EMPIRICAL ESTIMATION OF ACCIDENTAL TORSION USING SEISMIC RECORDS FROM 76 SYMMETRIC-PLAN BUILDINGS

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Abstract: *Accidental torsion is a phenomenon observed in symmetric-plan buildings subjected to ground motions, wherein the building edges undergo dissimilar displacements. This behavior can be attributed to the rotational excitations at the building base and irregular distributions of mass, stiffness, or strength within the building. Although accidental torsion was heavily researched in the 1990s, many questions still remain due to its inherent uncertainty. Building codes address accidental torsion by either applying a torsional moment at the floor center of mass (C.M.) or by moving the C.M. by 5% of the building dimension. However, these methods have not been extensively tested and may lead to different results. To approach these issues, this study examines accidental torsion of symmetric plan buildings through three phases. The first phase involves estimating an empirical relationship between the percentage increase in displacements (P.I.D.) due to accidental torsion and the coupled frequencies ratios of 76 buildings using data from approximately 600 ground motions, which can be accessed on the CESMD (Center for Engineering Strong Motion Data) website. The second phase uses artificial intelligence models to obtain an empirical correlation between the P.I.D. with the eccentricity at the C.M. (or torsional moment) for thousands of hypothetical cases. The third phase aims to verify code requirements using a probabilistic framework based on the results of the first two phases. This paper primarily focuses on the first phase of the study and compares the empirical relationship between the P.I.D. and coupled frequencies ratios. The proposed relationship follows the same trend as previous studies, but benefits from using coupled frequency ratios and data from 600 records in 76 buildings. Furthermore, the study evaluates whether building properties, such as material, structural system, and spectrum ratio, are related to the P.I.D. Additionally, this study empirically reaffirms the relationship between P.I.D. and the rotational-to-traslational frequency ratio.*

1. Introduction

Torsion around a vertical axis is a critical action for the seismic design of buildings because it increases the seismic demands on components located far from the center of mass. In general, there are two types of torsion: natural and accidental. Natural torsion is due to the eccentricity e_n between the center of mass and the center of rigidity of building diaphragms. Data recorded from previous earthquakes have demonstrated that even for cases where e_n is theoretically zero, displacements at the two edges of a building show an important torsional component suggesting that an additional eccentricity e_a should be considered. This unexpected increase in eccentricity has been usually called "accidental torsion". The theoretical estimation of accidental torsion is not practical because this unforeseen rotation is due to many uncertainties including the mass and stiffness distribution of structural and nonstructural components, as well as the incidence of torsional ground motions at the building base.

In 1961, the Uniform Building Code (International Conference of Building Officials, 1961) stated that a building should be capable of resisting a torsional moment equivalent to the story shear acting with an eccentricity of not less than 5% of the maximum building dimension at that level. Since then, for symmetric-plan buildings, American building codes require to include the effects of accidental torsion by either applying an static torsional moment at the center of mass (calculated as the seismic force multiply by an eccentricity e_a equals to 5% of the maximum building dimension) or by shifting the center of mass of the building an eccentricity e_a. In 1969, Newmark developed some rational basis for determining torsional earthquake effects in symmetrical buildings arising from earthquake wave motions. He concluded that e_a varies almost directly with the fundamental frequency of the building and with the transit time of the earthquake wave motion. His research suggests that e_a may be larger than 10% of the maximum diaphragm dimension for buildings with fundamental frequencies above 2 Hz. Since then, several studies have suggested alternative approaches to address more accurately the effects of accidental torsion in seismic building design. In the 1990s, research conducted at UC, Berkeley led to significant progress on the understanding of this phenomenon. These works proposed a procedure based on the relationship between the expected percentage increase in displacements (P.I.D.) due to accidental torsion and the uncoupled frequencies ratios of the structure (De la Llera & Chopra, 1995). Additionally, they compare this relationship with empirical data from 12 instrumented buildings (Wen-Hsiung et al., 2001). However, the methodology proposed in this investigation was not adopted by building codes due to the difficulty of imposing displacements instead of simply applying a torsional moment or shifting the center of mass. Although existing design codes provide practical procedures to account for accidental torsion, these methods are solely based on experts' opinions and has not been tested or compared against available evidence. In response to this need, this research aims to evaluate accidental code provisions using a three-phases methodology. The first phase is focused on developing an empirical correlation between P.I.D. and coupled torsional-to-traslational frequencies using recorded information from more than 70 buildings. In the second phase, artificial intelligence will be used to obtain a correlation between e_a and P.I.D. values for linear static and dynamic analyses. Finally, with this information, building code provisions will be assessed in the third phase. This paper concentrates on the first phase of the study.

2. Experimental Database Compilation

A short selection of the building database used in this study and their corresponding characteristics is shown in Table 1. The information and seismic records of 492 buildings were extracted from the official website of the CESMD. A filtering process was then applied based on the following two criteria: i) structures with regular configurations in plan and height; ii) structures with complete information. This process resulted in a set of 73 structures, from which a total of 583 seismic records were obtained.

The study analyzed seismic accelerations, displacements, and velocities measured at the base, roof and some intermediate floors. Structural materials include concrete, steel, wood, and masonry. The study evaluated different types of structural systems, classified as wall, frames, and combined structures. Other parameters considered were: number of stories, building heights, floor areas, floor plan dimensions, aspect ratios, and average soil velocity in upper 30 meters (V_{s30}). The floor area typically ranges from 1000-2400 m². Most buildings have between 2 and 7 stories. The structures are mainly located on type D soils.

Table 1. Example of analyzed structures.

Station	Structural system	Material	No. of stories	Heigth (m)	Base Dimensions (m x m)	No. of records	Site
CE03603	Frames	Steel	21	80.8	58.5 x 26.2	4	D
CE12266	Walls	Masonry	2	6.7	29.3 x 29.3	34	D
CE12267	Frames	Concrete	5	14.7	47.5 x 22.7	12	D
CE12284	Frames	Concrete	4	15.3	54.9 x 18.3	20	D
CE12493	Frames	Concrete	5	19.5	27.4 x 64.0	6	D

3. Methodology

This study evaluates accidental torsion in buildings with symmetrical design using the three phases illustrated in Figure 1. The first phase estimates an empirical relationship between the P.I.D. due to accidental torsion and the coupled torsional-to-lateral frequency ratios of 76 buildings. The methodology relies on data obtained from approximately 600 ground motions available on the CESMD website. In the subsequent phase, artificial intelligence models are utilized to identify an empirical correlation between the P.I.D. and the eccentricity at the center of mass (or torsional moment) across thousands of hypothetical scenarios. Finally, the third phase aims to evaluate code requirements through a probabilistic approach rooted in the outcomes of the first two stages. For the first phase, Matlab scripts were developed to conduct the calculation of fundamental frequencies and modes and percentage increase in displacements.

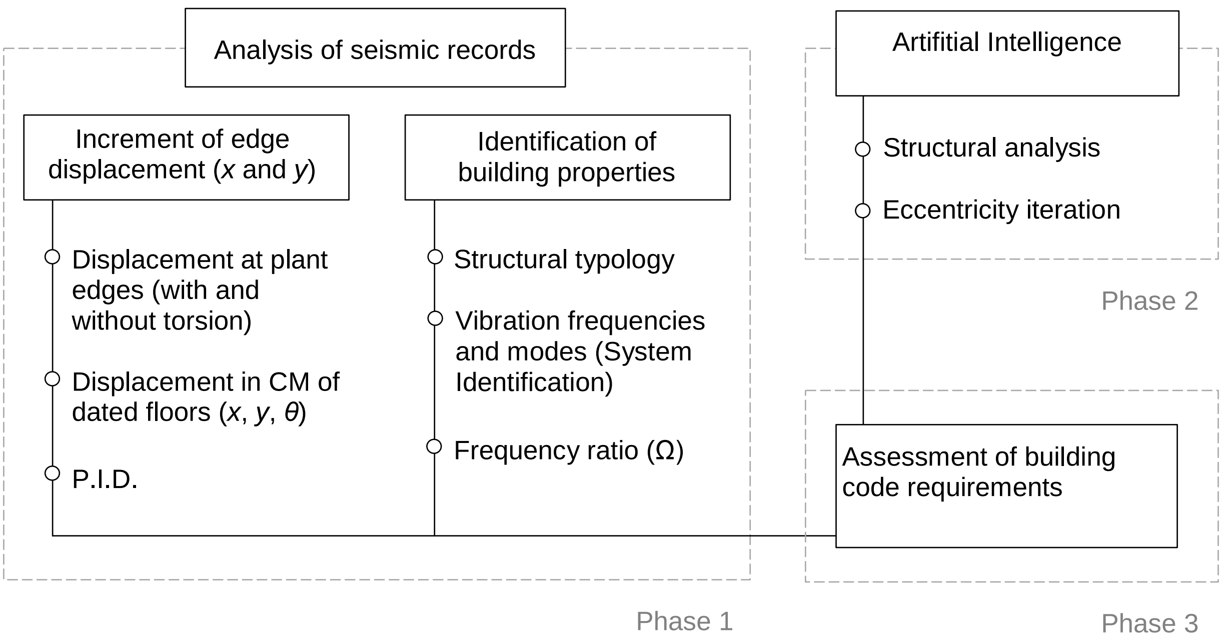

Figure 1. General research methodology.

3.1. System identification

Fundamental frequencies are determined for each of the buildings analyzed using three system identification methods based on the input measurements (accelerations at the base of the building) and the output responses (accelerations at the instrumented floors). These methods include: general subspace identification, stochastic covariance subspace identification, and frequency domain decomposition.

The study primarily utilizes the frequency domain decomposition method to identify the natural frequencies of structures. This approach exclusively employs data that is not derived from environmental vibrations. Its selection is justified by its fast-processing speed, easy implementation, and accuracy in estimating both natural frequencies and modal shapes of structures. General subspace analysis is noteworthy for its capacity to handle systems with unknown or complex dynamics. By utilizing the multivariate nature of the data, this methodology enables precise and efficient estimation of system parameters, despite any present noise or uncertainties. Modal frequencies and shapes of the building under investigation can be identified using this method by analyzing the accelerations recorded during a seismic event. The identification of stochastic covariance subspaces approach offers a reliable way of analyzing systems by characterizing the covariance structure of the data. It serves as a useful tool for identifying modal parameters in situations where there is environmental excitation.

Figure 2 displays the frequencies coupled to the first vibration mode in both translation and rotation modes of an example building. The frequencies are calculated through the three system identification methods explained previously. This graphical representation offers a snapshot of the resulting frequencies and simplifies comparisons between the outputs of the various methods.

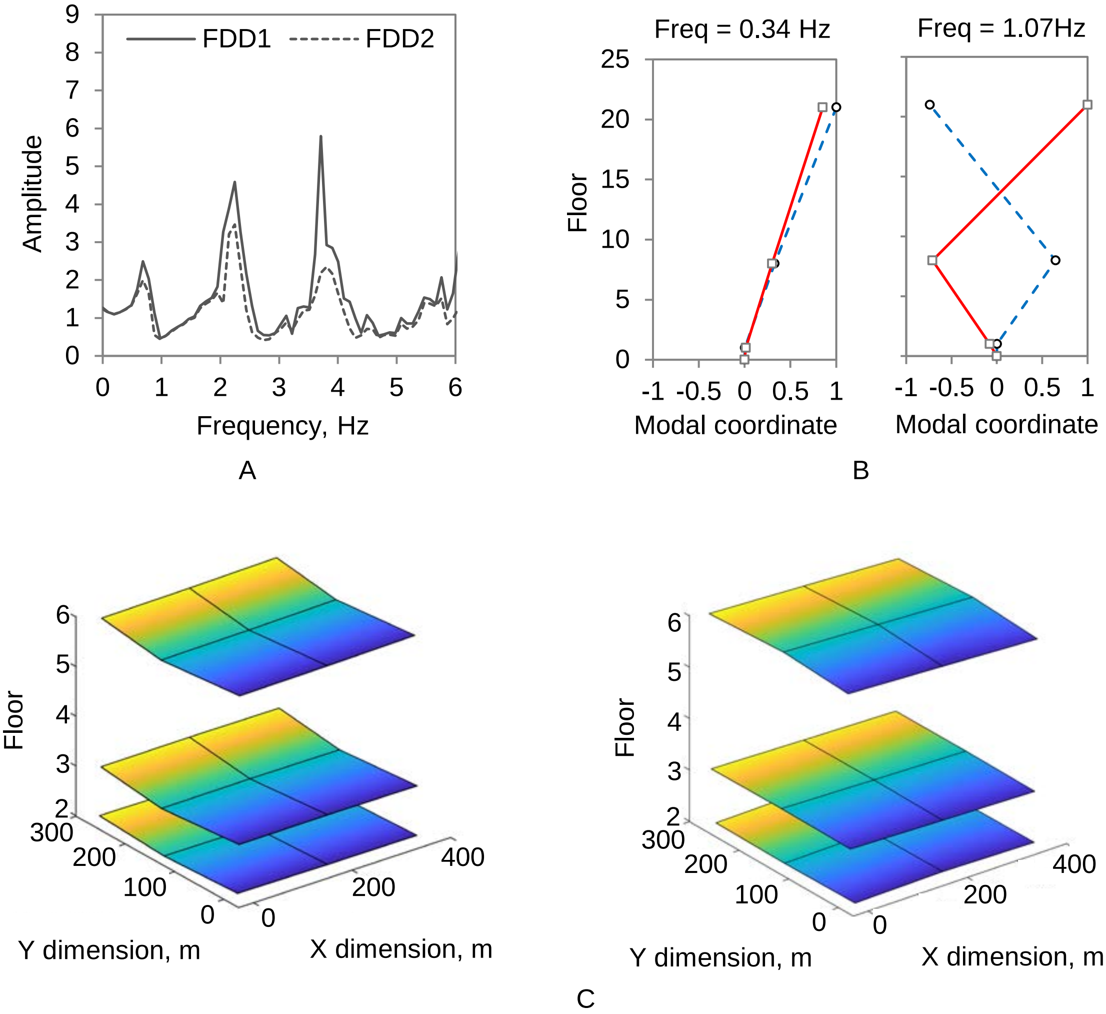

Figure 2. a. Frequency domain decomposition, b. General subspace identification, c. Covariance stochastic subspace identification.

3.2. Percentage increase in displacements (P.I.D.)

Using a reference method from the literature (Wen-Hsiung et al., 2001), the percentage increase in displacements was calculated. First, displacements at the locations of the sensors in both translational and torsional directions (d_x, d_y and θ) were obtained. This phase was conducted on floors equipped with three or more sensors, assuming that the floor diaphragm was rigid. Second, with an understanding of the sensor arrangement and the use of linear interpolation, it was possible to estimate the displacement at the edges of the floor. By interpolating the recorded displacements at the edges of the instrumented floors using a cubic spline curve, it was possible to determine the displacements at the edges of the non-instrumented floors with accuracy. Third, the displacements at the center of mass (CM) for all levels in the building are computed using the equation below (Figure 3):

$$u_{xCM} = \frac{(d_{x1} + d_{x2})}{2} \tag{1}$$

$$u_{yCM} = \frac{(d_{y1} + d_{y2})}{2} \tag{2}$$

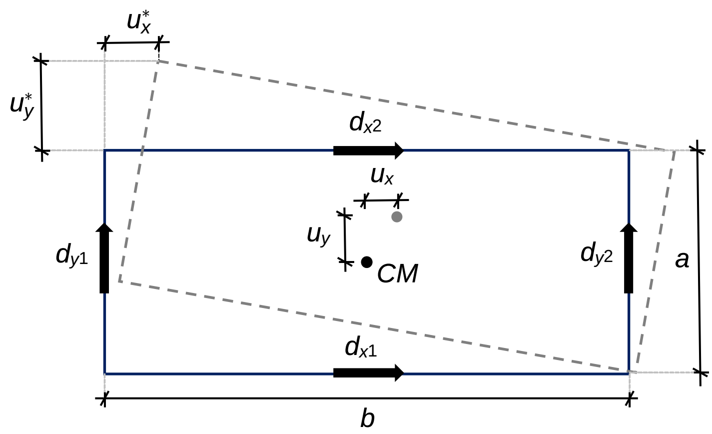

Figure 3. Geometry during rotation of a rigid diaphragm.

Fourth, the displacements including accidental torsion u_x^* and u_y^* are calculated using Equations (3) and (4). With this information, the maximum increases in displacements at the edges of each level over time is estimated reflecting the effects caused by the accidental torsion. The maximum increase in the center of mass displacement over time was determined to represent the impact without the influence of accidental torsion.

$$u_x^* = d_{x1} - d_{x0} \tag{3}$$

$$u_y^* = d_{y1} - d_{y0} \tag{4}$$

Finally, the percentage increase in displacements may be determined using Equations (5) and (6). Figure 4 shows and example of the calculations for one of the buildings studied.

$$PID_x = 100\left(\frac{u_y^*}{u_{xCM}} - 1\right) \tag{5}$$

$$PID_y = 100\left(\frac{u_y^*}{u_{yCM}} - 1\right) \tag{6}$$

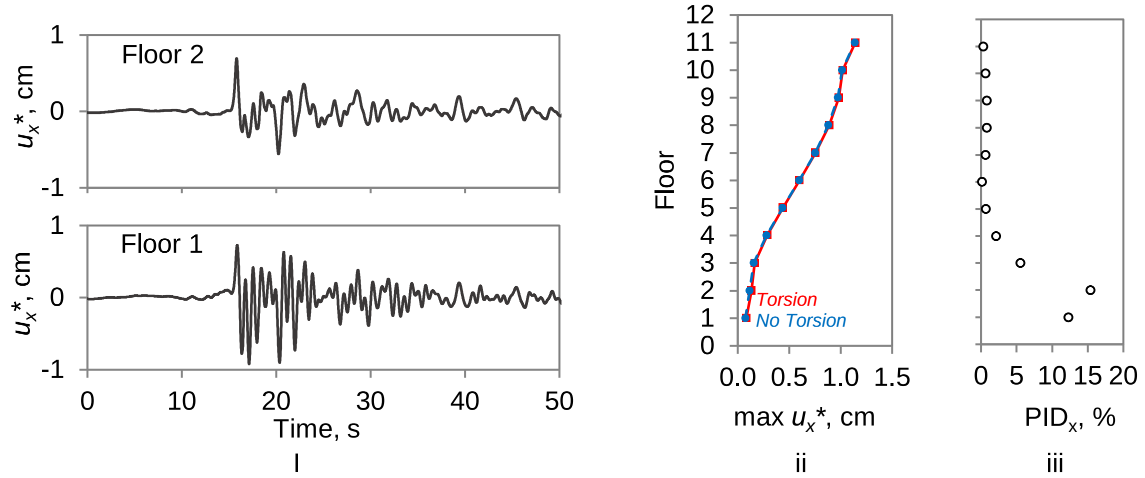

Figure 4. i. Displacements at edges, ii. Peak edge displacements, iii. Normalized displacements.

4. Results

Using data gathered from translational and rotational frequencies and P.I.D. calculations, correlations were established through classification by both material (Figure 5) and structural system (Figure 6). To accomplish this, displacements at both the roof and various levels were evaluated, categorized according to structural typology. The impact of accidental torsion was primarily observed in the roof of most structures, as illustrated in Figure 7. Therefore, the data presented pertains solely to this level. The very high P.I.D. values (larger than 50%) observed in Figures 5 and 6 are currently under investigation because they may be due to structural irregularities not visible from the information available at the source website.

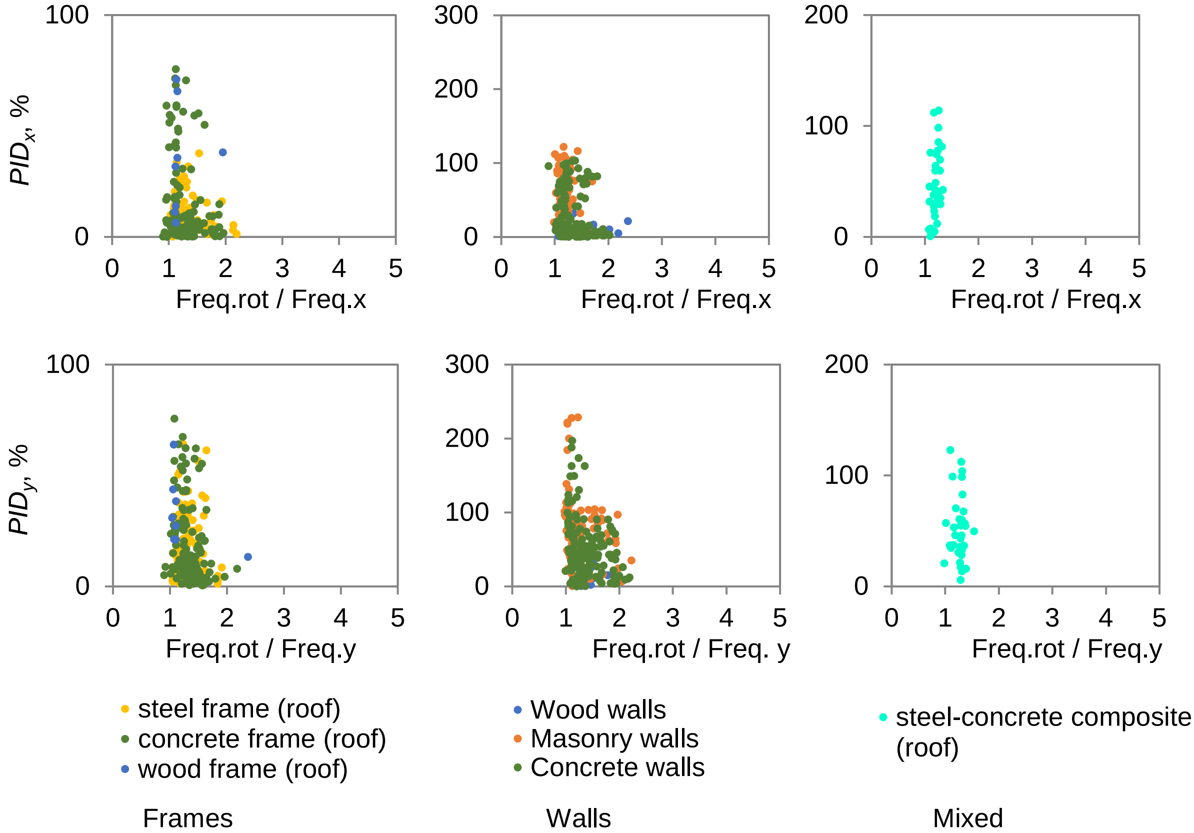

Figure 5. PID (on roof) vs. frequency ratio, sorted by structural system.

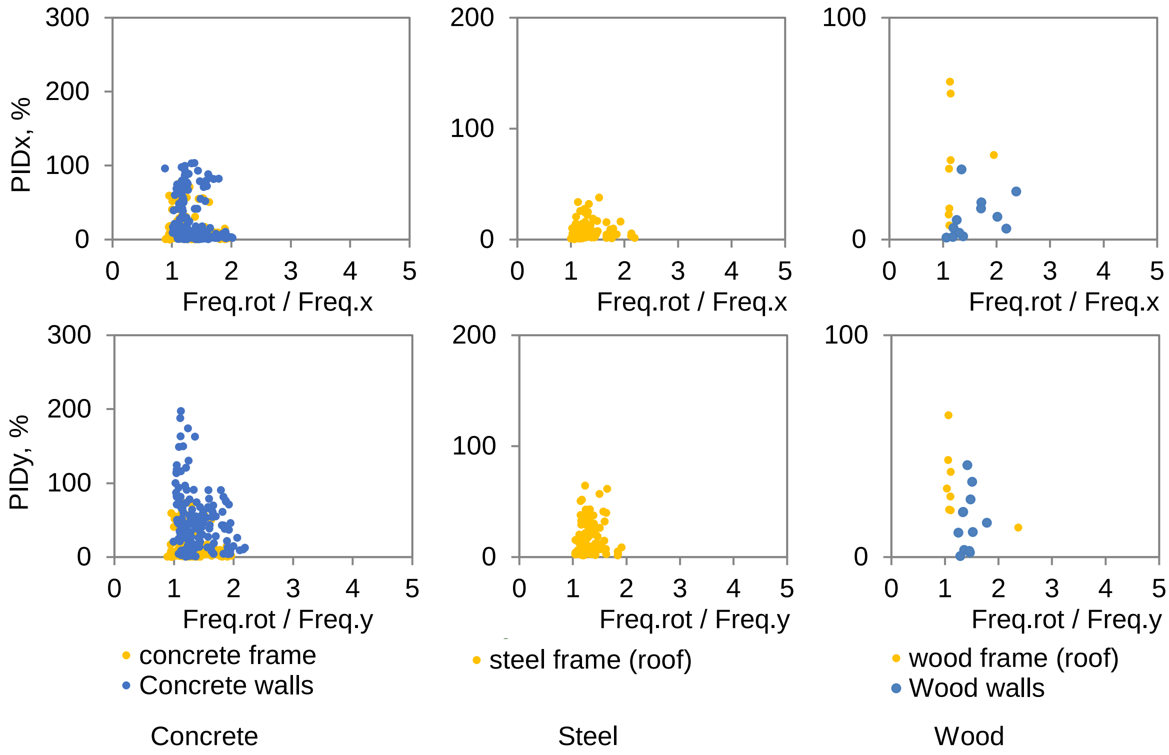

Figure 6. PID (on roof) vs. frequency ratio, sorted by material.

In this study, the accidental torsion levels calculated at the base and roof of all analyzed stations were compared as shown in Figure 7. The primary objective was to examine the impact of base movements on the magnitude of torsion observed at the roof. The purpose of these measurements was to identify potential fluctuations in torsional levels and comprehend the impact of base movements on the building envelope's torsional response.

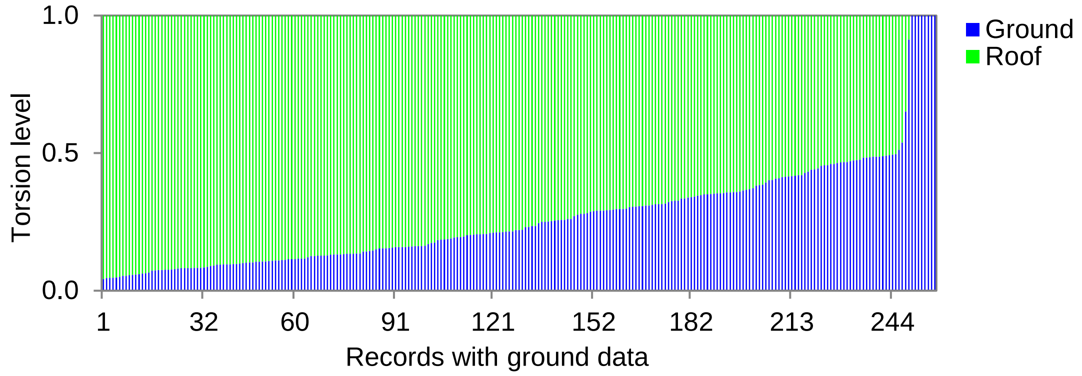

Figure 7. Comparison of the level of torsion in the base and roof of the measured buildings.

The correlation between the height of the structure in both directions and its fundamental period has been confirmed. During this process, the structures were categorized based on their principal materials, including concrete, steel, and masonry (wood was excluded due to an insufficient sample). This classification facilitated a detailed analysis of the behaviors and characteristics of the buildings taking into account their height and construction components. Figure 8 and Table 2 illustrates the correlation between height and fundamental period found in this study, classified by material.

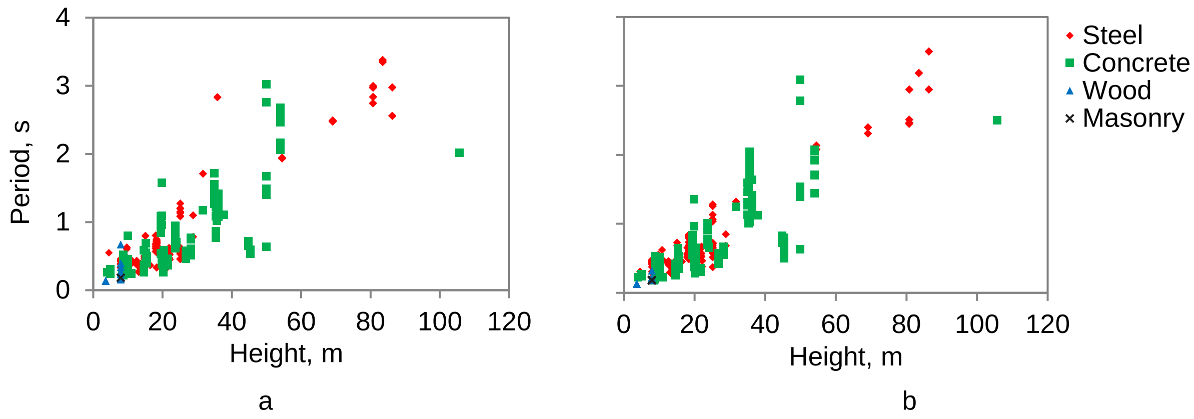

Figure 8. Height vs. fundamental period in: a. X direction, b. Y direction.

Table 2. Regressions to estimate the approximate period based on the height of the building and the material.

Material	**X's regression**	R^2	**Y's regression**	R^2
Concrete	$(0.0463)h^{0.8883}$	0.77	$(0.0441)h^{0.9032}$	0.94
Steel	$(0.0388)h^{0.9533}$	0.98	$(0.0399)h^{0.9504}$	0.98
Masonry	$(0.0430)h^{0.8432}$	0.94	$(0.0487)h^{0.8157}$	0.92

To ensure the study's credibility and rigor, numerous validation strategies with previous research were employed. Specifically, it was conducted an exhaustive comparison between frequency data obtained in this study and the results of Wen-Hsiung et al. (2001). As shown in Figure 11, it was found a minimal variation in frequencies between this study and the previous research. The highest difference observed was 5%, endorsing the reliability and consistency of the findings in this study. The data aligns with earlier research, substantiating the precision and credibility of the outcomes in the study and reinforcing trustworthy and representative conclusions.

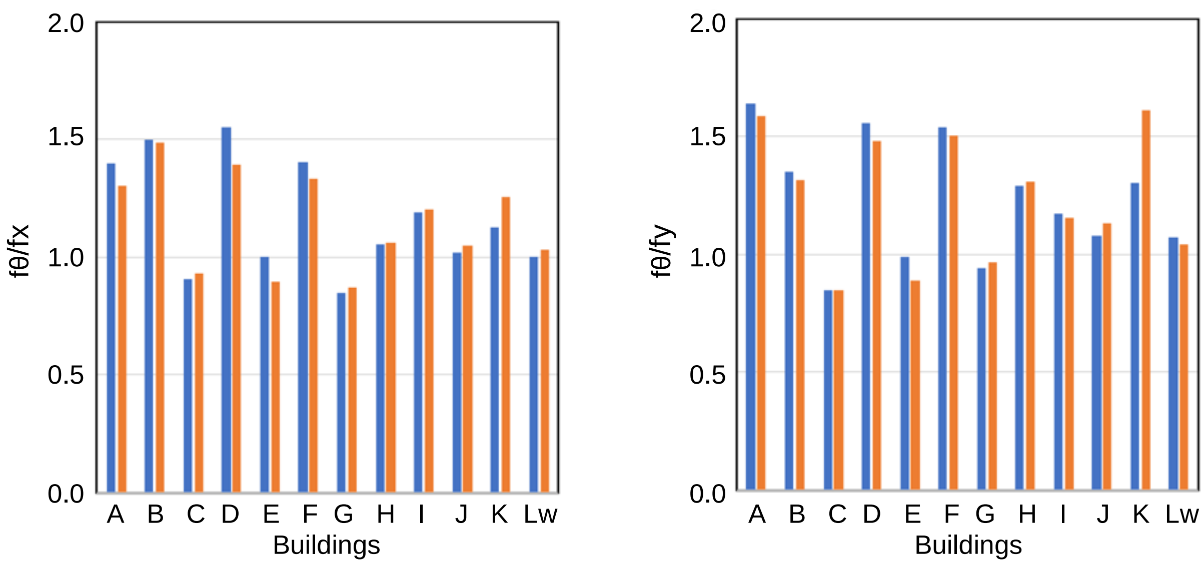

Figure 11. Comparison and validation of frequency ratio calculation.

5. Conclusions

A detailed examination of approximately 600 seismic records was conducted in this study, analyzing a total of 76 specifically chosen structures. The resulting data shed light on key typological characteristics of the structures under investigation, as well as the correlations between natural frequencies and normalized displacements.

Based on the findings, important conclusions were drawn. In agreement with previous research, this empirical study confirmed the inverse correlation between the percentage increase in displacement and the coupled frequencies' ratio. Furthermore, it became clear that there is no direct correlation between the building's material and structural system and the increase attributed to accidental torsion. These results challenge previous assumptions and prompt inquiries into the factors that affect accidental torsion on symmetric structures. Although there is no significant correlation between the type of material, building structural system and the increase in torsion, other variables, like geometric configuration and stiffness characteristics, were observed to have a decisive impact on the effects produced by accidental torsion. These findings underscore the importance of analyzing and addressing multi-faceted aspects of structural design when dealing with the risks linked to accidental torsion in buildings.

The study establishes a direct correlation between the rotational movement at the building base and the rotation recorded on its roof. It is crucial to note that the torsion in the base did not exceed 50% in 95% of the analyzed structures. This suggests that the effect of accidental torsion at the base can vary significantly from one structure to another, highlighting the complexity of the factors contributing to this phenomenon. This suggests that the effect of accidental torsion at the base can vary significantly from one structure to another, highlighting the complexity of the factors contributing to this phenomenon.

Additionally, empirical results reaffirm the correlation between a structure's height and its translational fundamental period. The presented findings endorse the information within current design codes and confirm that the height of a building greatly influences its dynamic characteristics. A detailed proposal was introduced for masonry, concrete, and steel structures (Table 2) to further advance in the design and construction of earthquake-resistant buildings.

In summary, this study has significantly contributed to the analysis of accidental torsion in structures. It is clear that there is an urgent need to continue researching and delving deeper into the factors that contribute to the generation of accidental torsion and its impact on structural behavior. The current findings provide a solid foundation for better understanding the effects of accidental torsion in the design and construction of buildings. However, further research is necessary to develop more precise and reliable methods that facilitate accurate estimation and adequate mitigation of the effects of accidental torsion. This study lays the groundwork for future stages outlined in this report, driving the search for solutions that promote greater safety and efficiency in the design and construction of structures.

6. References

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