# SEISMIC BEHAVIOR OF PERIMETER MOMENT RESISTING STEEL FRAMES

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**ABSTRACT :**

The seismic responses of steel buildings with perimeter moment resisting steel frames (MRSF) and interior gravity frames (IGF) are estimated and some aspects related with the building structural idealization are studied. The contribution of IGF to the lateral resistance is evaluated. The seismic responses of the buildings with perfectly pinned (PP) connections are compared to those of the buildings with semi-rigid (SR) connections. The relative importance of the $P$-$\delta$ effect in gravity columns is also studied. The study indicates that the contribution of IGF to the lateral structural resistance may be significant. This contribution is larger for lower stories for the buildings with PP connections. The contribution increases when the stiffness of the beam-to-column connection of the IGF is considered, particularly for upper stories. It is observed that the interstory shears are significantly reduced when the connections stiffness is taken into account. By the other hand, the interstory displacements are similar for the models with PP and SR connections. Resultant stresses also decrease but to a lesser degree. Results also indicate that the second order moments produced in gravity columns are comparable and even larger than those used to design these columns. It is concluded that, if the abovementioned structural system is used, IGF should be considered as part of the lateral resistance system, and that the stiffness of the connections and the $P$-$\delta$ effect should be included in the design of the IGF. Otherwise, the capacity of gravity frames may be overestimated while that of MRSF may be underestimated.

**KEYWORDS:** Seismic behavior, Moment resisting steel frames, Gravity frames, Semi-rigid connections

## 1. INTRODUCTION

The basic intent of building code seismic provisions is to provide buildings with the ability to support severe ground motions without collapse, but with some structural damage. Different structural configurations, structural systems and materials are used to fulfill this purpose. Among the different structural systems, moment resisting steel frames (MRSF) have been the most popular because they provide maximum flexibility for space utilization and because of their high ductility capacity. This structural system however, has significantly changed through the time. From the mid 60s to the mid 70s most connections in the structure were moment resisting connections (MRC). During the 80s, 90s and 2000s the use of MRC were tremendously reduced, because they were expensive and to eliminate weak-axis connections (FEMA 2000). MRC are used only on two frame lines in each direction, usually at the perimeter. As a result of this, the redundancy of the building is significantly reduced.

An important issue that deserves our attention is that perimeter MRSF are usually designed to resist the total lateral seismic loading, ignoring the presence of interior gravity frames (IGF). Due to the action of rigid floor diaphragms these IGF, however, will undergo the same lateral deformation as the MRSF. Consequently, the contribution of these columns to the lateral resistance could be significant, particularly for those building with relatively few MRC. Moreover, the $P$-$\delta$ effect caused by gravity loads through the lateral displacements produced by seismic loads could also be significant and consequently considered in the design.

Another simplification is related to the stiffness of the beam-to-column connection. Conventional analysis and design of steel frames is based on the assumption that beam-to-column connections are either fully restrained (FR) or perfectly pinned (PP). The beam-to-column connections of the IGF of the abovementioned structural models are assumed to be PP. Despite these classifications, almost all steel connections used in real frames are essentially semi-rigid (SR) with different rigidities. It has been established in the profession, both theoretically and experimentally, that these connection exhibit semi-rigid nonlinear response even if the applied loads are very small (Reyes-Salazar and Haldar 2000). The FR and PP connection consideration is nothing but an assumption made to simplify calculations and is a major weakness in current analytical procedures. These simplifications may result in erroneous values for resultant stresses because in reality FR connections posses some flexibility and PP connections posses some rigidity. There is some evidence that these shear connections can transmit up to 30% of the plastic moment of the beams they are connecting. The contribution of these connections to the structural strength and stiffness can be much important if the composite action of the slab is considered (Reyes-Salazar and Haldar, 1999; Liu and Astaneh-Asl, 2000).

In this paper, the seismic behavior of perimeter MRSF is studied. The contribution of IGF to the lateral resistance is estimated. The IGF are assumed to have, first PP connections, and then SR connections. The seismic responses, in terms of global response parameters (base shear and interstory displacements) and local response parameters (resultant stresses at individual members), for the models with PP connections are compared to those of the models with SR connections. The importance of the $P$-$\delta$ effect in gravity columns with respect to the moments used to design these columns is also estimated.

## 2. MATHEMATICAL FORMULATION

To satisfy the objectives of the study, the seismic responses of some steel building models are evaluated as accurately as possible using an efficient assumed stress-based finite element algorithm developed by the authors and their associates (Gao and Haldar 1995, Reyes-Salazar 1997). The procedure estimates nonlinear seismic responses in time domain considering material and geometry nonlinearities and that nonlinearity introduced by SR connections (Richard 1993). In this approach, an explicit form of the tangent stiffness matrix is derived without any numerical integration. Fewer elements can be used in describing a large deformation configuration without sacrificing any accuracy, and the material and connection nonlinearities can be incorporated without losing its basic simplicity. It gives very accurate results and is very efficient compared to the commonly used displacement-based approaches. The procedure and the algorithm have been extensively verified using available theoretical and experimental results. The development of the theory of this approach is not the objective of the study and cannot be presented here due to lack of space.

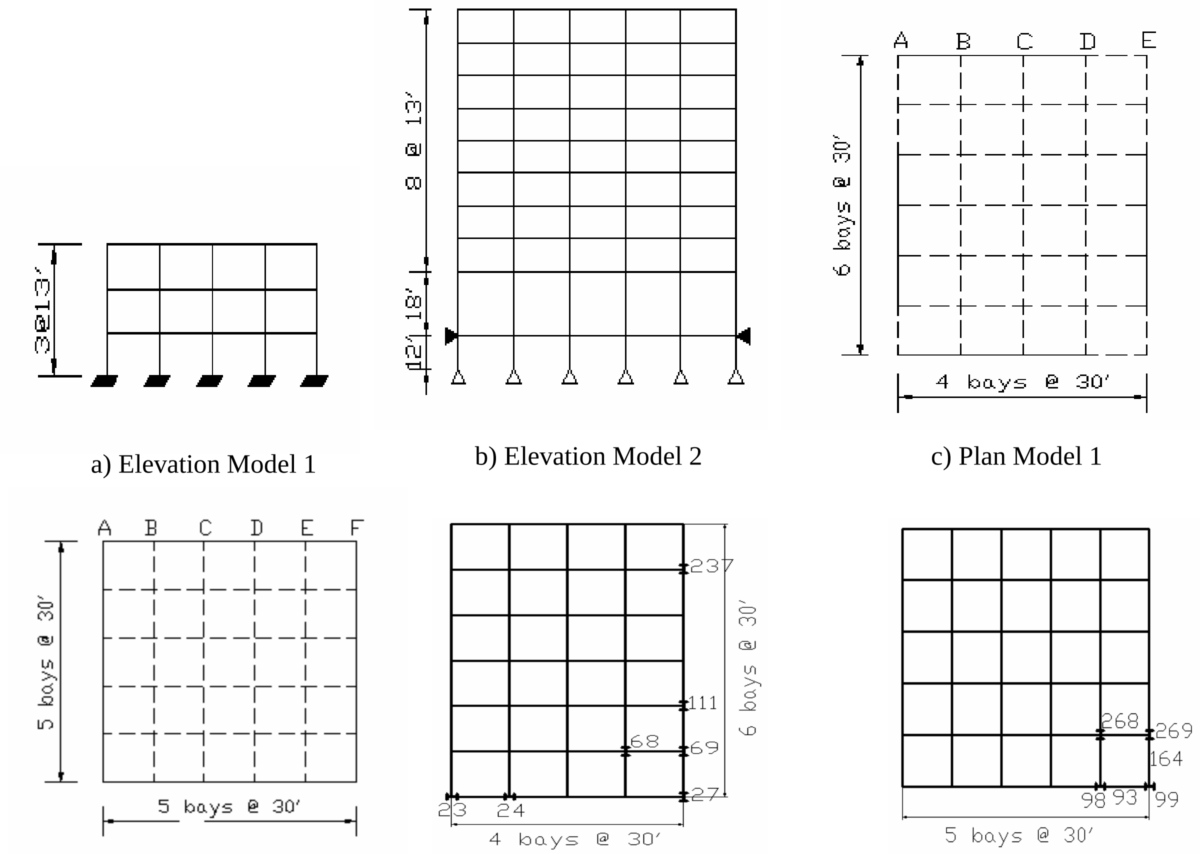
## 3. EARTHQUAKES AND STRUCTURAL MODELS

Three consulting firms were commissioned to perform the design of several model buildings as part of the SAC steel project (FEMA, 2000). The models were 3-, 9- and 20- story buildings which were designed according to the code requirements for the following three cities: Los Angeles (UBC, 1994), Seattle (UBC, 1994) and Boston (BOCA, 1993). The 3- and 9- story buildings, representing Los Angeles area and the Pre-Northridge Designs, are considered in this study to address all the issues discussed earlier. They will be denoted hereafter as Models 1 and 2, respectively. The fundamental periods of the buildings are 1.03 and 2.34 sec., respectively. The elevations of the models are given in Figs. 1a and 1b while the model plans are given in Figs. 1c and 1d. In these two figures the continuous lines represent MRSF and the dashed lines IGF. The particular elements considered in the study are given in Figs 1e and 1f. The beam and columns sections of the models are given in Table 1. The columns of the MRSF of Model 1 are considered to be fixed at the base while those of Model 2 are assumed to be pinned. In all these frames, the columns are assumed to be made of Grade-50 steel and the girders are of A36 steel. For both models, the gravity columns are considered to be pinned at the base. All the columns in the perimeter MRSF bend about the strong axis. The strong axis of the gravity columns is oriented in the NS direction. The designs of the MRSF in the two orthogonal directions were practically the same. Additional information for the models can be obtained from the SAC steel project reports (FEMA, 2000).

Table 1. Beam and columns sections for Models 1 and 2

| Model | Moment resisting frames | | | | Gravity frames | | |
|---|---|---|---|---|---|---|---|
| | Story | Columns | | Girders | Columns | | Beams |
| | | Exterior | Interior | | Below penthouse | Others | |
| 1 | 1\2 | W14x257 | W14x311 | W33X118 | W14x82 | W14x68 | W18x35 |
| | 2\3 | W14x257 | W14x312 | W30X116 | W14x82 | W14x68 | W18x35 |
| | 3\Roof | W14x257 | W14x313 | W24X68 | W14x82 | W14x68 | W16x26 |
| 2 | -1/1 | W14x370 | W14x500 | W36x160 | W14x211 | W14x193 | W18x44 |
| | 1/2 | W14x370 | W14x500 | W36x160 | W14x211 | W14x193 | W18x35 |
| | 2/3 | W14x370 | W14x500,W14x455 | W36x160 | W14x211,W14x159 | W14x193,W14x145 | W18x35 |
| | 3/4 | W14x370 | W14x455 | W36x135 | W14x159 | W14x145 | W18x35 |
| | 4/5 | W14x370,W14x283 | W14x455,W14x370 | W36x135 | W14x159,W14x120 | W14x145,W14x109 | W18x35 |
| | 5/6 | W14x283 | W14x370 | W36x135 | W14x120 | W14x109 | W18x35 |
| | 6/7 | W14x283,W14x257 | W14x370,W14x283 | W36x135 | W14x120,W14x90 | W14x109,W14x82 | W18x35 |
| | 7/8 | W14x257 | W14x283 | W30x99 | W14x90 | W14x82 | W18x35 |
| | 8/9 | W14x257,W14x233 | W14x283,W14x257 | W27x84 | W14x90,W14x61 | W14x82,W14x48 | W18x35 |
| | 9/Roof | W14x233 | W14x257 | W24x68 | W14x61 | W14x48 | W16x26 |

In this study, the frames are modeled as MDOF systems. Each column is represented by one element and each girder of the perimeter MRF is represented by two elements, having a node at the mid-span. Each node is considered to have six degrees of freedom. An additional element is needed to represents each SR connection. The models are excited by twenty recorded earthquake motion in time domain, recorded at the following stations: Paraíso, México; Mammoth H.S., USA; Convict Creek, USA; Infiernillo N-120, México; La Union, México; Relaciones Exteriores, El Salvador; Relaciones Exteriores, El Salvador; Long Valley Dam, USA; K2-2, USA; Redwood City, USA; MT:Kalispell, USA; Villita, México; Hall Valley Northridge, USA; Hall Valley Morgan, USA; K2-04, USA; Dauville FS, USA; Pleasant Hill FS 1, USA; Pleasant Hill FS 2, USA; Valdez City, USA and Hollister City, USA. The predominant periods of the earthquakes vary from 0.11 to 1.0. They were obtained from the Data Sets of the National Strong Motion Program (NSMP) of the United States Geological Surveys (USGS). Additional information regarding the earthquakes can be obtained from the data sets. The damping is considered to be 5% of the critical damping; the same damping is used in the codified approaches.




a) Elevation Model 1 b) Elevation Model 2 c) Plan Model 1

d) Plan Model 2 e) Studied elements for Model 1 f) Studied elements for Model 2

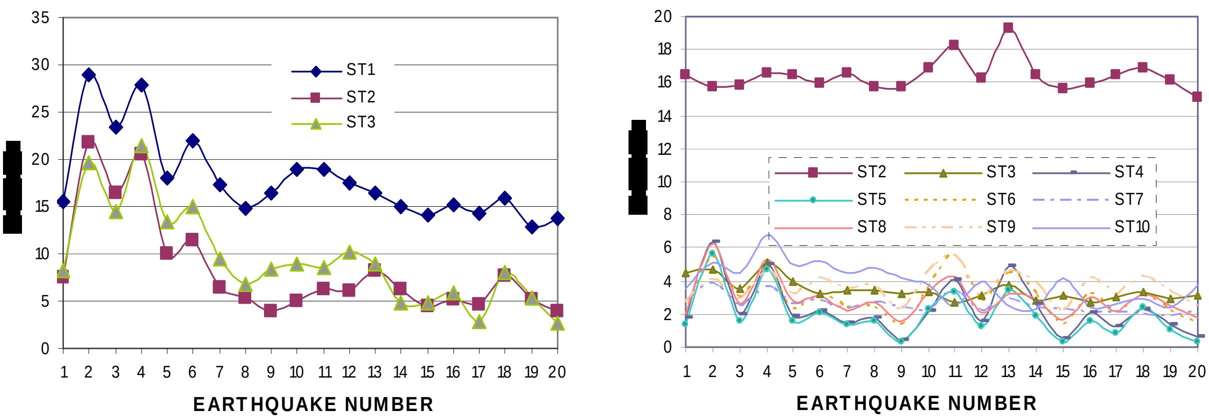
Figure 1. Elevations, plan and element location for Models 1 and 2

## 4. CONTRIBUTION OF GRAVITY FRAMES TO THE LATERAL RESISTANCE

### *4.1 Gravity Frames with PP Connections*

The contribution of IGF to the lateral resistance in terms of interstory shears, for the models with PP connections, is studied in this section of the paper. The shear ratio $V_1$, defined as $V_I/V_T$, is introduced for this purpose. This ratio is studied for both horizontal directions. The horizontal component with the major peak acceleration is applied in the North direction and will be denoted as *(X, 0, 0)*. The other horizontal component is applied in the other direction and is denoted as *(0, Y, 0)*. For a given direction and story, $V_I$ will represent the shear resisted by all the IGF in that story and $V_T$ will represent the total shear. Typical results of the $V_1$ parameter are shown in Figs. 2a and 2b for Models 1 and 2, respectively, for the *(X, 0, 0)* component. The symbol *ST* is used to represent the word "story". It is observed that the $V_1$ values significantly vary from one model to another and from one story to another without show any trend. Values of up to 29% are obtained for Story 1 of Model 1. Similar plots to those of Figure 2 were also developed for the *(0, Y, 0)* component, but are not shown because of lack of space. The major observations made before are also valid for this component.

The frames did not develop any plastic hinge when excited by any of the 20 recorded earthquakes. To study the effect of inelastic behavior in the $V_1$ parameter, the actual time histories were scaled up so that yielding was produced in all the models. Based on the past experience and for the uniformity of comparison, all the actual time histories were scaled up to develop a maximum average interstory drift of about 1 % by the trial and error procedure, instead of tracking the total number of plastic hinges developed. It was observed that about one to five plastic hinges were formed in the models when they develop the desired drift. Plots similar to those of Fig 2 are then developed for both models and both components but are not shown. It is observed that, since yielding was not significant, the $V_1$ values are practically the same for elastic and inelastic behavior. Based on the above results, it is concluded that the contribution of the IGF to the lateral resistance could be significant and consequently should not be overlooked in the design of the structural systems under consideration.




a) Model 1 b) Model 2

Figure 2. $V_1$ values for Models 1 and 2 with PP connections

### *4.2 Gravity Frames with SR Connections*

The magnitude of the $V_1$ parameter is estimated considering the stiffness of the beam-to-column connection of the IGF. It is assumed that the moment that a given connection can transmit is 30% of the plastic moment of the beam it is connecting. Only Model 1 and *(X, 0, 0)* component are considered. The results for this model and component are shown in Figure 3 for both PP and SR connections. It is observed that the contribution of the IGF to the lateral resistance increases when the stiffness of the connections is considered. The increment is particularly important for upper stories.

## 5. RELATIVE IMPORTANCE OF THE *P-δ* EFFECT

As stated earlier, the IGF are usually designed to resist only gravity loads. Due to the action of rigid floor diaphragms these IGF, however, will undergo the same lateral deformation as the perimeter MRSF when subjected to lateral seismic load and consequently the second order moments caused by gravity loads through the lateral displacements could by significant. The relative importance of these moments with respect to those considered in the design of the columns of the IGF is addressed in this part of the paper. The $M$ parameter, defined as $M_S/M_G$ is used for this purpose. $M_S$ represents the second order moment and $M_G$ the column moment produced by gravity loads. For gravity frames with PP connections $M_G$ is estimated as:

$$M_G = P_U(1.5 + 0.03h) \quad (1)$$

where $P_U$ represent the gravity axial load and $h$ the depth of the columns.

Values of $M$ are estimated for corner, lateral and interior columns of Model 1 and for interior column of Model 2. Only the statistics of Model 1 are presented. They are given in Table 2. The most important observation that can be made is that the values of $M$ are close to unity and even larger than this value in many cases indicating that the magnitude of the second order moment is as important as that moment considered in the design of gravity columns and consequently should not be neglected. The values of $M$ for Model 2 are similar to those of Model 1.

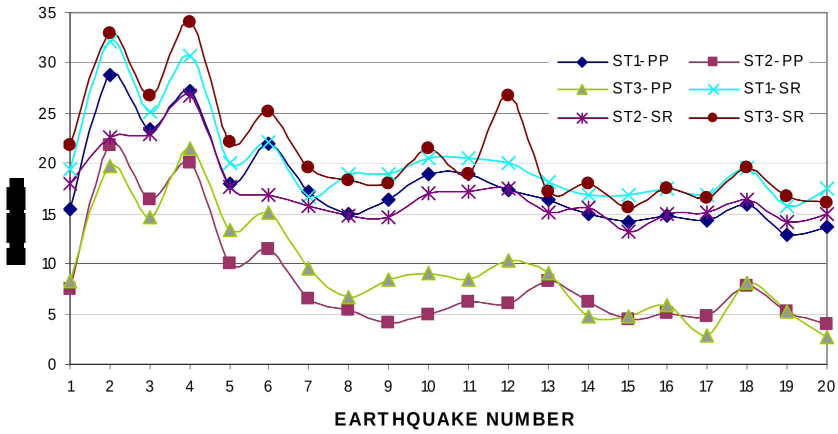



Figure 3. Values of $V_1$ for Model 1 with PP and SR connections

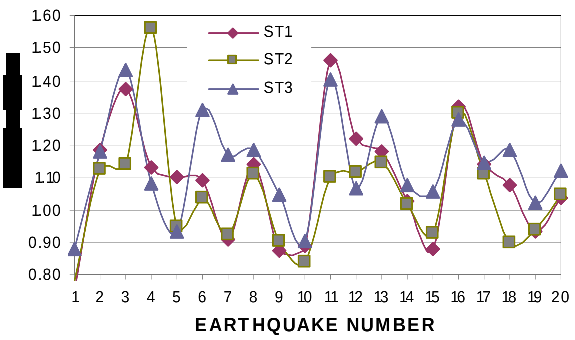
## 6. SEISMIC RESPONSE CONSIDERING PP AND SR CONNECTIONS

The effect of the stiffness of the connections on the structural seismic response, in terms of interstory shears and displacements, and resultant stresses on individual members, is addressed in this part of the paper. Only Model 1 and seismic component on the $X$ direction are considered. Interstory base shear is first discussed. The $V_2$ parameter, defined as $V_{PP}/V_{SR}$ is used for this purpose. For a given story, $V_{PP}$ will represent the average shear on that story when PP connections are considered in IGF of the model. $V_{SR}$ will represent the same, except that SR connections are used. Results are shown in Fig 4a. The most important observation that can be made is that the values of $V_2$ are larger than unity in most of the cases. Values close to 1.60 are observed in some cases indicating that the interstory shears are larger for the frame with PP connections. The implication of this is that the seismic behavior of the frame with SR connections can be quite different from that of the frame with the idealized PP connections. The reason for this is that the consideration of shear connections in the analysis adds some structural stiffness and at the same time a source of energy dissipation.

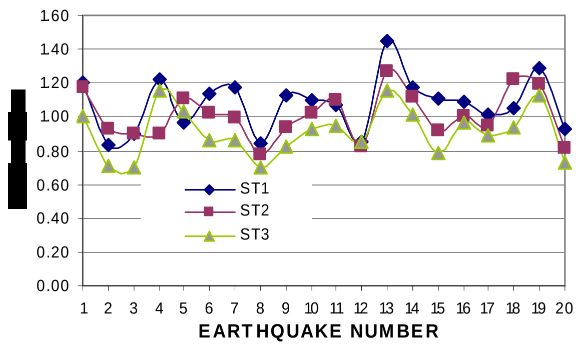
Table 2. Statistics for the $M$ parameter, Model 1

| BEHAVIOR | STORY | CORNER | | | | INTERIOR | | | | LATERAL | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *(X, 0, 0)* | | *(Y, 0, 0)* | | *(X, 0, 0)* | | *(Y, 0, 0)* | | *(X, 0, 0)* | | *(Y, 0, 0)* | |
| | | μ | σ | μ | σ | μ | σ | μ | σ | μ | σ | μ | σ |
| ELASTIC | 1 | 0.71 | 0.12 | 0.84 | 0.27 | 0.74 | 0.11 | 0.86 | 0.27 | 0.78 | 0.12 | 0.84 | 0.27 |
| | 2 | 1.07 | 0.20 | 1.24 | 0.40 | 1.18 | 0.22 | 1.27 | 0.41 | 1.18 | 0.22 | 1.24 | 0.40 |
| | 3 | 1.09 | 0.20 | 1.34 | 0.39 | 1.35 | 0.24 | 1.43 | 0.42 | 1.37 | 0.25 | 1.34 | 0.39 |
| INELASTIC | 1 | 0.72 | 0.12 | 0.87 | 0.30 | 0.74 | 0.11 | 0.87 | 0.29 | 0.78 | 0.12 | 0.87 | 0.30 |
| | 2 | 1.07 | 0.20 | 1.19 | 0.35 | 1.18 | 0.22 | 1.23 | 0.36 | 1.18 | 0.22 | 1.19 | 0.35 |
| | 3 | 1.09 | 0.20 | 1.29 | 0.35 | 1.38 | 0.24 | 1.38 | 0.39 | 1.38 | 0.25 | 1.29 | 0.35 |

Results for interstory displacements are next studied. The $D$ parameter, defined as $D_{PP}/D_{SR}$, is used in this case. The notations $D_{PP}$ and $D_{SR}$ represent average interstory displacements for the frame with PP and SR connections, respectively. The values of $D$ are shown in Fig 4b. As for the case of $V_2$, it is observed that the $D$ values vary from one earthquake to another and from one story to another without shown any trend. However, in this case the values can be larger or smaller than unity. The mean values for Interstories 1, 2 and 3 are 1.06, 1.01 and 0.94, respectively. It indicates that on an average basis the displacements of the frames with PP connections are similar to those of the frame with SR connections. Results in terms of axial loads and moments on some columns of the base of the MRSF are also estimated but are not shown. Results indicate that the values of these parameters decrease when the stiffness of the connection is considered, but the decrement is smaller than that of interstory shears.




a). Shears for PP and SR connections




b). Displacements for PP and SR connections

Figure 4. Shears and displacements for PP and SR connections

## 7. CONCLUSIONS

Some issues, related to the seismic behavior of steel buildings with perimeter moment resisting steel frames (MRSF) and interior gravity frames (IGF), are addressed in this paper. First, the contribution of IGF to the lateral resistance is estimated. The IGF are assumed to have, first perfectly pinned (PP) connections, and then semi-rigid (SR) connections. The seismic responses, in terms of global (shear and interstory displacements) and local response parameters (resultant stresses at individual members of the base), of the buildings with PP connections are compared to those of the buildings with SR connections. Finally, the importance of the *P*-$\delta$ effect in gravity columns with respect to those moments used to design these columns is also studied. Some models used in the SAC project are used for this purpose. The models are excited by twenty recorded earthquake motion in time domain. They are obtained from the Data Sets of the National Strong Motion Program (NSMP) of the United States Geological Surveys (USGS) and were selected to represent the characteristics of strong motion earthquakes.

The numerical study indicates that the contribution of IGF to the lateral structural resistance may be significant. This contribution is larger for lower stories for the buildings with PP connections. The contribution increases when the stiffness of the beam-to-column connection of the IGF is considered, particularly for upper stories. From a comparison of the results of the models with PP connections and the results of the models with SR connections it is observed that the interstory shears are significantly reduced when the connections stiffness is taken into account. By the other hand, the interstory displacements are similar for the models with PP and SR connections. Resultant stresses, in terms of axial loads and moments at some base columns, also decrease but to a lesser degree. Results also indicate that the second order moments produced in gravity columns as a result of the gravity axial load and seismic lateral displacements are comparable and even larger than those used to design these columns. Based on the results of this study, it is concluded that, if the abovementioned structural system is used, IGF should be considered as part of the lateral resistance system, and that the stiffness of the connections and the

*P*-*δ* effect should be included in the design of the IGF. Otherwise, the capacity of gravity frames may be overestimated while that of MRSF may be underestimated

**ACKNOWLEDGEMENTS**
This paper is based on work supported by El Consejo Nacional de Ciencia y Tecnología (CONACyT) under grant 50298-J and by La Universidad Autónoma de Sinaloa (UAS) under grant PROFAPI-07. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the sponsors.

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