.1 m. The height of the first story is 4.6 m (to top of steel