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Economical-Structural Performance of Steel Moment Resisting Building Frames Using the Section Variation Technique.

Desempeño Económico-Estructural del Momento Resistente de Acero en Marcos de Edificios usando el Método de la Variación de Sección.

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Abstract

Pre-engineered steel structures have become an indispensable tool in the construction industry because of their widespread use in large shopping malls, exhibition halls and industrial buildings. Such special buildings generally contain stacked materials, heavy machinery and a heavy-duty crane. Seismic loads are critical for these structures, as the location of the building changes depending on seismic activities. In this research, the performance of a typical structural steel building to be used as a shopping mall and constructed using the section variation technique is studied for all five seismic zones of Uniform Building Code 97, namely 1, 2A, 2B, 3 and 4. This study investigated the effects of the variation of the seismic forces in various seismic zones for special and ordinary steel moment-resisting building frames with response modification factor values of R=8.5 and R=4.5, respectively. The parameters studied were the economy and the structural factors, design performance and detailing of the structures. The results indicate that structural steel can be saved by up to 7% for main frames and 60-130% for the lateral bracing by using special moment-resisting building frames (R=8.5) if proper detailing/construction of the steel moment-resisting frames is carried out according to the guidelines set forth by the AISC seismic provisions.

Abstract

Estructuras de acero con ingeniería previa se han convertido en una herramienta indispensable en la industria de la construcción debido a su uso generalizado en los grandes centros comerciales, salas de exposiciones y edificios industriales. Tales edificios especiales generalmente contienen materiales apilados, maquinaria pesada y una grúa de servicio pesado. Cargas sísmicas son críticos para estas estructuras, como la localización de los cambios de construcción en función de las actividades sísmicas. En esta investigación, la realización de un edificio de acero estructural, característica que se utilizará como un centro comercial y construido utilizando la técnica de la sección se estudia la variación de las cinco zonas sísmicas del Código Uniforme de Construcción 97, es decir, 1, 2A, 2B, 3 y 4. Este estudio investigó los efectos de la variación de las fuerzas sísmicas en diferentes zonas sísmicas para estructuras de edificios de acero resistentes a momentos, especial y normal, con los valores del factor de modificación de la respuesta de R = 8,5 y R = 4,5, respectivamente. Los parámetros estudiados fueron la economía y los factores estructurales, el rendimiento del diseño y el detalle de las estructuras. Los resultados indican que el acero estructural se puede ahorrar hasta un 7% para las tramas principales y 60-130% para el arriostramiento lateral mediante el uso de marcos especiales resistentes a momento de construcción (R = 8,5) si un adecuado detallado/construcción de marcos acero resistentes a momento se lleva a cabo de acuerdo con las directrices establecidas por las disposiciones sísmicas de AISC.

Keywords: Structural Economic Performance, Pre-Engineered Structures, Special Moment-Resisting Frames, Economy of Structures, Structural Detailing.

INTRODUCTION

Large spaces without any hindrance, such as warehouses, sheds and exhibition halls, are used for different purposes. Steel structures provide the most economical and efficient solution for long spans in both directions and low-cost working spaces. The traditional solution for large spans is to use portal and gable frames with straight and haunch connections using normal hot-rolled sections. This option may be expensive and can only provide a limited amount of space.

This type of design may cause serviceability problems and be a violation of the optimum economy level. The use of heavy sections will also impose additional self-weight on the columns and foundations, which makes their design uneconomical. The additional accumulated mass increases the earthquake loading of the structure. One innovative method of developing large-span structures is to construct steel structures with the section variation technique, known as pre-engineered/pre-fabricated buildings (Saleem, M; 2009). The basic philosophy in the design of such buildings is to vary the section as the bending moment and shear force change along the span. The depth of the section and the thicknesses of the web and flanges can be varied to make the structure economical (Segui W; 1999, Williams A; 2003, Azam Khan; 2006 and Akmal U; 2009).

Until recently, many structural engineers incorrectly believed that steel structures can inherently withstand seismic loads and that no special provisions are required to improve their seismic behavior. However, the Northridge earthquake (M6.7) of 1994 exposed many connection failures that were not predicted (Robert Tremblay et. al.; 1995). One year later, nearly 50 steel buildings collapsed due to the Kobe earthquake (M6.9), confirming the possible weakness of these structures during seismic activity (Wai-Fah and Charles; 2002). Recent research has demonstrated that structural steel buildings can perform better during any seismic activity than structures composed of any other materials if the steel buildings are properly designed by considering all seismic risks. According to AISC, the seismic design of buildings should comply with the AISC Seismic Provisions for Structural Steel Buildings and Seismic Provisions Supplement No. 1. With respect to seismic applications and the seismic response modification coefficient, buildings may be divided into two categories, low-seismic applications and high-seismic applications.

STATE OF THE ART

This paper will open a new window for researchers and design engineers regarding effect of seismic loading on the steel buildings. As, seismic loading can get little attention from the design engineers in case of steel structures. For example, in low-seismic applications (when the seismic response modification factor R is less than three), seismic loading may not be critical. In high-seismic applications (when the seismic response modification factor R is greater than three), the code requirements are based on the assumption that portions of the building's seismic load-resisting system (SLRS) will undergo a controlled inelastic response when subjected to major seismic events. The objective of this research is to study the effect of various seismic locations, the types of frames based on seismic detailing and the importance of strict quality control in the construction of pre-engineered steel structures on the economy, performance behavior and construction techniques.

METHODOLOGY

To study the performance of steel structures in various seismic locations, a pre-defined structure is selected, analyzed and designed for constant gravitational and wind loadings but with a seismic intensity for different seismic locations (zones). A linear static analysis is carried out to study the effective performance of such structures. The pre-engineered building selected for this study is a typical shopping mall, which is categorized as a low-rise steel structure and consists of moment-resisting frames. In such structures, the induced forces about the major axis are resisted by the stiffness of the frame in the major direction, whereas out-of-plane loads are resisted by braces (cable, tubes, girt and portal). Figures 1, 2 and 3 present details of the planes and sections for the selected building.

A regular elastic and P-Δ analysis of the structure is carried out using the commercially available software STAAD PRO 2007 for varied seismic force intensities according to UBC-97 by keeping the dead, live and wind loads constant for all seismic locations. Table-1 and 2 provides detail regarding dead, live and wind loads.

Table-3 and Table-4 provides details of six seismic locations and five types of 2-D frames. The analysis is carried out for all five frames and six seismic locations for ordinary and special steel moment-resisting frames based on seismic detailing. Each frame is first designed to achieve the minimum weight design for gravity and wind loading. The member sizes obtained are used to study the effect of seismic loading in other seismic locations. Finally, the member sizes are revised to obtain the most economical design for each seismic location.

Figure 1. *First and second mezzanine floor plans. Source: Self Elaboration.*

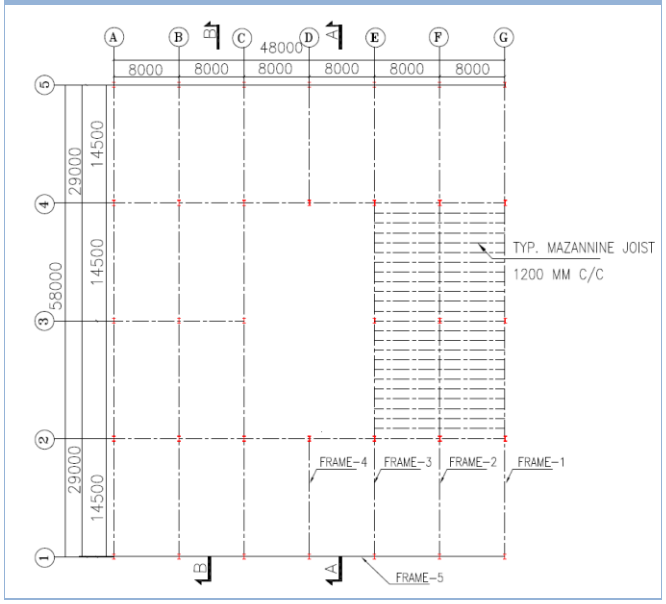


Figure 2. *Roof plan. Source: Self Elaboration.*

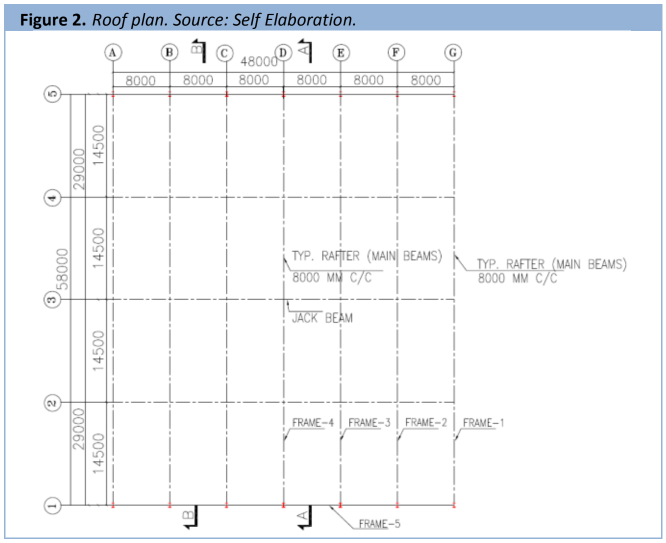
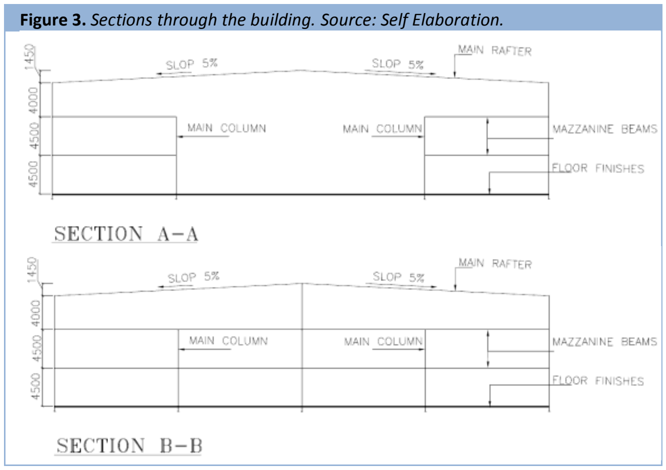


Figure 3. *Sections through the building. Source: Self Elaboration.*



AISC REQUIREMENTS FOR SPECIAL MOMENT-RESISTING FRAMES *(Seismic Provisions for Structural Steel Buildings AISC-2005)*

The following requirements are imposed by AISC for the design of special moment resisting frames:

1) The section must be seismically compact and must satisfy the requirements of Table I-8-1 of the AISC seismic provisions.

2) Within the area of the protected zone (the protected zones are the areas at each end of the beam subjected to inelastic rotations), discontinuities generated due to erection operations and the fabrication procedure must be repaired.

Table 1. *Loading used for structural analysis and design. Source: Self Elaboration.*

Type of Load	Load
Dead + collateral load on the mezzanine	400 kg/m^2
Dead + collateral load on the roof	40 kg/m^2
Live load on the mezzanine	250 kg/m^2
Live load on the roof	100 kg/m^2

Table 2. *Miscellaneous information for analysis and design. Source: Self Elaboration.*

Property	Extent
Basic wind speed	140 kmph
Exposure category	B
Soil profile type	D
Yield strength of steel	345 Mpa
Type of cladding and outside wall	Metallic and ductile
Inside partition	No inside partition

3) Connections of the special moment-resisting frames must satisfy following requirements:

a. The connection must be capable of sustaining an interstory drift angle of 0.04 radians.
b. At the column face, the flexural resistance of the connection must be at least equal to 80% of the full plastic moment capacity of the connected beam at the above-mentioned interstory drift angle.
c. The following seismic load effect is used to calculate the shear strength of the connection:

$$E \bullet 2(1.1 R_y M_p)/L_h$$

Where R_y is the ratio of the anticipated yield stress to the specified minimum yield stress, F_y; M_p is the nominal plastic moment capacity; and L_h is the distance among plastic hinge positions. In addition to the above-mentioned requirements, the structure must be designed considering second-order effects so it can accommodate any additional deformations generated in the structure at the connections.

4) For special moment-resisting frames, the ratio of the summation of the moments at the beam-column joint (above and below the joint) to the summation of the moment in the beams at the intersection of the beam and column centerline must be greater than or equal to one. There are few exceptions to this requirement, which can be found in the AISC seismic provisions.

5) Complete joint penetration grove welds are to be used for beam flanges, shear plates, webs of the beams and demand critical welds, as described in Section 7.3b of the AISC-2005 seismic provisions for structural steel buildings.

Table 3. *Six seismic locations studied according to Table 16-I of UBC-97.*

Location	Zone	Peak ground acceleration
Location 1	Zone 1	0.075
Location 2	Zone 2A	0.15
Location 3	Zone 2B	0.20
Location 4	Zone 3	0.30
Location 5	Zone 4	0.40 distance from the fault > 15 km
Location 6	Zone 4	0.40 distance from the fault < 15 km

Table 4. *Five types of two-dimensional frames considered for the analysis and design. Source: Self Elaboration.*

Type of frame	Frame no.
Exterior frame	Frame 1
Interior frame	Frame 2
Interior frames at the sides of opening	Frame 3
Central frame	Frame 4
Side wall truss (for out of plane seismic and wind load)	Frame 5

Table 5. *Limit on the lateral sway of the building imposed by the Metal Building Manufacturer Association (MBMA)'s manual against lateral loads (Table 3.2 of MBMA, 2002)*

Type of cladding	Limit
Metal panel cladding, lower end on the foundation, others on the bare frame	H/60 to H/100
Precast walls, lower end on the foundation, others on the bare frame	H/100
Reinforced masonry walls, lower end on the foundation, other on the bare frame	H/500
Pre-assembled units resting completely on the columns and frame	H/500
Curtain walls, lower end on the spandrel and other on the frame	H/500
Partitions resting on the frame	H/500

6) The individual thickness t of column webs or web doubler plates must be greater than or equal to the sum of the panel depth between the continuity plates and panel zone width between the column flanges divided by 90.

7) To develop the full shear strength of the doubler plates, these components must be designed according to the detailed requirements of the AISC seismic provisions.

8) The lateral support at the beam-column connection must be designed according to the AISC seismic provisions.

9) The lateral bracing of the beam and the splicing of the column must be performed according to the AISC seismic provisions.

Figure 4. *Percentage difference in the weight for each seismic location for frame 1. Source: Self Elaboration.*

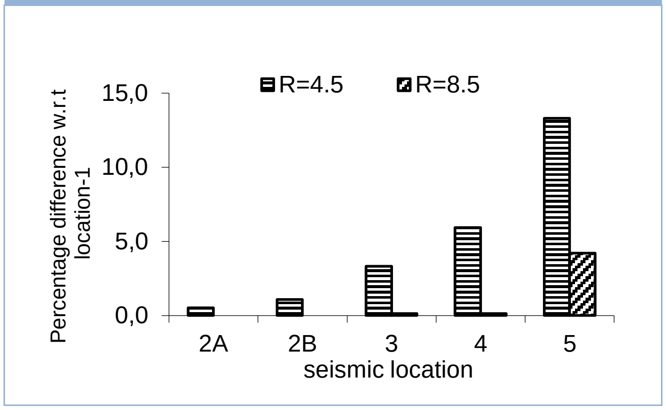


Figure 5. *Percentage difference in the weight for each seismic location for frame 2. Source: Self Elaboration.*

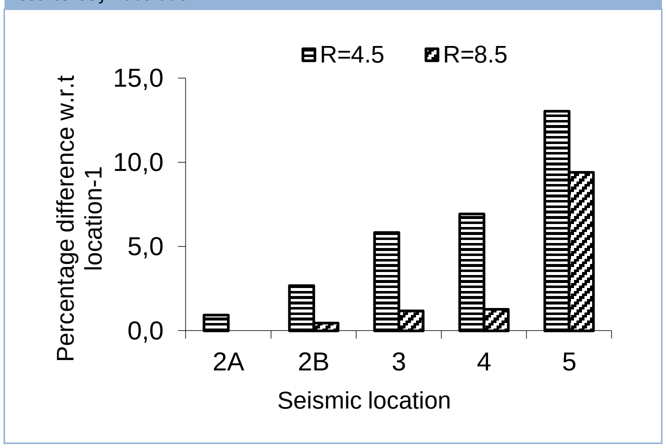


Figure 6. *Percentage difference in the weight for each seismic location for frame 3. Source: Self Elaboration.*

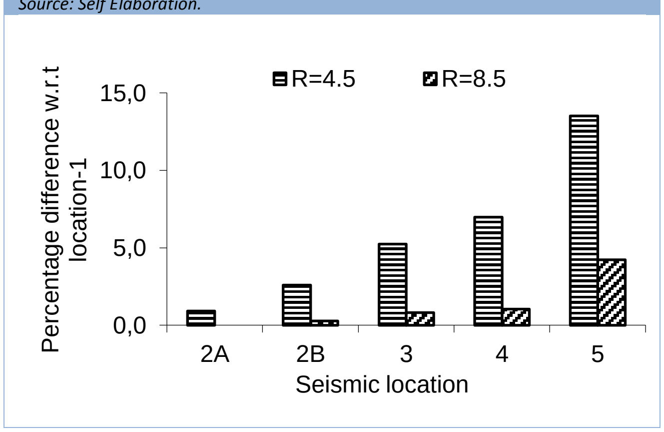


Figure 7. *Percentage difference in the weight for each seismic location for frame 4. Source: Self Elaboration.*

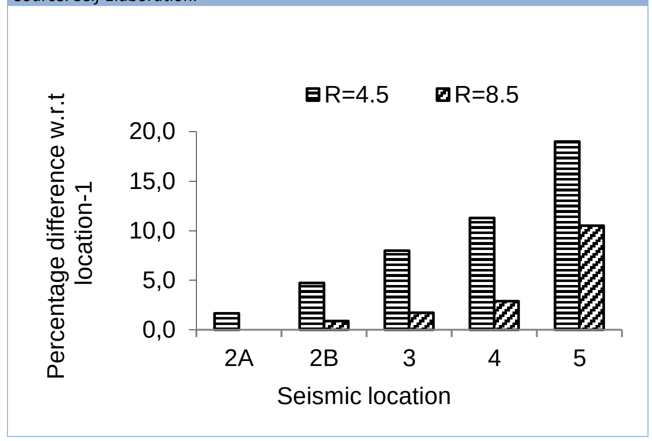


Figure 8. *Percentage difference in the weight for each seismic location for frame 5. Source: Self Elaboration.*

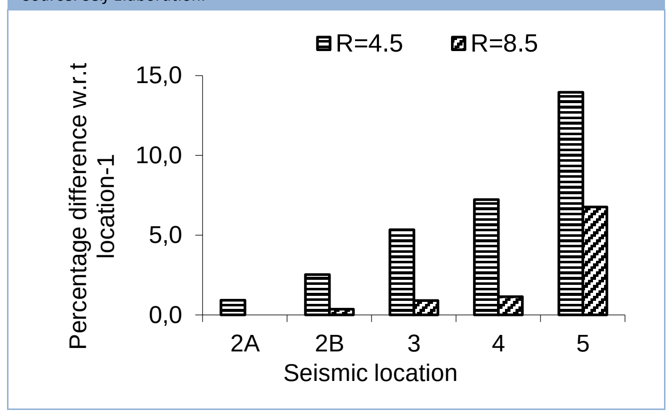
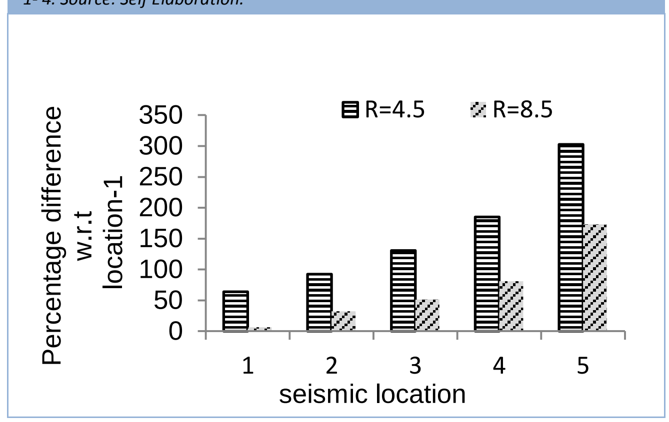


Figure 9. *Percentage difference in the weight for each seismic location for frames 1- 4. Source: Self Elaboration.*



RESULTS AND DISCUSSION

The following parameters were investigated after designing the five frames for all six seismic locations for ordinary and special moment-resisting frames.

1) The percentage differences in the weight of the frames for various seismic locations with respect to zone 1 are shown in Figures 4-9. Using the ordinary moment-resisting frames, the increase in the weight of the structural steel is approximately 1.0%, 2.5%, 5.3%, 7.2% and 14% for frames 1 to 4 and for seismic locations 2 to 6, respectively, with respect to seismic location 1. For the bracing elements, the weight of the structural steel is approximately 64%, 92%, 131%, 185% and 302% for seismic locations 2 to 6, respectively, with respect to seismic location 1.

2) Using the special moment-resisting frames, the increase in the weight of the structural steel is approximately 0.0%, 0.4%, 0.9%, 1.1% and 6.8% for frames 1 to 4 and for seismic locations 2 to 6, respectively, with respect to seismic location 1. For the bracing elements, the weight of the structural steel is approximately 7%, 32%, 52%, 81% and 173% for seismic locations 2 to 6, respectively, with respect to seismic location 1. Using the special moment-resisting frames is more economical, but their use is associated with the strict requirements of the 2005 AISC seismic provisions, as discussed in Section 3. To fulfill these requirements, highly skilled labor, strict supervision and highly sophisticated equipment are required to execute the construction corresponding to particular design requirements, which is nearly impossible in developing countries.

3) Figures 10 and 11 illustrate the sway of the interior frame in various seismic locations for ordinary and special frames, respectively. The sway of the first mezzanine level is 10.86, 19.91, 24.89, 32.60, 39.83 and 59.76 mm for ordinary moment-resisting frames. The sway of the first mezzanine level is 5.87, 10.76, 13.47, 17.62, 21.53 and 32.31 mm for special moment-resisting frames in all six seismic locations. The height of the building up to the first mezzanine level is 4.5 m. All of these sways are within the acceptable limits. The sway for the ordinary moment-resisting frame is significantly larger than that for the special moment-resisting frame.

4) The sway of the bracing lateral truss for various seismic locations for ordinary and special moment-resisting frames is shown in Figures 12 and 13, respectively. The sway is greater for ordinary moment-resisting frames. For seismic location 5 and R=4.5, the value of the sway is more than the allowed value(for allowed values refer to table-5), which indicates that the amount of bracing must be increased.

Figure 10. *Sway of the interior frame for frame unfactored seismic loads when R=4.5. Source: Self Elaboration.*

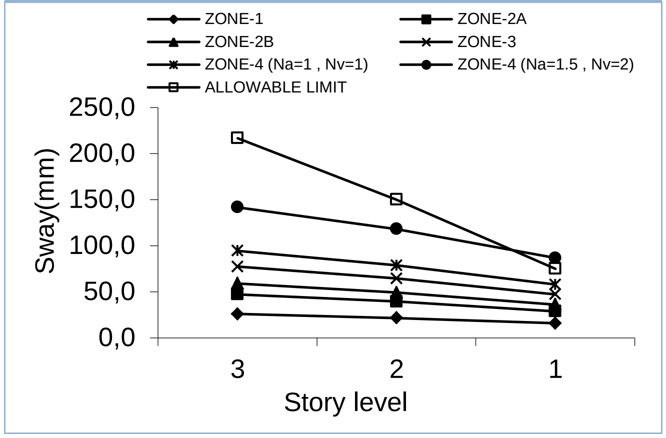


Figure 11. *Sway of the interior against factored seismic loads when R=8.5. Source: Self Elaboration.*

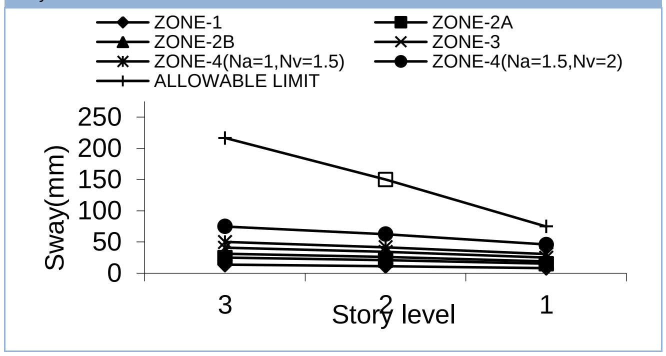


Figure 12. *Sway of the side-wall truss against seismic loads when R=8. Source: Self Elaboration.*

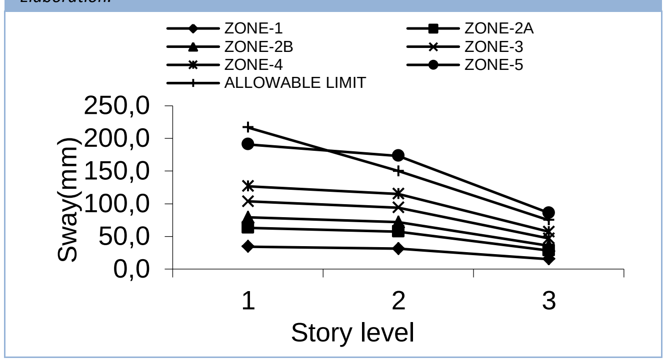
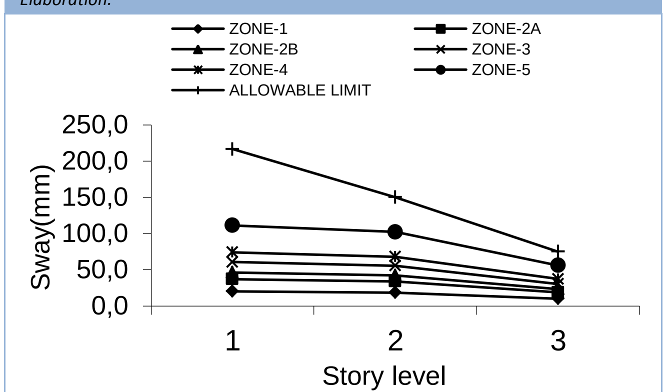


Figure 13. *Sway of the side-wall truss seismic loads when R=4.5. Source: Self Elaboration.*



CONCLUSIONS

Using ordinary moment-resisting frames, the requirements of structural steel increase considerably (from 1% to 14% for the main frame and from 64% to 303% for the bracing elements) as the seismic demand increases from zone 1 to zone 4, the most critical zone. By using the special moment-resisting frames, the requirements of the structural steel increase from 0% to 7% for the main frame and from 6.6% to 173% for the bracing elements as the seismic demand increases from zone 1 to zone 4.

The amount of structural steel can be saved by up to 7% for the main frame and from 60% to 130% for the bracing by using special moment-resisting frames (R=8.5), provided the design and construction satisfy the detailing according to the guidelines set forth by the AISC seismic provisions.

If there is less construction quality control, ordinary moment-resisting frames (R=4.5) should be used instead of special moment-resisting frames, even at the highest seismic location, as the structure may fail if the requirements of the special moment-resisting frames are not satisfied. However, AISC specifications require the use of special moment frames in zone 3 and zone 4.

The drift of the structure due to unfactored seismic loading is significantly greater in ordinary moment-resisting frames compared to special moment-resisting frames. Thus, if there is any drift limitation due to functional requirements, special moment-resisting frames should be used instead of ordinary moment-resisting frames.

ACKNOWLEDGEMENT

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