IOP Conference Series: Materials Science and Engineering

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To cite this article: V H Sobrado *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **910** 012001

Analysis of seismic bidirectionality on response of reinforced concrete structures with irregularities of l-shaped plan and soft story

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Abstract. The seismic design of buildings is usually performed using one-way analysis for each of main axes independently. However, seismic events have fairly random behaviour and impose bidirectional solicitations on structures. In this work, the study of the response in structures subjects to earthquake loads with irregularity of l-shaped plan and soft story is carried out. For this, the linear time-story analysis (LTHA) of these has been carried out imposing seismic solicitations in two orthogonal directions. Thus, the structural response with incidence angle variations of 10° is obtained and compared with the response derived from the unidirectional analysis. Variations of up to 50% and 72% are obtained for model structures with l-shaped plan and soft story respectively.

1. Introduction

There are many countries that are exposed to the risk of a large seismic event, especially those located in the Ring of Fire. History shows that these events have produced economic and human losses, for example, in Armenia 1999 (Colombia), Pisco 2007 (Peru), Maule 2010 (Chile), Salta 2015 (Argentina) and Muisne 2016 (Ecuador) [1]. The earthquake in Puebla 2017 (Mexico) caused the collapse of a building, not because of design problems or soil-structure interaction, but because of seismic directionality, since the response obtained were greater than those calculated with unidirectional seismic analysis [2]. Thus, it's necessary that the seismic design of buildings is carried out considering the nature of seismic events, in this way the behaviour of models will be closer that of actual structures.

A large part of seismoresistant design codes indicate that the study of structures must be carried out by means of unidirectional seismic analysis on each main axis independently; However, this consideration isn't correct, since seismic movements are two-dimensional phenomena in the horizontal plane and have a random behaviour [3]. An important question of structural dynamics is whether the answers calculated with the traditional analysis are like the most accurate answers obtained considering the seismic bidirectionality. An important question of structural dynamics is whether the response calculated with the traditional analysis is like the most accurate the response obtained considering the seismic bidirectionality. In this regard, Kostinakis et al. [4] studied the influence of the angle of incidence in symmetrical buildings relative to their structural axes. They noted that the maximum response doesn't depend on the angle in symmetrical structures with equal stiffness in the two orthogonal directions; instead, the angle is influential in buildings that have different stiffness in their structural axes. On the other hand, Magliulo et al. [5], Cantagallo et al [6], Armaloo and Emami [7] conducted studies of the seismic behavior of irregular structures in plane. Results show that the angle of incidence significantly influences the response of the structures. In turn, Heredia and Machicao [8] developed a study of the structural demand of torsionally rigid and flexible models. The increase in response is greater in torsionally flexible models and increases with the degree of irregularity. These investigations show that the response of structures is influenced by the seismic bidirectionality.

This study considers two types of three-level reinforced concrete (RC) structures, one with l-shaped plane irregularity and other with soft story irregularity. First, the Response Spectrum Analysis (RSA) is performed, according to the traditional process indicated by the seismic design codes [9-11]. Second, LTHA is performed considering seismic bidirectionality with incremental incidence angles of 10°. Finally, the variation in interest response obtained by both types of analysis is analysed.

2. Methodology

2.1. Analysis methodology

The development of the present investigation considers two types of analysis, one to analyse the structures considering the seismic unidirectionality and the other to carry out the study of the seismic bidirectionality. On the one hand, RSA is performed, considered within many seismoresistant design codes. This traditional method performs the analysis unidirectionally on the orthogonal x and Y axes independently using elastic pseudo-acceleration spectra and damping factor C-0.05 [12]. LTHA is performed in accordance with Equation 1 using the modal combination method and transient time functions, as it is suitable for seismic solicitations [13].

$$\boldsymbol{k}x(t)+\boldsymbol{c}\dot{x}(t)+\boldsymbol{m}\ddot{x}(t)=\boldsymbol{r}(t) \tag{1}$$

Where:

$\boldsymbol{m}$, $\boldsymbol{c}$ and $\boldsymbol{k}$ represent the mass, viscosity, and stiffness matrix of the structure respectively.

$\ddot{x}(t)$, $\dot{x}(t)$ and $x(t)$ represent the acceleration, velocity, and displacement of the structure respectively.

$r(t)$ are external forces that occur according to the passage of time.

In this one bidirectionality is considered, so solicitations are imposed in two directions perpendicular at the same time. These solicitations are studied for incidence angles with variations of 10°. The minimum seismic records to be used are three; these must be corrected by signal filtering and baseline, further, scaled according to the seismic parameters of the zone [14]. In addition, the structural models to be used are RC, framed structural system, and levels between three to four floors.

2.2. Consideration of seismic bidirectionality on structure response

Bidirectionality influences design seismic responses and can be a source of structure collapse [2]. The seismic responses that are calculated are at a global level and then the following equation is presented which considers a factor of amplification by bidirectionality to the responses calculated by unidirectional analysis.

$$R_f=KR_0 \tag{2}$$

Where, R_f is the final response that considers the bidirectionality in one axis, R_0 is the response that is obtained from the unidirectional seismic analysis in each axis and the K factor depends on the type of irregularity of the building and the response to be obtained; these factors are presented in results.

3. Results

3.1. Structural Models

To validate this study, we will consider two structures whose configurations have l-shape plane (model 1) with a mezzanine height on the first level of 4 m and the following 3 m, and the other with soft story (model 2) with a height of the first level of 4.5 m and the following 3 m. These structures correspond to common buildings in Lima. Soil with shear wave propagation speeds between 500 m/s and 1500 m/s is considered. The structural elements of both structures have sections of 45x70 cm2 the columns and 30x60 cm2 the beams. The study models are shown in figure 1.

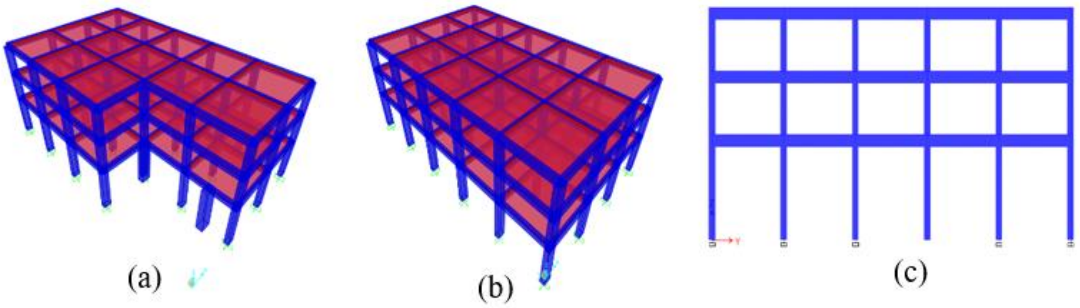

Figure 1. Model 1 with l-shaped plane irregularity (a), Model 2 with soft story irregularity (b) and Model 2 elevation (c).

3.2. Seismic solicitations

The following pseudo-acceleration spectra were used in RSA for the model and for each structural axis, this is shown in figure 2.

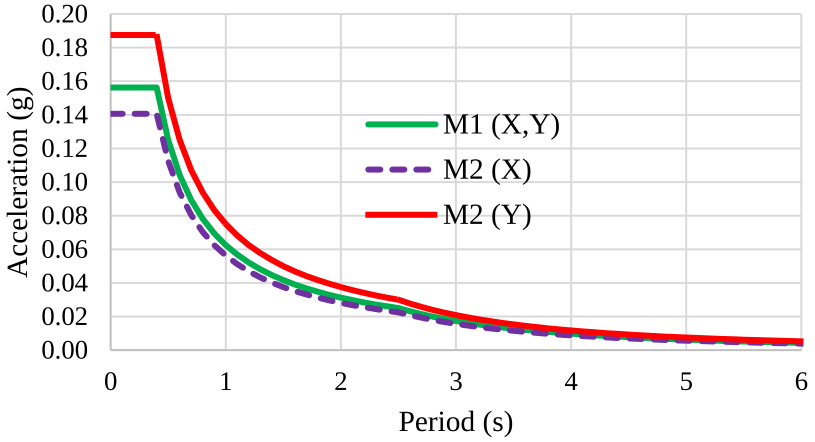

Figure 2. Pseudo-acceleration Response Spectrum

In LTHA, three seismic records of the Parque de la Reserva station, Cercado de Lima, Lima (latitude: -12.70, longitude: -77.04) are used. The following figure 3, figure 4 and figure 5 show the mentioned accelerograms:

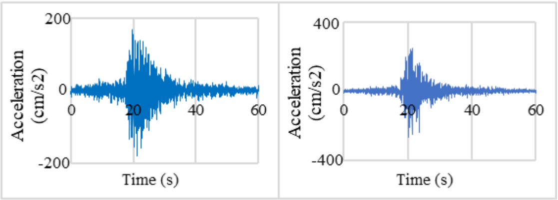

Figure 3. Accelerogram 1996 (EW, left and NS, right)

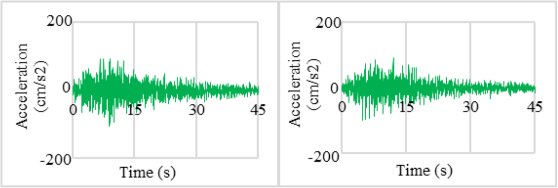

Figure 4. Accelerogram 1970 (EW, left and NS, right)

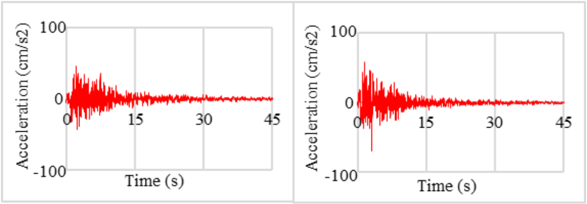

Figure 5. Accelerogram 1974 (EW, left and NS, right)

3.3. Basal shear

Figure 6 and figure 7 show variations of the basal shear as a function of the seismic incidence angle. These have been obtained with two types of analysis (RSA and LTHA). In model 1, it's observed that in the X axis there are variations of up to 31.61% (0°) and in the Y axis there are variations up to 49.67% (40°). In model 2 there are variations of 72.39% (130°) in the X axis and 18.77% (10°) in the Y axis.

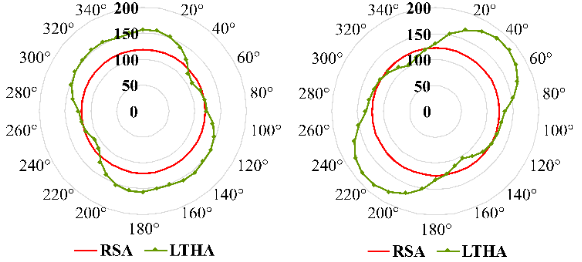

Figure 6. Basal shear (t) of Model 1 (X-axis, left and Y-axis, right).

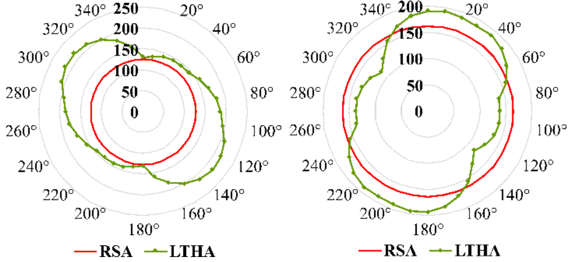

Figure 7. Basal shear (t) of Model 2 (X-axis, left and Y-axis, right)

3.4. Bending moment

Like the basal shear, the bending moment is analysed. In model one (figure 8), variations of up to 45.91% (40 °) and 32.15% (130 °) were calculated on the X and Y axes respectively. Also, in model 2 (figure 9) there were variations of 20.99% (10 °) on the X axis and 69.24% (130 °) on the Y axis.

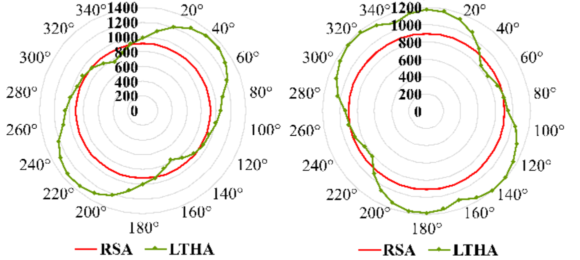

Figure 8. Bending moment (t-m) of Model 1 (X-axis, left and Y-axis, right).

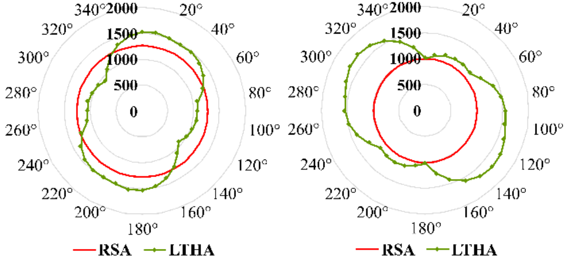

Figure 9. Bending moment (t-m) of Model 2 (X-axis, left and Y-axis, right).

3.5. Lateral displacement

Following figures show lateral displacements in the first level that are taken for each structure analysed. In model 1 (figure 10), variations of up to 31.13% (0 °) can be observed in the X axis and 48.59% (40 °) in the Y axis. On the other hand, in the model 2 (figure 11) are presented variations of up to 71.52% (110 °) on the X axis and 18.95% (190 °) on the Y axis.

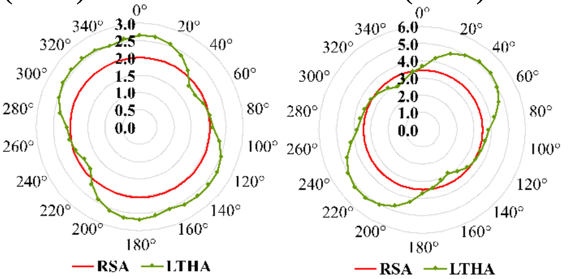

Figure 10. Lateral displacements of first floor (mm) of Model 1 (X-axis, left and Y-axis, right).

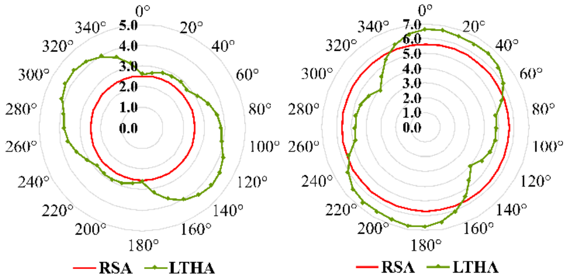

Figure 11. Lateral displacements of first floor (mm) of Model 2 (X-axis, left and Y-axis, right).

With displacement results obtained for each level, drift control has been carried out in accordance with FEMA 356 considerations for reinforced concrete structures [11].

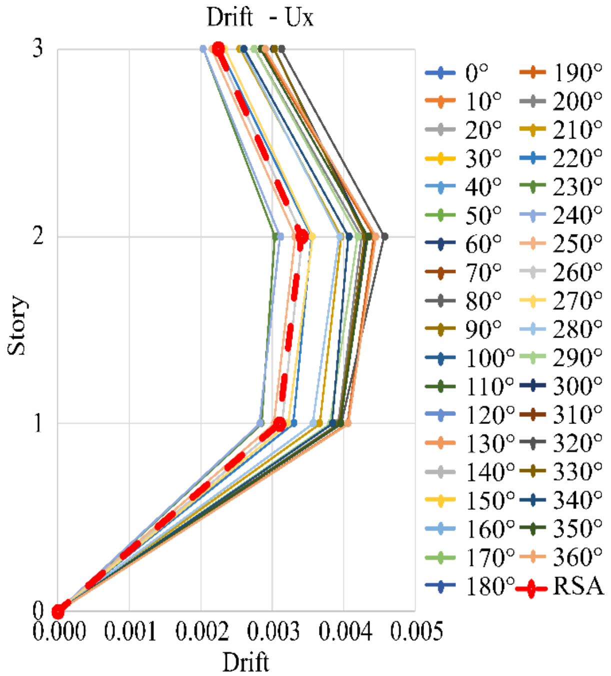

Figure 12. Model 1 drifts, X-axis.

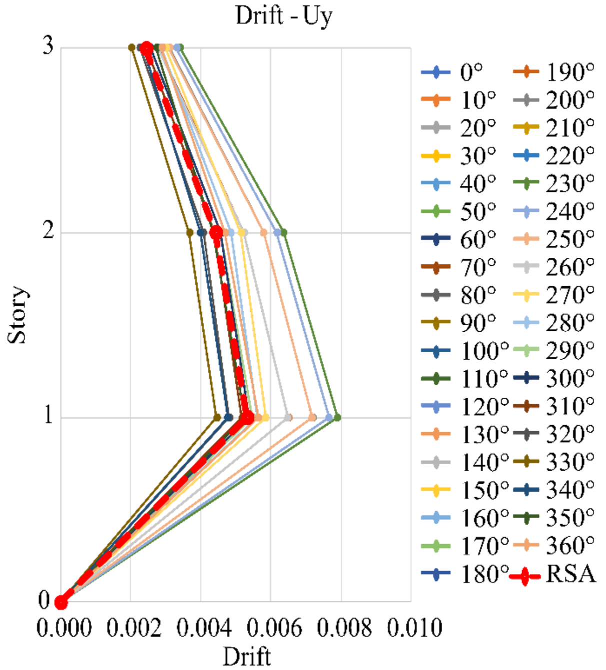

Figure 13. Model 1 drifts, Y-axis.

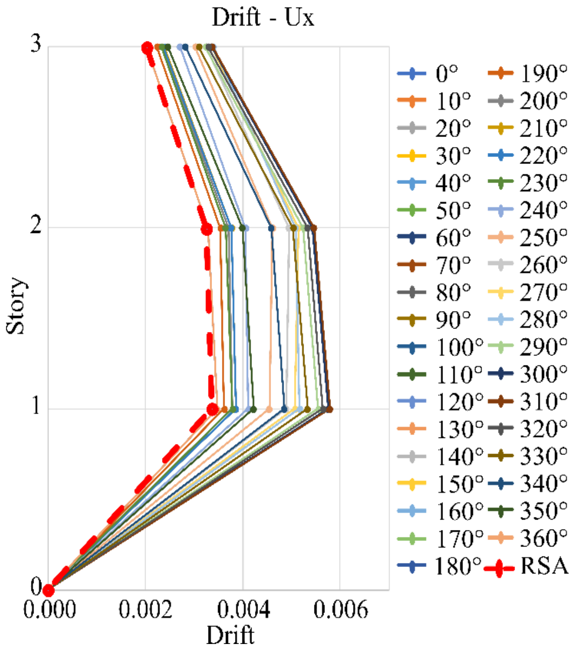

Figure 14. Model 2 drifts, X-axis.

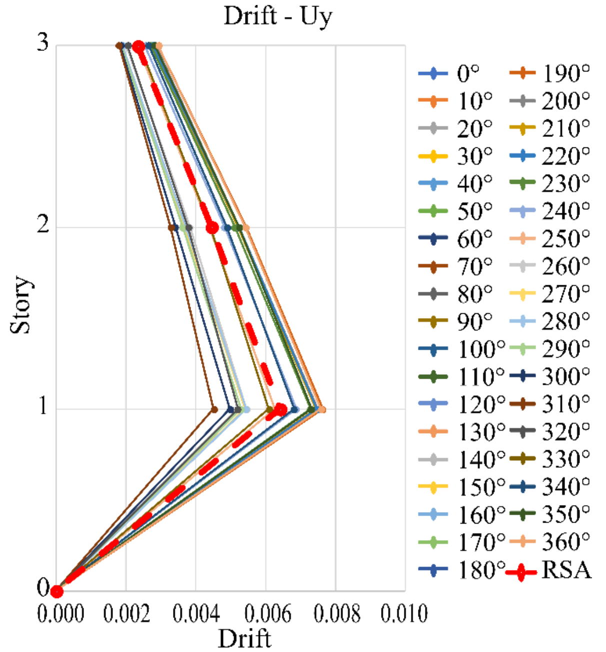

Figure 15. Model 2 drifts, Y-axis.

In the figure 12, figure 13, figure 14 and figure 15 can be observed that in most of the incidence angles analysed the obtained drifts exceed the mezzanine distortion limit obtained according to the RSA. The case of the X resistant axes for both models these don’t exceed the seismic performance limit (0.007), since they have been conservatively designed, but in the Y-resistant axes for the two models in some angles of incidence they don’t comply with said condition.

3.6. Seismic bidirectionality amplification factor

According to results obtained, the following amplification factors by seismic bidirectionality are considered considering the maximum variations obtained for the studied responses. For structures with irregular incoming corner the factor K is 1.5 and for structures with irregular soft floor K is 1.7. The factor K is applicable for responses such as displacements, basal shear and bending moment.

4. Conclusions

The unidirectional analysis doesn’t reflect the most exact responses of buildings, since the maximum responses obtained aren’t presented in the axes that are commonly analysed; that is, responses calculated with the unidirectional analysis underestimate actual responses of structures. The effect increases as structures present a greater degree of irregularity within their configuration, as is the case with the l-shaped plane compared to the soft story model, in which variations of up to 50% and 72% respectively are obtained. In view of this, it’s necessary to include a factor for increasing global responses in order to consider the seismic bidirectionality in responses calculated through the unidirectional analysis. For structures with l-shaped plan irregularity the factor K is 1.5 and for structures with soft story irregularity the factor K is 1.7. These factors by seismic bidirectionality are applicable to structures with types of irregularity studied. For future investigations it’s recommended to analyse buildings considering mass irregularity or vertical discontinuity in structural elements taking into account the seismic bidirectionality.

5. References

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