SEISMIC RESPONSE OF STEEL MOMENT FRAME CONSIDERING GRAVITY SYSTEM AND COLUMN BASE FLEXIBILITY

P. Torres-Rodas¹, F. Flores² and F. Zareian³

ABSTRACT

High ductility and architectural versatility characteristics make Steel Moment Frames (SMF) one of the most commonly used lateral resisting systems for building structures. Collapse assessment of such buildings are typically suffering from two modeling simplifications: 1) neglecting the gravity system model, and 2) neglecting column base flexibility by using idealized boundary conditions (i.e. fix or pin). This study assesses the seismic performance of an 8-Story SMF and takes into consideration the effects of the column-base flexibility and the inclusion of the gravity system in such assessment. The flexibility of the column-base connection is included by aggregating deformations of various components of the base connection while the gravity system is included by taken into consideration the continuous stiffness provided by the gravity columns. Nonlinear dynamic response history analysis using design level ground motions was used to compare the influence of the different properties on the story drifts and residual displacements. Moreover, using the FEMA P-695 methodology, the influence of these modeling simplifications on the collapse performance is established. Previous research indicates that the flexibility of column bases has a detrimental effect on the building’s seismic performance. However, the positive effects that considering the gravity system brings evens out in the seismic behavior of the structure.

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Seismic Response of Steel Moment Frame Considering Gravity System and Column Base Flexibility

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High ductility and architectural versatility characteristics make Steel Moment Frames (SMF) one of the most commonly used lateral resisting systems for building structures. Collapse assessment of such buildings are typically suffering from two modeling simplifications: 1) neglecting the gravity system model, and 2) neglecting column base flexibility by using idealized boundary conditions (i.e. fix or pin). This study assesses the seismic performance of an 8-Story SMF and takes into consideration the effects of the column-base flexibility and the inclusion of the gravity system in such assessment. The flexibility of the column-base connection is included by aggregating deformations of various components of the base connection while the gravity system is included by taken into consideration the continuous stiffness provided by the gravity columns. Nonlinear dynamic response history analysis using design level ground motions was used to compare the influence of the different properties on the story drifts and residual displacements. Moreover, using the FEMA P-695 methodology, the influence of these modeling simplifications on the collapse performance is established. Previous research indicates that the flexibility of column bases has a detrimental effect on the building’s seismic performance. However, the positive effects that considering the gravity system brings evens out in the seismic behavior of the structure.

Introduction

The seismic performance of Steel Moment Frames (SMFs) has been extensively studied in the last decades with the use of analytical models that are calibrated with experimental program results. These studies explored various modes of response and stability of SMFs resulting in detailed design guidelines. Nowadays, and with the advances in computational capacity, the response of SMFs is investigated using sophisticated Nonlinear Dynamic Analysis tools within the context of Performance Base Earthquake Engineering. Guidelines such as ATC 72-1 [1] are adopted to model inelastic behavior of structural components.

Recent studies have demonstrated the influence of base flexibility on the seismic response of SMFs. Aviram et al. [2] presented the results of a parametric study on a low-rise building (4-story) with base flexibility varying from pinned to fix conditions. Results indicate that reduction in rotational stiffness of base connections leads to damage concentration that could induce a soft story mechanism. Zareian and Kanvinde [3] studied the response of four SMFs (2-, 4-, 8- and 12-story structures) with respect to a range of base fixities examining the influence of base flexibility on various aspects of SMF performance such as internal force distribution, probability of collapse, and building deformations. The results confirm previous findings from Aviram et al. where base flexibility has a detrimental effect on the performance of SMFs. Zareian and Kanvinde concluded that characterization of rotational stiffness of base connections is critical especially for mid- and high-rise buildings. Specifically, their study demonstrated that
an incorrect estimation of base fixity could lead to an alarming increase in interstory drift ratios, concentration of deformations in soft stories, and increase in probability of collapse.

On the other hand, studies that have addressed the influence of the gravity framing system on the performance of SMFs indicate that it has a beneficial effect. Gupta and Krawinkler [4] studied the response of SMFs at various hazard levels. Different models were analyzed with the use of nonlinear static and dynamic analysis. Two of these models included the gravity system. The main conclusion stated by the authors was that the dynamic response of the building improves considerably at large drifts when the gravity frames are included. However, the improvement depended on the number of gravity frames, the properties of the gravity connections, the orientation of the columns, the columns boundary conditions, and the magnitude of drift demand. Among all these parameters, the contribution of the gravity column continuity appeared to be the most important.

Liu and Astaneh [5] carried out cyclic tests to evaluate the flexural capacity of simple connections. The results showed that shear tabs, which are common connections used as part of the gravity system, had a moment capacity approximately equal to 20% M_p (plastic moment of the beam) if the contribution of the concrete slab is neglected, and 35% M_p if it is considered. Moreover, it was found that gravity connections have a high rotation capacity reaching inelastic rotations that varied from 0.09 to 0.14.

More recently, Flores et al. [6, 7] showed that the influence of gravity framing on the collapse performance of SMFs is significant. The study used the buildings from the ATC-76-1 [8] project to assess collapse probability based on FEMA P-695 methodology [9]. The results confirm previous findings about the beneficial effects of gravity framing. Specifically, the authors concluded that gravity connections have a significant influence on the reduction of probability of collapse in low-rise buildings. Moreover, the gravity columns improve the collapse performance of taller buildings. According to Flores et al., the main effect that gravity columns have--if they are continuous--is to reduce drift concentrations which is one of the main modes of failure in SMFs with flexible connections.

Although an abundance of published research about the seismic performance of SMFs is available, a closer inspection indicates that a study that include the beneficial effect of gravity framing combined with the detrimental effects of base flexibility is absent. Motivated by this observation, this study evaluates the effect of base flexibility when the gravity columns are incorporated in the analysis. By utilizing the FEMA P-695 methodology, this study presents a series of sophisticated nonlinear static and dynamic analysis with the aim to investigate, in a parametric manner, the detrimental effect of base flexibility including the gravity system.

**Building Configuration**

For the purpose of investigating the effect of base flexibility on SMFs, including the gravity system, an 8-story building was adopted from the ATC76-1 project [8]. This building has three bays, with a bay width of 20 ft. The height of the first story is 15ft, other stories are at 13ft. The plan view of the building is shown in Fig. 1. The assumed dead load is 100 psf uniformly distributed over each floor, and the cladding load is applied as a perimeter load equal to 25 psf.
The unreduced live load applied on the floors is 50 psf and 20 psf on the roof. The beam to column connections have a Reduced Beam Sections (RBS) detailing. The building was designed according to seismic design requirements of ASCE 7-05 [10] and detailed based on AISC 341-05 and AISC 358-05 [11]. The base connection is detailed as an embedded baseplate with grade beams, and is designed based on the method developed by Grilli and Kanvinde [12]. The rotational stiffness of this connections is estimated based on the approach proposed by Torres-Rodas et al. [13] which considers deformations associated with concrete bearing, and the flexural and shear deformations of the embedded column.

![Figure 1. Building Plan View](image)

**Building Model & Nonlinear Response History Analyses**

The building is modeled as a two-dimensional frame. The beams and columns are modeled as elastic elements with concentrated plastic hinges at their ends as illustrated in Figure 2. Each beam consists in three elements: one linear-elastic in the middle and two rotational spring at the RBS locations. The hysteretic response of the plastic hinges of beams and columns is represented by the well-known Bilinear Model with strength and stiffness deterioration developed by Ibarra et al. [14] and modified by Lignos and Krawinkler [15]. These phenomenological springs cannot simulate moment-axial load interaction, so the interaction is implemented in an approximate manner. A representative axial load is computed by performing gravity and nonlinear static analysis. An expected average axial force is obtained under the combined actions of gravity and lateral loads (i.e. $P_{\text{gravity}} + 0.5P_{\text{lateral}}$). Once this axial load is computed, the reduced bending strength is calculated according to the AISC moment-axial load interaction equations [11].

The panel zone is modeled as a hinged parallelogram with a rotational spring that represent inelastic distortions due to column web shear yielding. Guidelines laid out in ATC 72-1 [1] are used to determine the properties of these springs. A “leaning column” is loaded with vertical loads to capture destabilizing P-Δ effects with large-displacement formulation to simulate sideways collapse. Column bases are simulated as elastic rotational springs. The stiffness of these springs is determined using an approach developed by Torres-Rodas et al. [13] and by aggregating deformations of various components (e.g., concrete foundation, and the flexural and shear deformations of the embedded column) under applied forces.

The effect of the gravity columns in the seismic performance of SMFs is included following
the approach proposed by Flores et al. [7]. Findings from the latter research indicate that gravity connections improved the collapse performance of a 4-story building, however, they had almost no influence on the collapse performance of an 8-story building. Moreover, it was shown that gravity columns do not yield if the gravity connections have low strength capacity. Flores et al. modeling approach consists of combining all the gravity columns into a single elastic element pinned at the base as shown in Fig. 2. This element represents all the gravity columns and its stiffness is varied to arrive at an optimal value using pushover analysis [7]. The factor $I_{Gcol}/I_{SMF}$ displayed in Fig. 2 is the ratio between the moment of inertia of all the gravity columns to the moment of inertia of all the columns of the SMFs. In this investigation, gravity columns are designed based on conventional engineering methods.

The software program OpenSEES [16] is used for all the simulations. For the nonlinear dynamic analysis, Rayleigh damping of 2.5% is assigned to the first period ($T_1$) and to the period equal to 20% of the first period (i.e. $T^* = 0.2T_1$). Damping is modeled using Zareian and Medina [17] recommendation.

![Building model with flexible connections and lumped gravity columns](image)

**Figure 2.** Building model with flexible connections and lumped gravity columns

**Discussion of Results**

This section presents the results of the analysis performed for the 8-story building. Two types of analysis are conducted: Nonlinear Static Pushover Analysis (NSP) and Nonlinear Dynamic Analysis (NDA). Eight sets of simulations are carried out for the 8-story building. These sets of simulations can be divided in two groups. The first group consist of models with varying degree of fixity at the base and excluding the gravity system in the analysis; the second group similar to group one, however, the gravity system is indicated similar to what is shown in Figure 2. The
aim is to compare the response of the building with and without the gravity system including the detrimental effects of base flexibility. The rotational stiffness computed according to the methodology suggested by Torres-Rodas et al. [13] is considered as the “true base stiffness,” henceforth, is denoted as $\beta$. However, this rotational stiffness may vary due to epistemic errors (i.e. uncertainty associate with imperfect models) and different types of foundation. To address this variability, $\beta$ is multiplied by 2.0 and 0.5, accounting for plausible range of variation in base stiffness with respect to the considered “true stiffness.”

NSP analysis consists of applying a predetermined pattern of lateral loads along the height of the building (i.e. first mode of shape). Two key quantities are obtained from NSP: $i)$ overstrength factor, $ii)$ period-base ductility. These parameters are summarized in Table 1 and pushover curves are shown in Figure 3.

Table 1. Pushover Results

<table>
<thead>
<tr>
<th>System</th>
<th>First Period (s)</th>
<th>Ductility $\mu_T$</th>
<th>Overstrength $\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Gravity framing &amp; Fix Bases</td>
<td>2.20</td>
<td>2.52</td>
<td>3.27</td>
</tr>
<tr>
<td>No Gravity framing &amp; $2\beta$</td>
<td>2.35</td>
<td>2.23</td>
<td>3.24</td>
</tr>
<tr>
<td>No Gravity framing &amp; $\beta$</td>
<td>2.45</td>
<td>2.04</td>
<td>3.20</td>
</tr>
<tr>
<td>No Gravity framing &amp; $0.5\beta$</td>
<td>2.56</td>
<td>1.89</td>
<td>2.93</td>
</tr>
<tr>
<td>Incl. Gravity framing &amp; Fix Bases</td>
<td>2.19</td>
<td>3.15</td>
<td>3.29</td>
</tr>
<tr>
<td>Incl. Gravity framing &amp; $2\beta$</td>
<td>2.34</td>
<td>2.93</td>
<td>3.27</td>
</tr>
<tr>
<td>Incl. Gravity framing &amp; $\beta$</td>
<td>2.44</td>
<td>2.86</td>
<td>3.23</td>
</tr>
<tr>
<td>Incl. Gravity framing and $0.5\beta$</td>
<td>2.53</td>
<td>2.82</td>
<td>3.01</td>
</tr>
</tbody>
</table>

![Figure 3. Pushover curves, a) neglecting gravity system, b) including gravity system](image)

The results summarized in Table 1 shows how the gravity columns do not influence the period of vibration of the structure nor its overstrength. However, they have a significant influence on ductility (ductility has increased in average by 40%). It can also be concluded that the influence of the gravity columns is directly related to the improvements on the secondary stiffness which in turn is related to the structure’s collapse performance.
NDA analysis is carried out to assess the effect of gravity framing on the seismic performance of SMFs under various degrees of base flexibility. Two metrics of performance are obtained for each case of interest: i) Adjusted Collapse Margin Ratio (ACMR) and probability of collapse, and ii) interstory drift ratios at design level of shaking (i.e. 10%-50 years PE). The ACMR and probability of collapse are estimated based on the methodology described in FEMA P695 and the investigation by Deierlein et al. [18]. This methodology requires implementation of Incremental Dynamic Analysis (IDA) [19], in which individual ground motions are scaled to increasing intensities until the building collapses. It was considered that “collapse of each ground motion” is achieved when dynamic instability is observed, or the building reaches interstory drifts ratios of 10%.

Figs. 4 and 5 summarize the results from IDA simulations. Fig. 4 presents the sensitivity of ACMR with base flexibility for both groups i.e. considering the influence of gravity framing and ignoring it. Clearly, in both cases the ACMR tends to drop when base flexibility increases. In the latter case (i.e. neglecting the gravity system), the ACMR decreases from 1.82 (for fix bases) to 1.68 (for base flexibility = 0.5$\beta$) indicating a drop of 8%. In the former group (i.e. where gravity system is considered) the ACMR decreases from 2.11 (for fix bases) to 1.98 (for base flexibility = 0.5$\beta$) which in turn is a drop of 6%. This trend confirms the findings presented in the parametric study carried out by Zareian and Kanvinde [3]. Another important observation is that in all cases, the inclusion of gravity system in the analysis increases the ACMR. However, the IDA results indicate the importance of adequate characterization of base flexibility.

![ACMR graph](image)

Figure 4. Adjusted Collapse Margin Ratio for the 8-story SMF

Even though ACMR provides a good measure as to how detrimental the base flexibility is and how beneficial the gravity columns are, the probability of collapse is the parameter that would show the complete picture of the influence of these parameters. The probability of collapse is computed at MCE level using the variabilities suggested in the ATC76-1 report for bare SMF. For further information regarding these parameters, the readers are referenced to the FEMA P-695 methodology and to the study performed by Deierlein et al.[18].

Figure 5 illustrates the effects of the base flexibility and gravity columns on the probability of collapse. It can be seen how probability of collapse increases from 9.65% to 12.97% when the gravity columns are neglected. This represents an increment of 3.32% and
demonstrates the importance of incorporating the base flexibility. In addition to the IDA simulations, this study presents the results of NDA of the building at design hazard level (i.e. 10% -50years PE). A suite of 40 ground motions selected by Medina and Krawinkler [17] are scaled to represent the design level shaking for Type D soil in Los Angeles area. Two important parameters are monitored: i) Interstory drift ratios (IDR) ii) Axial Force-Moment interaction in first story columns.

![Figure 5. Probability of Collapse](image)

Fig. 5 shows the response of the building from the NDA at design level shaking. It is evident that base flexibility significantly increases interstory drift ratios. Especially, and when gravity framing is not considered, inadequate representation of rotational stiffness of base connection leads to worrying results. For the fix base model, the median value of peak IDR is 2.61%. However, it increases considerably with reduced base fixity up to a value of 4.20% for the case where rotational stiffness is half of the “true flexibility”. Even though previous research has demonstrated that gravity columns are more influential when large drifts are experienced by the building, it can be seen from Fig. 5 that for all cases the IDR is reduced once the gravity system is included. This reduction in drift demand is larger when column bases are flexible.

![Figure 6. Median Peak Interstory Drift Ratios (in percent)](image)
In addition to the median peak interstory drift ratios, the interaction of axial load and flexural moment in the first story columns is explored. For each ground motion, the critical combination of compression force and moment is recorded. This critical combination is defined as the greatest interaction over the NDA of each ground motion computed with the AISC interaction equation for beam-column elements. The median value of these critical interactions is computed for each case of analysis. Referring to Fig. 7, two conclusions are drawn: first, the median value of this peak M-P interactions tend to increase with more flexible base columns. Second, the values are almost identical for both types of system i.e. considering and neglecting gravity framing. This conclusion indicates that stress concentrations at the first story are relatively insensitive to the inclusion of gravity system. However, more research including buildings with different heights and plan configurations is necessary to generalize this finding.

![Figure 7. Median M-P Ratio of exterior column](image)

**Conclusions**

This research presents a parametric study on the effect of column base flexibility in an 8-story SMF considering the influence of gravity columns. The analyzed building was designed per ASCE 7-05 and the Seismic Provisions AISC 2010 guidelines. The scientific basis for this investigation is a series of sophisticated nonlinear static and dynamic simulations of the SMF. The simulations employ state of the art tools and methods to capture geometric and material nonlinear response. The main difference with previous studies in the field are: i) the inclusion of the beneficial influence of gravity framing in the seismic performance of SMFs with the detrimental effect of column base flexibility, ii) the rotational stiffness of column base connections is estimated based on a method validated against large-scale experiments.

The simulations of the 8-story building are divided in two groups: i) neglecting the influence of gravity framing ii) considering the beneficial effects of gravity system. The gravity system is included in the SMFs by combining all the gravity columns into a single elastic element pinned at the base. Each group of simulations is analyzed through NSP and NDA under a range of base fixities, from flexible to fix. Based on current design practice, an embedded type connection is designed for this building and its rotational stiffness is approximated obtaining a benchmark
value. This benchmark value is denoted as “true stiffness” (i.e. $\beta$) of the connection. Considering possible variations in base flexibility, this research examines the sensitivity of response to a range of rotational stiffness from $0.5\beta$ to $2.0\beta$.

Results obtained from NSP indicates that gravity columns tend to increase the period-base ductility and the overstrength of the system. However, an increase in base flexibility decrease both parameters. Referring to Table 1, the first modal period of the building remains almost identical when the gravity systems is included in all cases of base fixity, but the period elongates when the base flexibility increases, being relatively insensitive to the inclusion of the gravity framing. The period-base ductility appears to be sensitive to both base flexibility and inclusion of gravity columns in the building model. On the other hand, the overstrength of the system seems to be only sensitive to the range of values of base flexibility investigated, decreasing when it increases, and relatively insensitive to the modeling of gravity columns.

Results from collapse assessment reveal that the structure is sensitive to base flexibility and gravity columns. When the latter is not included in the simulations, the response is unacceptable for cases that base flexibility is included (i.e. probability of failure greater than 10% at MCE level). The beneficial influence of including gravity columns in the analysis evens out the detrimental effect of reduction in base fixity. In all cases where the flexible connections are included, the probability of collapse is higher than 10% but reduced to an acceptable value when the gravity columns are included.

Finally, the results obtained from NDA at design level shaking highlight the necessity for accurately characterizing base fixity. The interstory drift ratios are sensitive to both stiffness of gravity columns and base flexibility. The inclusion of gravity system, in average, reduces drift ratios in approximately 15%. However, the median peak interstory drift ratio exceeds the 2.5% for all the ranges of base flexibility, with some alarming drifts above 3%.

In general, all the metrics of response are affected in a negative way when the base flexibility increases. However, the results presented in this study are subjected to several limitations. First, only one building is analyzed; alternative building height and plan configuration may lead to different results. Moreover, the gravity columns are modeled in an approximate way; a more sophisticated model to represent gravity columns may affect the findings of this study. More research is recommended to address these limitations.

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