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SEISMIC DESIGN CONSIDERATIONS FOR LONG SPAN METAL BUILDINGS

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Abstract

The assessment of seismic design of long span Metal buildings is controlled by several factors and considerations. The basic considerations for seismic design are related with the ductility capacity of the structure, allowable inter-story drift, response-modification coefficient R, second order effects, lateral torsional buckling for members, foundation stiffness assumptions for support the structure to include soil-structure-interaction, and some other complementary aspects. The seismic design criteria for long span Metal buildings are usually out of the scopes of the building design codes. The seismic design of long span metal buildings requires a set of specific considerations in order to fulfill the basic requirements of most building codes: guarantee the safety of the occupants and the contents and minimize structural and non-structural damages in order to guarantee as much as possible the continuity in the functionality after the design level earthquake. This paper presents a case study of the structural design for a long span metal building, with steel moment resisting frame in the transverse direction, and steel ordinary concentric braced frame in the long-direction. The structure is located in an intermediate seismic zone. The typical spans are 30 m and 14 m in the transverse and long direction respectively. The total height of the structure is 20 m. The steel moment resisting frame is composed of built-up sections conforming beams and columns. The foundation system is a deep foundation formed by a group of piles, a rigid pile-cap and a base column which allows an adequate connection to the column. The seismic design considerations are based on several Standards codes and books reference as ASCE/SEI 7-10, ASCE/SEI 41-13, Metal Building Manual, AISC 360-10, AISC 341-10 and NSR-10. The case study presents a summary of the most relevant impacts in the structural design methods on the final expected behavior of the structure, for each one of the considerations related to the seismic design. Finally, an approach for the assessment of the main seismic design considerations for long span metal buildings is presented as a guideline for structural design analysis of these complex structures.

Keywords: seismic design; long span; metal buildings.

1. Introduction

This paper presents a detailed review and recommendations of the basic considerations for the seismic design of long span metal buildings. These type of structures are classified as non-residential and low-rise structures. Steel built-up sections are used to construct the structure. The seismic design of long span metal buildings requires a set of specific considerations in order to fulfill the basic requirements of most building codes: guarantee the safety of the occupants and the contents and minimize structural and non-structural damages in order to guarantee as much as possible the continuity in the functionality after the design level earthquake. The basic considerations discussed herein are related with the ductility capacity of the structure, response-modification factor R, allowable inter-story drift, second order effects, lateral torsional buckling, foundation stiffness assumptions for the support of the structure to include soil-structure-interaction, connections detailed requirements, and additional factors relevant for an acceptable seismic behavior of these type of structures. Usually, most building design codes do not consider specifically these type of structures, especially in relation to the seismic design criteria for moment resisting frames composed of built-up sections.

The structural design of a long span metal buildings located in intermediate seismic zone is presented as a case of study. The typical spans are 30 m and 14 m in the transverse and long direction respectively. The total height of the structure is 20 m and 12m of column height. The structural system considered are steel moment resisting frame (MRF) in the transverse-direction and steel ordinary concentric braced frame (OCBF) in the long-direction. The foundation system is a deep foundation formed by a group of piles a rigid pile-cap and a base column which allows an adequate connection to the column. The seismic design considerations for the assessment and analysis are based on several Standards codes and book references such as the ASCE/SEI 7-10 [1], ASCE/SEI 41-13 [2], Metal Building Manual [3], AISC 360-10 [4], AISC 341-10 [5] and NSR-10 [6].

A complete summary about the most relevant impacts in the structural design methods for the final expected behavior of the structure, for each one of the considerations for the seismic design are presented in the case of study. Finally, an approach for the assessment of the main seismic design considerations for long span metal buildings is presented as a guideline for structural design analysis of these complex structures.

2. General considerations

The seismic design of long span metal buildings requires a set of specific considerations in order to fulfill the basic requirements of most building codes: guarantee the safety of the occupants and the contents and minimize structural and non-structural damages in order to guarantee as much as possible the continuity in the functionality after the design level earthquake. Several aspects such as geometry configuration of the structure, minimum clear span requirements, clear height, roof system configuration, exterior and interior wall configuration and components attached to the structure may affect the expected behavior of the structure and therefore have to be considered in the assessment. Those aspects are mostly defined for the owner, mechanic engineer or architect of the project and usually no structural engineering criteria is used in its definition. Based on those aspects, the structural engineer assesses the seismic design of the structure. The seismic design follows a series of steps which includes: the identification of the seismic zone, the selection of the structural system configuration, the definition of the loads acting on the structure, the geometric and configuration limitations, the identification of additional requirements for the design, the analysis of the structure, the consideration of additional effects on the members such as the lateral torsional buckling (LTB) and second order effects, the selection of the foundation system and the evaluation of the soil-structure-interaction effects. General seismic design considerations are required in order to consider the abovementioned effects and guarantee a safe and functional seismic design. Those aspects are discussed below.

2.1 Structural system configurations and response-modification factor R

The structural system configuration selection is based on the geometry configuration, minimum clear span requirements, seismic zone location, and additional aspects. Steel MRF and steel concentric braced frame (CBF) are the typical structural system for long span metal buildings. Considering space and clear span limitations, it is common to specify different structural system configuration on each direction of the structure [3]. The most common structural arrangement consists of steel MRF in the transverse span direction and steel CBF in the long direction [3]. Fig 1 presents the typical structural systems configurations used in the long span metal buildings.

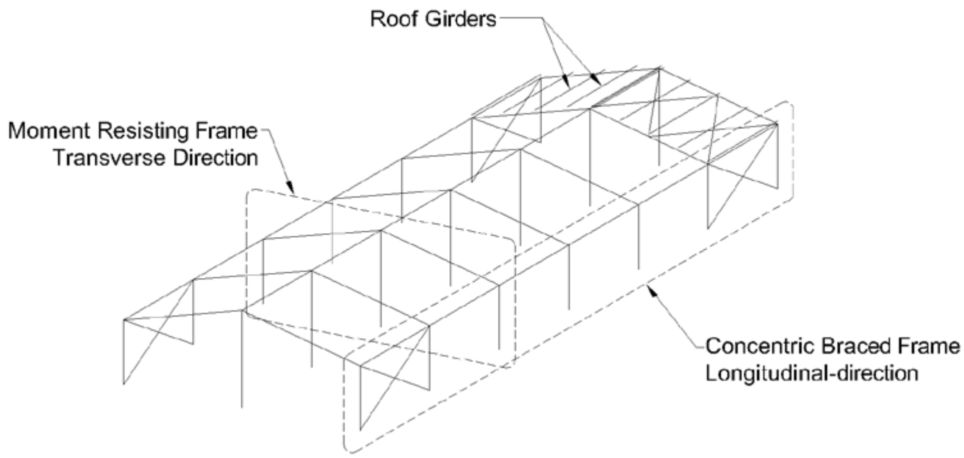


Fig. 1 – Typical structural system configurations

The seismic design detailing of the structural system configuration depends on the seismic zone location and defines the response-modification factor. These parameters are determined based on the recommendations of the building codes. Buildings codes Nonetheless, the response-modification factors stablished on the building codes such as Building code [1, 6] are not suitable for these type of structures.

2.2 Load considerations

The loads acting on the structure are defined by the gravitational loads, the horizontal loads and additional special loads. The gravitational loads shall include the dead loads, live loads, snow loads, ponding loads and equipment loads. The horizontal loads shall include seismic and wind forces. The additional special loads shall include thermal loads, dynamic loads, settlement loads and other special loads. The loads considerations are defined by the roof system configuration and geometry configuration, the external and interior wall configuration, the attached components to the structure.

The roof system and geometry configuration defines the dead, roof live, snow and ponding loads. The typical dead load value varies from 0.10 kN/m2 to 1.0 kN/m2. This value depends on the configuration of the roof panel system; roof panel sandwich system with thermal and acoustic insulation or roof system with single steel sheet. The roof live load is established in the building codes building codes and depends on the slope of the roof system, and the accessibility to the roof. The snow load is established in the building codes and depends of the location of the structure and the slope of the roof system. The ponding load depends on the slope of the roof system and the drainage system. It is recommendable use a roof system as lighter as possible for great long span between purlins.

The exterior and internal wall configuration defines the additional dead loads acting on the structure. The loads shall be considered if the exterior and internal wall configuration is attached to the structure. The exterior walls configuration can be constructed in masonry or light wall partitions. For the case of masonry, it is recommendable to isolate its behavior from the one of the main structure. On the other hand, for light wall partitions systems it is usually recommended to attach such elements to the main structural system including some gravity intermediate columns simply supported if needed in between the main columns. The additional elements attached to or supported by the principal structure system shall be considered in the analysis both as loads and as rigid elements if they are not isolated from the structure. It has to be developed a detailed assessment of the type of load, points of applications, and value of the load. The elevated pipe racks system, the cranes system are some representative loads acting on the structure.

The seismic forces are defined based on the design response-spectrum. The design response-spectrum shall be defined following the recommendations of the local or national building code applicable. The soil properties and characterization shall be evaluated by means of an integral soil study which includes both in-situ and laboratory testing on undisturbed samples. The construction importance factor shall be stablished carefully, because, it will generate an increase in the design response-spectrum. This factor usually depends of the use of the structure, its contents and the type of occupation. Usually the owner of the structure participates in the definition of the relative importance of a particular structure when they are part of a complex system as for example in commercial or industrial layouts.

Wind forces are to be estimated based on local regulations as established by local building codes. Wind loads usually control the design of façade and some roof elements. Also, wind loads can impose important global effects to the structure imposing high flexural moments at the base of the columns or possible tension forces in critical columns.

The thermal loads shall also be included in the analysis. This type of loads is defined by the outside ambient conditions taking into account the roof system, the wall system and the processes that are developed inside the structure. The absolute maximum variation in temperature of the main structure is to be estimated. Also the absolute differential variations in a particular element (for example one side with respect to the other) can generate critical design demands. It is important to consider the variations in thermal load considering the long span and continuity in the roof or walls. The settlement loads are determined based on the soil field-test study. It is recommended to use a minimum total settlement of about 1 cm for individual columns. Differential settlements have a limit of L/1000 and L/160 for buildings with walls and components susceptible to fragile damage and building steel structures without fragile components respectively (values extracted from table H.4.9-1 from [6]).

Recommended standard dead loads values obtained from similar already designed structures are used for preliminary assessments. The total roof weight value is usually on the order of 0.25 kN/m2. This value includes roof system, ducts for electrical supplies, illumination system and fire protection network. For self-weight for purlins usually a value around 0.10 kN/m2 is estimated. To consider the self-weight of the rest of the structure usually a value around 0.50 kN/m2 is estimated.

2.3 Limitation requirements

The long span metal buildings structures have several limitation requirements. Deflection limits for horizontal and vertical elements are required. The considerations for the design of purlins and girders is controlled by a combination of span of the purlins/girders, acting loads, and vertical deflection limits. Typical values of vertical and horizontal deflection for different load combinations are presented in the [1, 3, 7]. It is advisable to carefully define these limits that can be modified depending of the roof or wall system. A vertical deflection limit of L/180 is usually recommended for roof elements for load combination of the total dead load plus half of the roof live load or snow load (value extracted from [1, 3, 7]). A water ponding analysis on the roof system shall be included after the selection of roof purlin/beam shape in order to guarantee that no important ponding effects may occur on the roof, once considering the combined deflection of the roof cover, the purlins and the main beams.

Usually, building codes not specify maximum inter-story drifts limits for these type of structures. The designer could use the values established in regular building codes as reference. The inter-story drift limits are usually imposed to guarantee functionality aspects related to the attached components and to limit second order effects. Nonetheless, it is recommendable not to exceed an inter-story drift of 3%, because this may cause importance second order effects due consideration to the considerable masses at the roof level. Those effects can compromise the stability of the system and could easily increase the possibility of collapse. For greater values of inter-story drift you must do a special analysis.

2.4 Analysis considerations

The building codes usually allows two types of analysis for seismic design: the equivalent lateral forces procedure and the modal response spectrum analysis. The common practice for seismic design of these structures, considers independent analysis in the main directions, using typical 2-D models as required. It is recommendable to develop a complete 3D model of the entire structure to include torsional effects, evaluate the diaphragm action of the roof and lateral elements and to use the modal response spectrum method to conduct a detailed seismic assessment of the integrated building.

2.5 Additional considerations

2.5.1 Lateral Torsional Buckling considerations

The long span metal buildings are structures conformed with steel built-up sections that not necessarily accomplish with the slender and compact limits requirements of the [4, 5]. These elements usually have non compact or slender webs or flanges. Lateral Torsional Buckling - LTB analysis shall be conducted in order to determine the capacity of the built-up sections and install additional lateral restraining elements on the flanges of the section.

2.5.2 Soil-Structure-Interaction considerations

The soil-structure-interaction SSI, intend to evaluate the effects on the main structures once considering the flexibility of the foundation. The additional flexibility due to SSI effects can compromise the stability of the steel structure and the attached components to the structure. The [1] on chapter 19 presents the basic considerations to incorporate the effects of SSI. For more detailed SSI considerations refers to chapter 8 of [2]. Special considerations are required to correctly include the approximate stiffness of the foundation into the analysis.

3. Seismic Design Considerations

3.1 Structural system configurations and response-modification factor R

The building codes present several values of possible response-modification factor R for long span metal buildings. The different R values are presented and discussed for the Building codes for Colombia and the United States (USA). Aspects such as the seismic design category, the detailing requirements and the maximum heights limits are included in the seismic design considerations.

3.1.1 Colombian building code

The Colombian building code, [6] recommends a value the response modification factor, R = 3.0, for self-supported structures that are not included in the usual structural types considered by the code. The R value is presented in Table A-1.3-5 “Response-modification factor for some specials structures”. However, these R value are not suitable for long span metal buildings either. Furthermore, the document AIS 180-13 [8] “Seismic recommendations for structures different to buildings” presents different R values depending of the structural system configuration. The table 4-1 presents response-modification factor for non-buildings structures similar to buildings structures. The selection of R values depends on the seismic design category, the height limits and detailing requirements.

The steel moment resisting frames are divided in three systems, steel special moment frames SMF, steel intermediate moment frames IMF and steel ordinary moment frames OMF. The use of steel SMF in high seismic zones shall be avoid, because, the detailing requirements established in chapter F.3 from [6] are not applicable for non-compact and slender built-up sections with special detailing. In that case the recommended value for R is 7.0. The use of steel IMF in high seismic zones is allowed, but it requires a detailed revision of the detailing requirements established on chapter F.3 of the [6] for non-compact and slender built-up sections with intermediate detailing. The R values varies from 1.5 to 4.5. The use of steel OMF in intermediate and low seismic zones are allowed with some restrictions to the structure height limits. The detailing requirements for this system established on chapter F.3 from [6] are applicable for non-compact and slender built-up sections. The R values varies from 1.0 to 2.5.

The concentrically building frame system are divided in two systems: steel special concentrically braced frames SCBF and steel ordinary concentrically braced frames OCBF. The steel SCBF are not suitable for these type of structures, because the detailing requirements are out of the scopes for non-compact and slender built-up sections. The steel OCBF are suitable for this type of structures. The detailing requirements are less enforced with unlimited height and shall comply with the chapter F.2 from [6]. This structural system is allowed in all seismic zones. The R value varies from 1.5 to 3.0.

3.1.2 United Sates building codes

The most widely used building code in the USA, the [1], presents a value of R = 3.0 for "steel systems not specifically detailed for seismic resistance, excluding cantilever column systems". The R value is presented in Table 12.2-1 "Design coefficients and factors for seismic force – resisting systems". This value is not recommended. Also, the chapter 15 in table 15.4-1 "Seismic coefficients for nonbuilding structures similar to buildings" presents several R values.

The steel moment resisting frames are divided in three systems, steel SMF, steel IMF and steel OMF. The steel SMF presents a R value of 8.0. It has to accomplish with the [5] detailing requirements. This structural system is not recommended. The steel IMF presents R values that varies from 1.5 to 4.5. This system has height limits from some seismic category design. It requires accomplish with the [5] detailing requirements. The steel OMF presents R values that varies from 1.0 to 3.5. It has height limits and are not permitted for some seismic design categories. It has to accomplish with the [4, 5] detailing requirements.

The concentrically building frame system are divided in two systems: steel SCBF and steel OCBF. The steel SCBF are not suitable for these type of structures because the detailing requirements are out of the scopes for non-compact and slender built-up sections as prescribed [5]. The steel OCBF presents R values that varies from 1.5 to 3.25. It has height limits and is not permitted for some seismic design categories. It has to accomplish with [4, 5] detailing requirements.

3.1.3 Ductility Capacity

The ductility capacity of this structures are limited and cannot have a greater value of response-modification factor R. Recently research [9, 10] demonstrates that the typical fail of these types of structures under seismic forces is produced by LTB. Also, tests conducted on full-scale specimens [9] demonstrate that the system cannot develop a high ductility because the system has a concentrated lower mass and high stiffness.

Additionally, the seismic detailing requirements for building structures presented in [4, 5] has limits on the ratios of dimensions for I-shape members. Steel built-up sections are used in the construction of long span metal buildings due to the long span between supports. These built-up sections do not accomplish with all the limits for compact sections of the Building codes. Furthermore, the beam-column connection is not suitable to be prequalified connections.

3.3 Inter-story drift limits

The recommendable inter-story drift limit is 2% for these type of structures, this values is extracted from the table 12.12-1 "Allowable story drift" from [1]. It is not recommendable use greater limits. If the structure has attached components susceptible to damage for greater inter-story drift, it is recommendable use special detailing of the connection to the structures. Special slip connections are permitted. It is recommendable install this system or unattached the components before increased the inter-story drift limit.

3.4 Seismic forces and Analysis considerations

The seismic forces shall be determined based on the design response spectrum obtained from the applicable Building Code Standard. The recommended critical damping value of 2% shall be use to analyze this type of structures. The design response spectrum shall be converted to an equivalent design response spectrum with critical damping of 2%. The total masses considered in the analysis shall include dead loads, permanent loads and a fraction of the equipment live loads. The assessment model for this type of structure shall include all geometry detailing. This structures shall not include diaphragm assumptions unless the roof achieve this behavior.

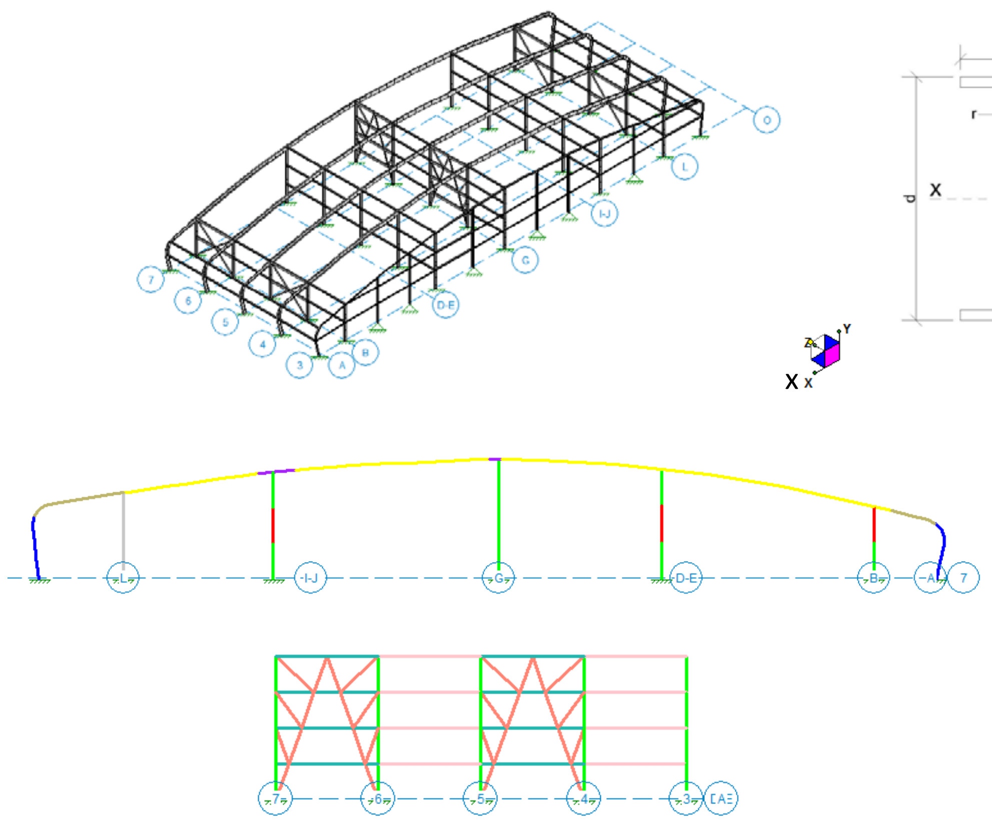
The dead loads shall include the pipe racks elements and supporting system if they are attached to the structure. The loads shall be applied at its respective height. The modal response spectrum analysis is recommended for the assessment of this type of structures. The modal response base shear shall be adjusted to the 0.85 of the equivalent lateral force procedure. Omissions in these aspects can produce wrong results on the structural behavior and misleading in a wrong design.

Pipe racks supporting structures supported for the principal structure of long span metal buildings shall be designed in accordance with chapter 13 “Seismic design requirements for nonstructural components” from [1] and chapter A.8 “Seismic design requirements for structural elements that not be part of the principal seismic resisting forces system” from [6]. An individual analysis of this supporting structure shall be developed. The reactions due to gravitational loads shall be included in the complete model of the structure to avoid high modes of vibrations.

4. Case of Study

4.1 General considerations

The case of study presented in this paper correspond to a long span metal building. The total length is 124 m and 62 m in the transverse and longitudinal direction. The typical spans are 30 m and 14 m in the transverse and long direction respectively. The total height of the structure is 20 m an in the eave is 10 m. The roof has an average slope of approximately 16%. The structural system considered are steel MRF in the transverse-direction and steel OCBF in the longitudinal-direction. The structure is located in intermediate seismic zone and wind zone 2 with wind speed of 22 m/s (80km/h) and exposure category C. The structure is classified as partially enclosed building. The foundation system is a deep foundation formed by a group of individual piles for each column. The roof system is formed by a sandwich light sheet. The exterior walls are attached to the structure and has the same material than the roof system. The Building codes considered for the design are [1, 4-6]. The soil profile corresponds to seismic design category D for the [1, 6] Building codes. The material is steel A572 Gr 50. The total self-weight for the structure is 0.62 kN/m^2. Fig. 2 presents the geometry configuration of the structural system.



Legend	Color	Section shape
C1		I360X930X15X9
C2		H400X19X600X12
C3		H400X32X600X12
C4		W24x84
V1		I360X15X1230X12
V2		I360X19X1240X12
V3		I360X930X15X9
V4		HSS18x6x4
V5		HSS20x8x6
VB1		TU8x8x8

Fig. 2 – Geometry configuration of case of study

The loads values considerations for the analysis are presented in the Table 1.

Table 1 – Loads considerations for the case of study

Item	Load type	Load value
Roof panel sandwich t = 50 mm	Dead load	0.15 kN/m^2
Electrical and illumination system	Dead load	0.05 kN/m^2
Fire protection network	Dead load	0.05 kN/m^2
Girders	Self-weight	0.10 kN/m^2
Additional steel structure	Self-weight	0.50 kN/m^2
Racks	Self-weight	0.23 kN/m^2
Total roof load	Dead load	1.08 kN/m^2
Roof live	Live load	0.50 kN/m2
Snow	Live load	1.00 kN/m2

The seismic resisting force system selected for the structure was steel OMF for the transverse-direction and steel OCBF for the long-direction. The response-modification factor R = 2.0 for steel OMF was selected from the reference document [8]. The structural system is allowed in intermediate seismic zones with height limit until 30 m. The detailing requirement are minimum and shall comply with chapter F.2 from [6]. The response-modification factor R = 1.5 for steel OCBF was selected from [1, 8]. The structural system is allowed in intermediate seismic zones and has unlimited height limit. The detailing requirements are minimum and shall comply with chapter F.2 from [6] and [4] for the [1]. The maximum value of R is the 1.25 times the R value of the other direction [6]. Then, R = 1.88 for transverse direction.

Fig. 3 presents the design response-spectrum considered for the analysis. The design response-spectrum is obtained from [6]. The importance factor defined is 1.10.

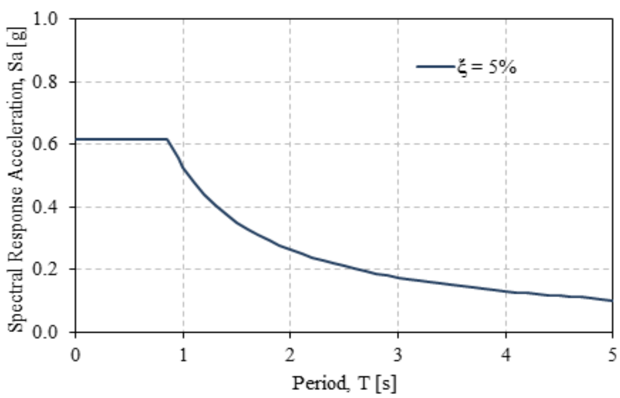


Fig. 3 – Design response-spectrum

4.2 Results

The analysis was conducted using the software RISA 3D. For these case of study, the wind forces do not control the design of the Main Wind-Force Resisting System. The design is controlled by the seismic forces. The maximum vertical deflection ratios are 0.88 and 0.57 for the purlins and roof beams. The maximum inter-story drift value obtained from the analysis is 0.61% and 0.48% in the transverse and longitudinal direction respectively. The maximum over strength ratios values are 0.99 for principal beams and columns, 0.60 for purlins, 0.78 for secondary beams and 0.68 for braces.

4.3 Lateral torsional buckling analysis

The LTB analysis is conducted for a typical steel OMF in the transverse direction. A detailed model of finite elements composed by area elements are developed using the software SAP2000 V17. The model is considered fixed supported at base. All loads are applied over the elements as punctual and distributed loads. The stiffness of the longitudinal OCBF and roof girder beams are included as linear elastic springs. The LTB is conducted with the buckling load for gravitational loads and seismic loads independently. Second order effects are considered. Fig. 4 presents the geometry of the model developed for the LTB analysis.

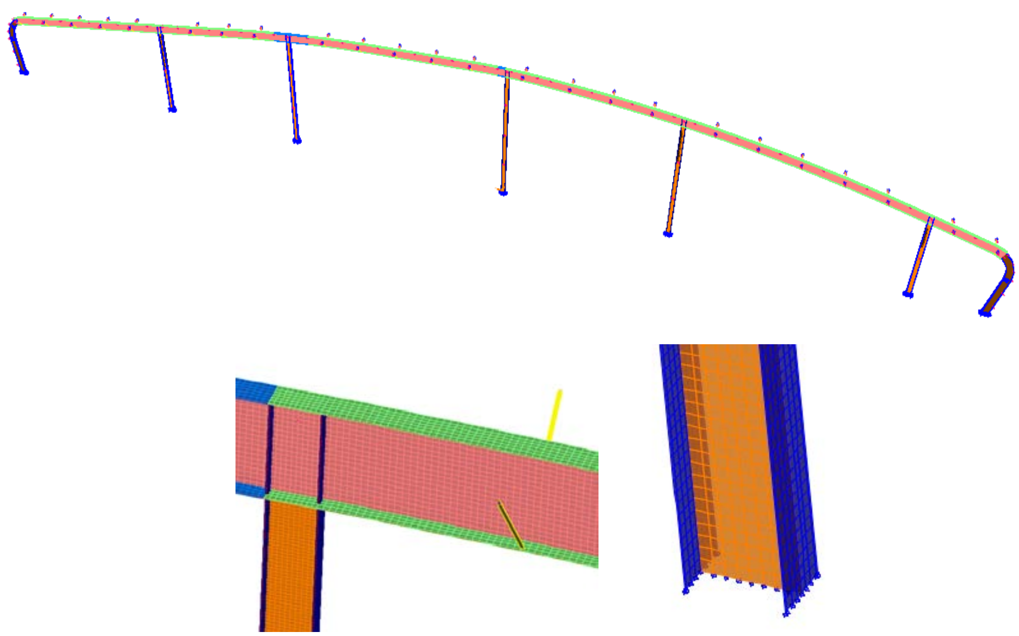
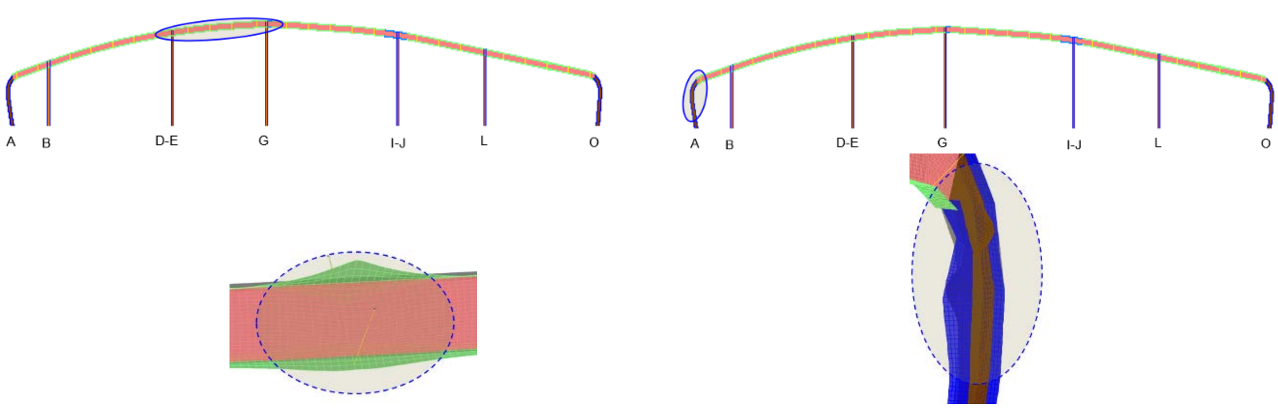


Fig. 4 – Model for lateral torsional buckling

The results from the analysis determines a minimum factor of 2.1 and 2.4 for ultimate gravitational loads combination and full seismic loads. Fig. 5 presents the principal modes for the LTB.



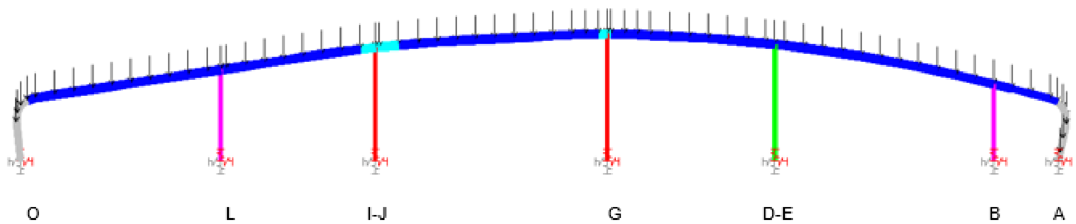
(a) (b)

Fig. 5 – Principals modes for lateral torsional buckling due to (a) gravitational loads, (b) seismic loads

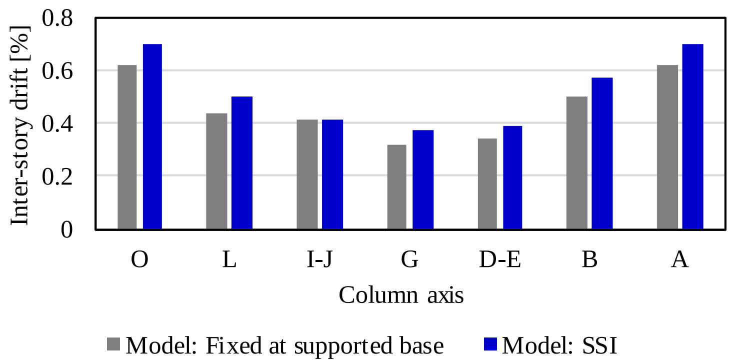
4.4 Soil-structure-interaction analysis

The SSI analysis is conducted for a typical steel OMF supported with linear elastic springs. The stiffness of foundation considers translational and rotational linear spring for each direction. Analyses are conducted in software ALLPILE and SAP2000 V17 to obtain the stiffness of the translational and rotational linear spring for each degree of freedom.

Fig. 6 presents the results for the deformed shape for seismic load in a typical steel OMF.



(a)



(b)

Fig. 6 – Inter-story drift results (a) typical steel OMF, (b) inter-story drift results

The maximum inter-story drift obtained from the analysis is 0.7%. The results of the analysis including the SSI shows an increment of 13% of the horizontal displacement respect to the fixed supported at base model. This value is conservative and not compromise the stability and integrity of the structure. The forces acting on the elements decreased in 5% of the fixed supported at base model.

5. Conclusions

The seismic design of long span metal buildings requires a set of specific considerations in order to fulfill the basic requirements of building codes. The principal considerations of seismic design are presented in Fig. 8 as a guideline. The principal considerations are divided in three groups, that corresponds to process of the design for these type of structures. For each group is presented the specific considerations and recommendations to fulfill with the requirements of applicable building codes.

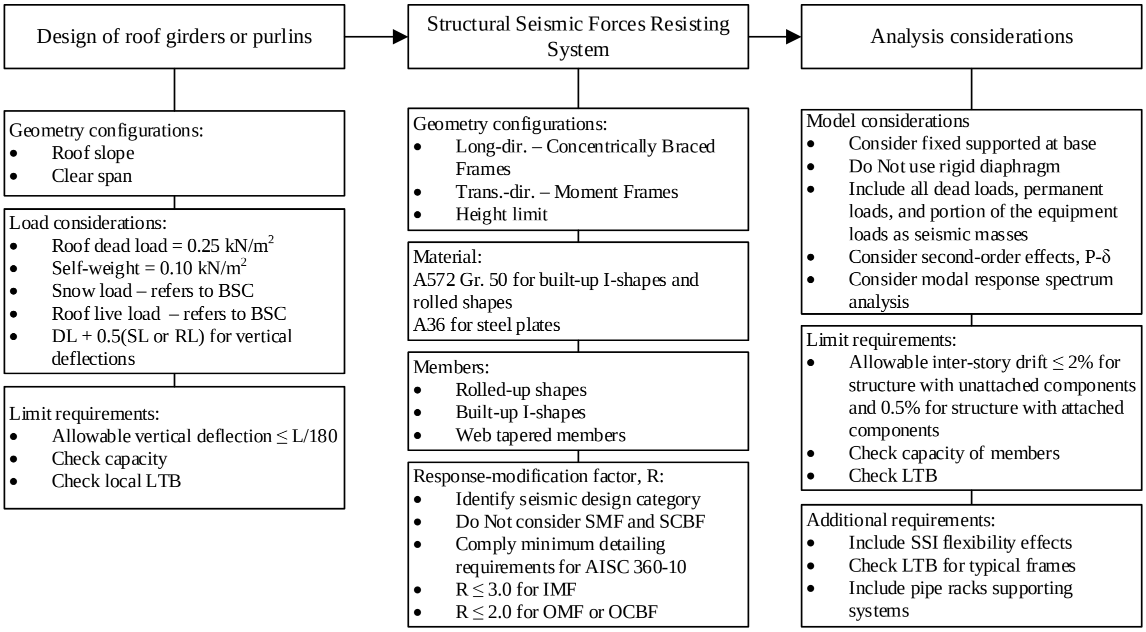


Fig. 7 – Guideline process for the seismic design considerations

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