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Impact of irregularities in elevation on RC structures according to Eurocode 8

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Abstract: Eurocode 8 is undergoing a revision process encompassing novel ductility classes, damage limitation limits, local ductility conditions corresponding detailing prescriptions and structural irregularity criteria. This work specifically evaluated the impact of irregularity in elevation criterion on structural seismic response.

To evaluate this effect, five moment-resisting frame (MRF) buildings underwent a thorough inspection. Robot Structural study Professional® was used to design those structures in accordance with the current generation of Eurocode 8, and SeismoStruct® software was used to evaluate the structural seismic response. The outcomes were compared to assess the impact of the prEN1998-1-2 expected imposed irregularities in elevation caused by height increase and resistance change.

The study's findings showed that, while not all abnormalities have this effect, DCM buildings showed effects in their structural response because of forced irregularities in elevation.

Keywords: Eurocode 8, irregularity in elevation, seismic response, RC structures.

1. Introduction

Building performance during strong earthquakes has been observed, and this information has been used to instruct engineers and builders on how to properly and improperly construct seismic load-resisting structures. (Verderame et al. 2011; Braga et al. 2011; Palermo et al. 2014). With the evolution of design techniques, engineered structures have performed relatively well in areas that have been inhabited for a long time and are subject to quite regular firm ground shaking. Structural engineers can get a great deal of knowledge about construction materials and techniques by studying such design procedures, even though they are not always appropriate due to regional variances. (Varum et al. 2022).

Several damage mechanisms in buildings have been repeatedly seen and determined to be improperly configured structurally. These include torsion caused by asymmetrical masonry infills, first-story soft-story buildings, and inadequate longitudinal and transverse reinforcement detailing (Jara et al. 2020).

To assess the effect of irregularity in elevation on a structure's seismic response, this paper compares five moment-resisting frame (MRF) buildings. These structures have the same regular plan configuration, but variation on height (from 3m to 6m of height), and non-torsional flexibility.

In the context of this study, the design calculations for DCM structures were performed following the guidelines outlined in Eurocode 8 (CEN 2005a). The draft of Eurocode 8 (CEN 2024) was also considered. The method used is the force-based approach. The force-based approach includes the response spectrum method, a linear analysis incorporating overstrength and non-linear response through the behaviour factor (q). A push-over analysis approach has been applied to the designed structures to assess their seismic response.

2. Object of research and analysis

2.1 Buildings geometry and structural system

The structures in this study consist of one building configuration, all five-storey, as shown in Figure 1 that were developed from the structure studied by (Maranhão et al. 2024). The structural system for the buildings consists of a series of frames with a spacing of 6,0 m on the x-axis and 7,0 m on the y-axis, typical of residential buildings. The floor-to-floor height is 3,0 m for all storeys. The models had their heights increased by 0,5 m to a maximum of 6 meters of elevation on the ground storey or on the 3rd storey. The solid slab thickness is 15.0 cm at each storey. All the structures were designed using Robot Structural Analysis Professional® (Autodesk 2024) and considering Eurocode criteria. Table 1 presents the main geometrical characteristics of each analyzed structure.

Figure 1 – Frame building system configuration.

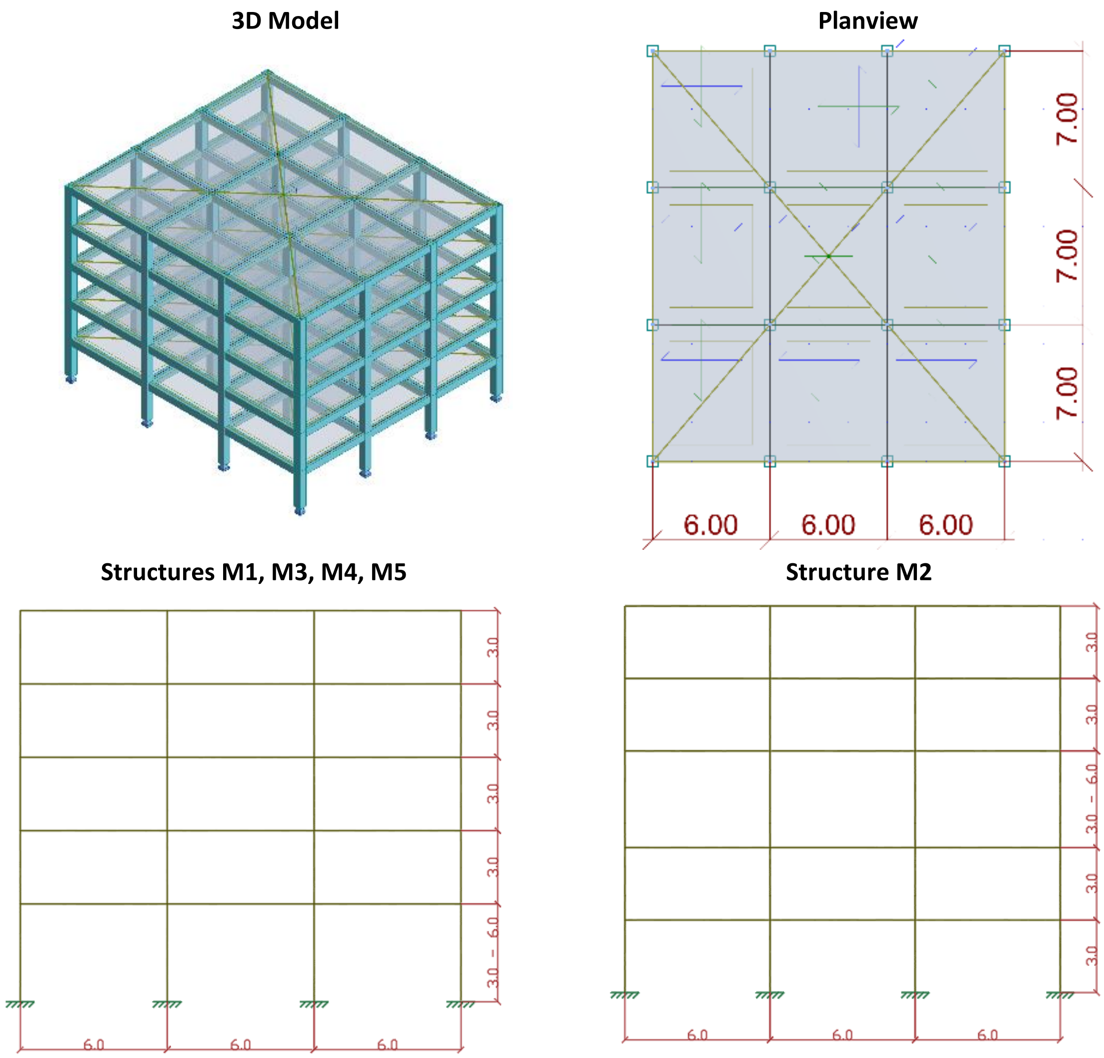


Table 1 – Geometry of the MRF structures.

<table>
<tr><th>Structure</th><th>Storey</th><th>Columns</th><th>Beams</th><th>Slabs height</th><th>Storey elevation increase</th></tr>
<tr><td>M1</td><td>All</td><td>55x55 cm</td><td>40x55 cm</td><td rowspan="10">15 cm</td><td>1</td></tr>
<tr><td>M2</td><td>All</td><td>55x55 cm</td><td>40x55 cm</td><td>3</td></tr>
<tr><td rowspan="3">M3</td><td>Up to storey 2</td><td>55x55 cm</td><td>40x55 cm</td><td rowspan="3">1</td></tr>
<tr><td>Storey 2 to 4</td><td>50x50 cm</td><td rowspan="2">40x50 cm</td></tr>
<tr><td>Storey 4 to 5</td><td>45x45 cm</td></tr>
<tr><td rowspan="3">M4</td><td>Up to storey 2</td><td>55x55 cm</td><td rowspan="3">40x55 cm</td><td rowspan="3">1</td></tr>
<tr><td>Storey 2 to 4</td><td>50x50 cm</td></tr>
<tr><td>Storey 4 to 5</td><td>45x45 cm</td></tr>
<tr><td rowspan="2">M5</td><td>Up to storey 3</td><td>55x55 cm</td><td rowspan="2">40x55 cm</td><td rowspan="2">1</td></tr>
<tr><td>Storey 3 to 5</td><td>45x45 cm</td></tr>
</table>

2.2 Materials

All primary seismic members (beams and columns) of the structures under analysis are considered using the following materials:

- Concrete C30/37.
- Reinforcement steel B500.

The concrete properties are defined per EN 1992-1-1 (CEN 2004) and EN 206-1 (CEN 2007) standards, and its mechanical properties are shown in Table 2.

Table 2 – Concrete mechanical properties.

Mechanical properties of concrete C30/37		
Characteristic compressive cylinder strength of concrete	f_{ck} (MPa)	30
Mean value of concrete cylinder compressive strength	f_{cm} (MPa)	38
The design value of concrete compressive strength	f_{cd} (MPa)	20
Characteristic axial tensile strength of concrete	$f_{ctk,0,95}$ (MPa)	2.0
Mean value of axial tensile strength of concrete	f_{ctm} (MPa)	2.9
Design value of tensile strength	f_{ctd} (MPa)	1.3
Elasticity modulus	E_{cm} (GPa)	33
Ultimate compressive strain in the concrete	$e_{cu,1}$ (‰)	3.5

The nominal concrete cover c_{nom} is calculated by adding to the minimum cover (c_{min}) the allowance in design for deviation Δc_{dev} according to EN 1992-1-1 (CEN 2004). Assuming Exposure Class XC1, related to environmental conditions following EN 206-1 (CEN 2007) as specified in EN 1992-1-1 (CEN 2004), the assumed nominal cover c_{nom} is 30 mm. The steel reinforcement utilized in this study is classified as B500, and its mechanical properties are characterized according to EN 10080 (CEN 2005b), as presented in Table 3.

Table 3 – Reinforcement steel mechanical properties.

Reinforcement steel B500		
Characteristic yield strength of reinforcement	f_{yk} (MPa)	500
Mean strength of reinforcement	f_{ym} (MPa)	555
Design yield strength of reinforcement	f_{yd} (MPa)	435
Elasticity modulus	E_s (GPa)	200
Yielding strain	e_{sy} (‰)	2.5

3. Seismic response of designed structures

The software employed for the particular purpose in this research was SeismoStruct (Seismosoft 2021). The software has been extensively quality-checked and validated in scientific environment. It is a Finite Element package capable of predicting the large displacement behavior of space frames under static or dynamic loadings, considering both geometric nonlinearities and material inelasticity (Seismosoft 2022).

The accuracy of this software in nonlinear analysis of framed structures is demonstrated in this report, and has also been laid evident by the successes in recent Blind Test Prediction Exercises, such as 'Concrete Column Blind Prediction Contest 2010' (UCSD, San Diego, USA), '15WCEE Blind Test Challenge' (LNEC, Lisbon, Portugal) and the Blind Prediction Contest organized in 2011 by the "Earthquake Resistance and Disaster Prevention Branch of the Architectural Society of China", where SeismoStruct ranked first amongst tens of entries from around the world (Seismosoft 2022).

It was used a static pushover analysis as a modelling approach. Pushover analysis is one of the methods available for evaluating buildings against earthquake loads. It is utilized to determine the performance of the building under different irregularity conditions (Dya and Oretaa 2015).

Although it is acknowledged that other types of analysis such as the dynamic time-history analysis is more accurate, the preliminary assessment nature of the objective would allow a simple static pushover analysis to be used. Several studies have also utilized this type of analysis in studying irregular buildings (Chintanapakdee and Chopra 2004; Athanassiadou 2008; Dya and Oretaa 2015; Nezhad and Poursha 2015).

4. Results and discussion

4.1 Seismic response demands

Table 4 presents the maximum, minimum, average and standard deviation values of natural frequencies of studied structures. As we can see, structures behave similarly in matter of natural frequency, without much deviation even though the increasing of height.

Table 4 – Natural frequencies.

Data	F_1	F_2	F_3
	(Hz)		
Maximum	2.04	2.12	2.27
Minimum	1.28	1.31	1.43
Average	1.64	1.70	1.84
Standard deviation	0.24	0.25	0.26

Figures 2 and 3 presents the evolution on each floor of all structures, both in X and Y axis.

These figures and tables allow us to make the following conclusions:

- Only M1 structure with 3.0 and 3.5 m of height present regularity in elevation due to reduction of less than 30% of lateral stiffness between storeys, according to prEn1998-1-2 (CEN 2024).
- We can infer that the increasing of height in first or middle storey (which generate soft and weak storey respectively) strongly and negatively impacts the lateral stiffness. The weak storey mechanism produces a stronger impact on this matter than soft-storey structures.
- The reduction of cross-section of the columns also negatively impacts the lateral stiffness.
- It´s important to highlight that, only A5 structure presents a resistance variation higher than 30% in 4th storey. So according to prEn 1998-1-2 (CEN 2024), this represents irregularity in elevation. However, that fact didn't demonstrate a huge difference in lateral stiffness behavior.

Figures 4 and 5 represent the absolute displacement response and storey drift of studied structures, Figure 6 shows de Base Shear of each structure, with each studied height. Table 5 shows the observed maximum displacement and storey drift at each height studied. Figure 7 illustrate the percentage of maximum displacement observed in each structure in comparison with the structures with 3,0 m of elevation.

Table 5 – Maximum displacement and storey drift

Height	Structure	Storey	Displacement (mm)	Height	Structure	Storey	Storey drift (%)
3.0 m	M3	5	197.71	3.0 m	M1	1	3.01%
3.5 m	M2	5	185.72	3.5 m	M1	1	2.68%
4.0 m	M2	5	230.13	4.0 m	M2	1	2.88%
4.5 m	**M2**	**5**	**309.90**	4.5 m	M2	1	2.88%
5.0 m	M2	5	271.58	5.0 m	M2	3	3.38%
5.5 m	M2	5	265.48	5.5 m	M2	3	3.44%
6.0 m	M2	5	280.32	**6.0 m**	**M2**	**3**	**3.58%**

Figure 2 – Lateral Stiffness in X-axis

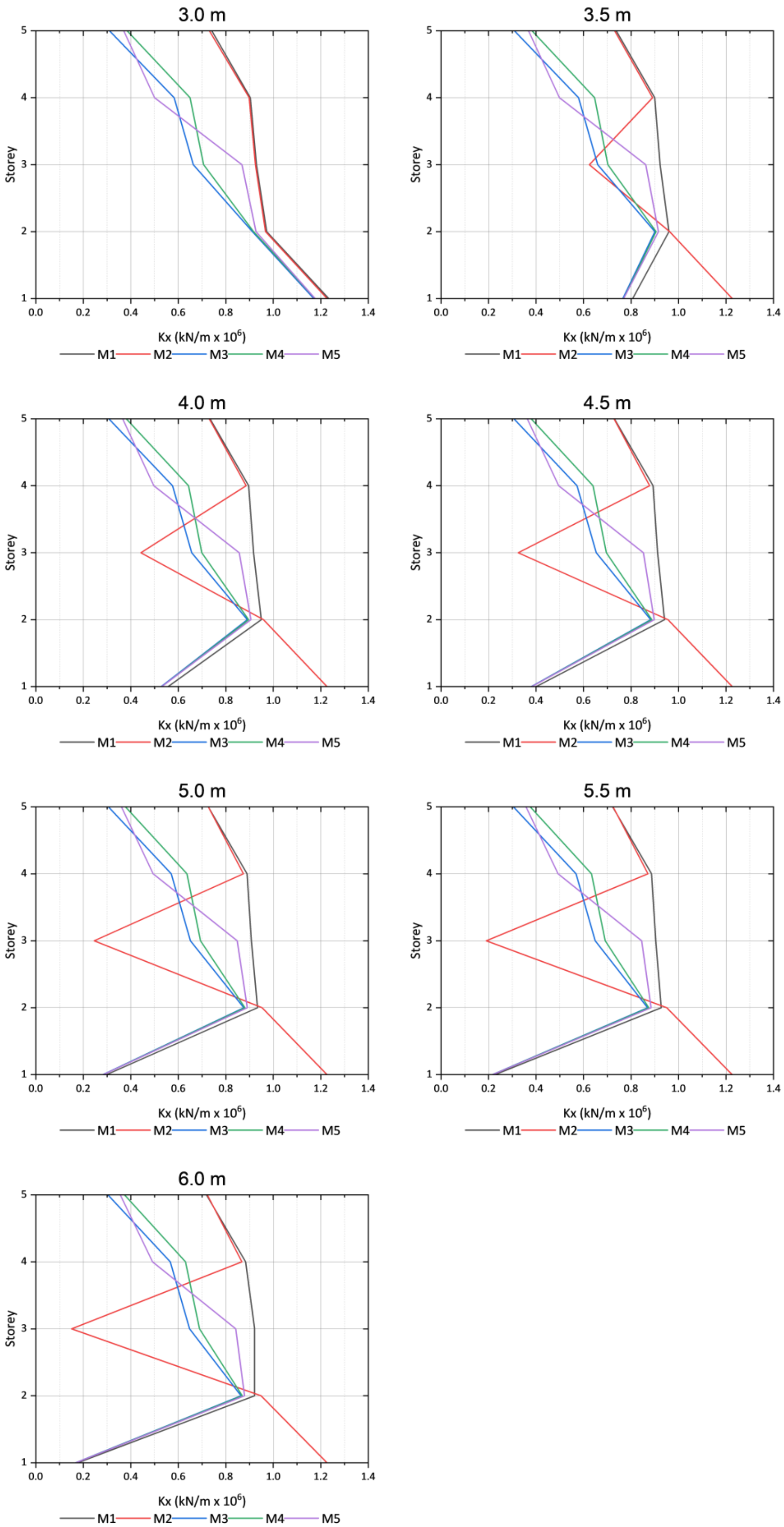


Figure 3 – Lateral Stiffness in Y-axis

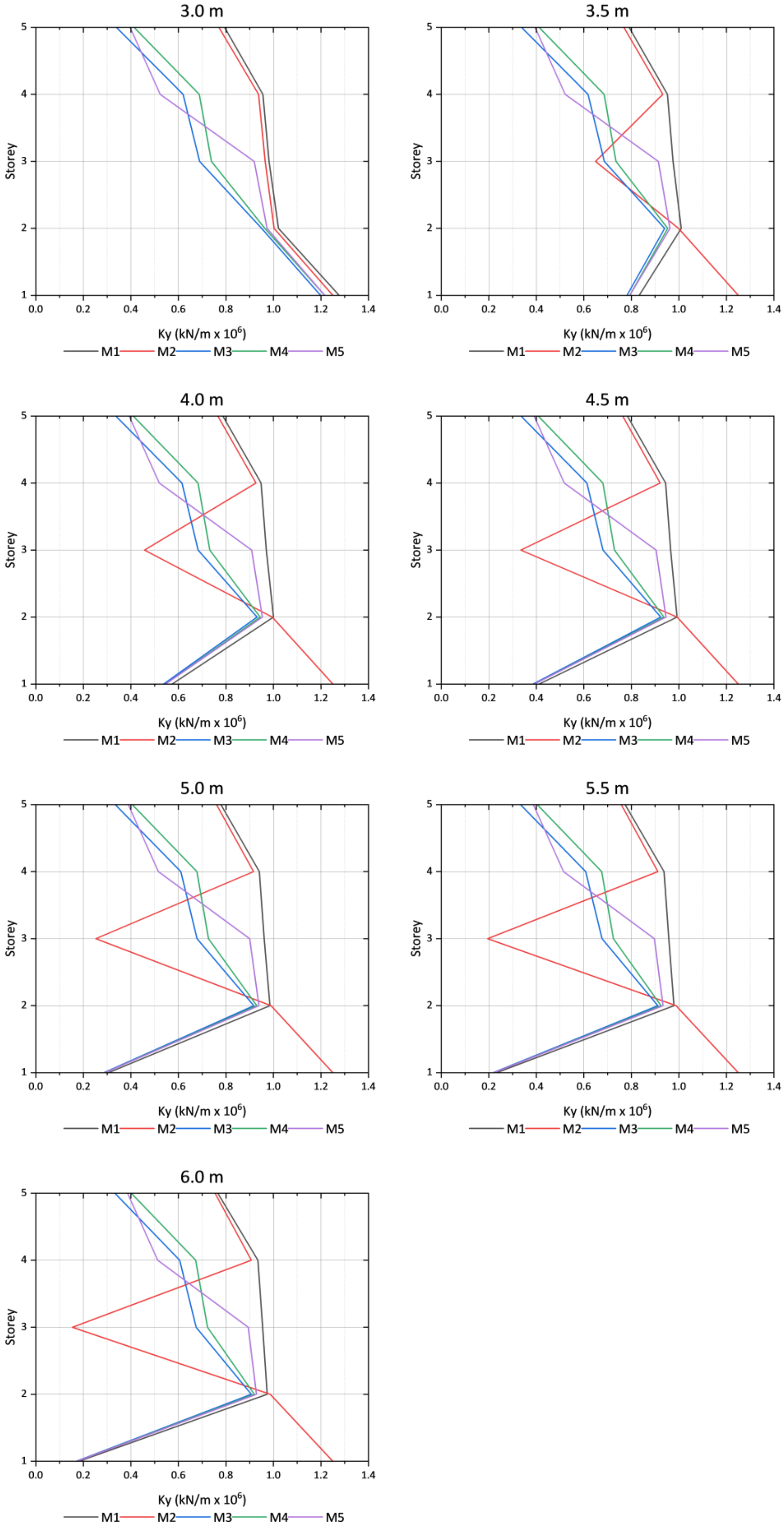


Figure 4 – Absolute displacement response

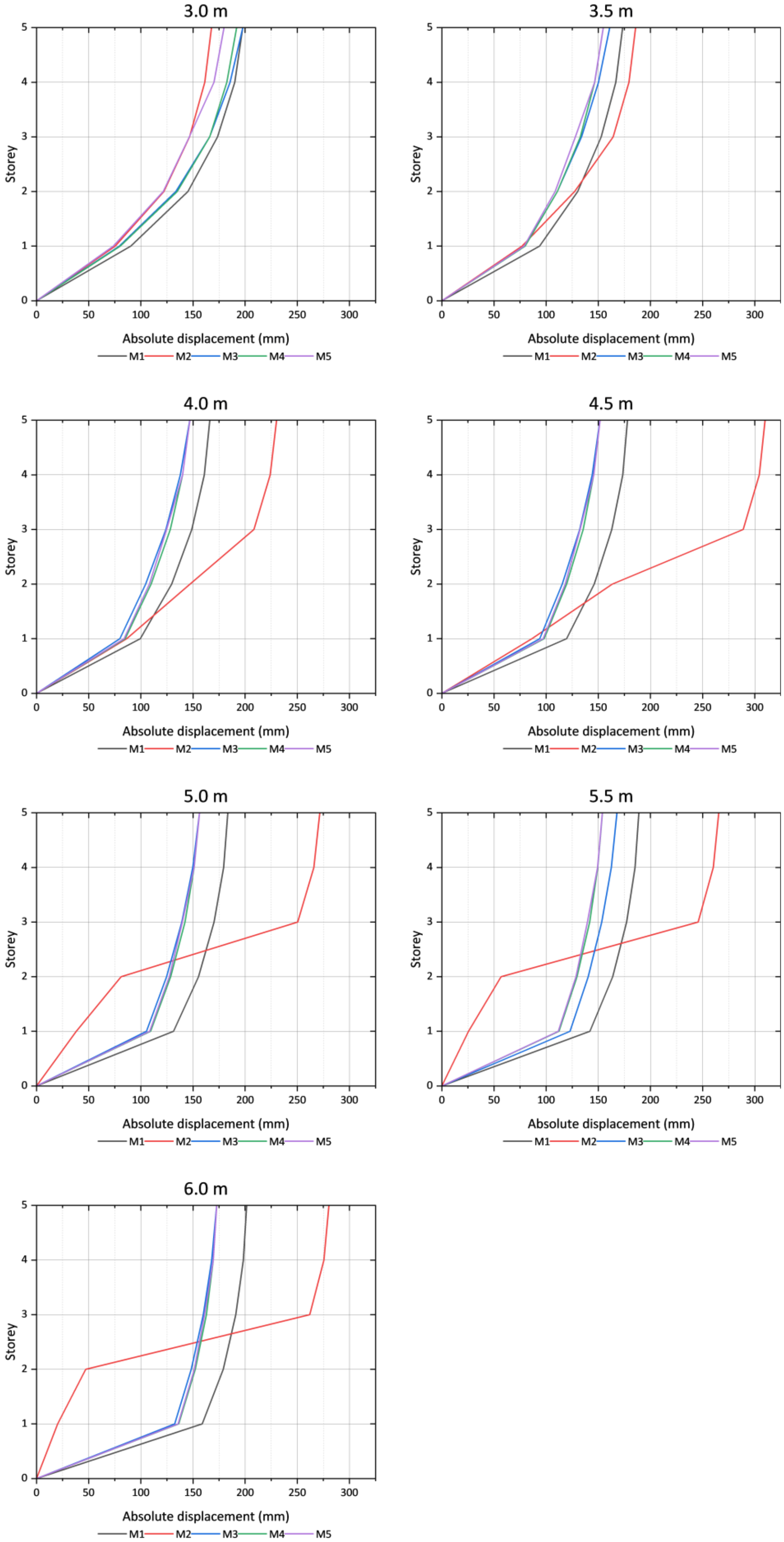


Figure 5 – Inter-storey drift

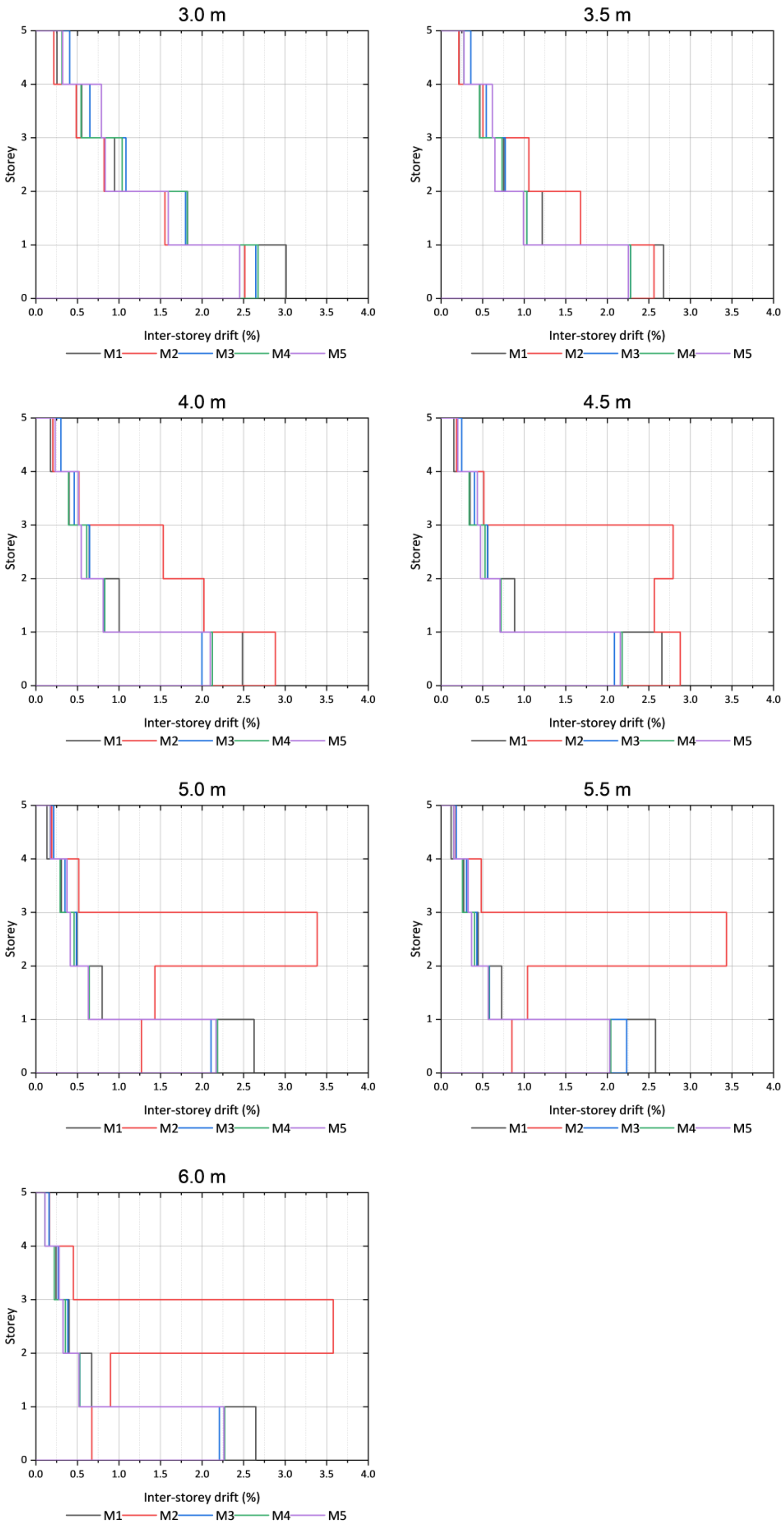


Figure 6 – Maximum Base Shear of each studied structure

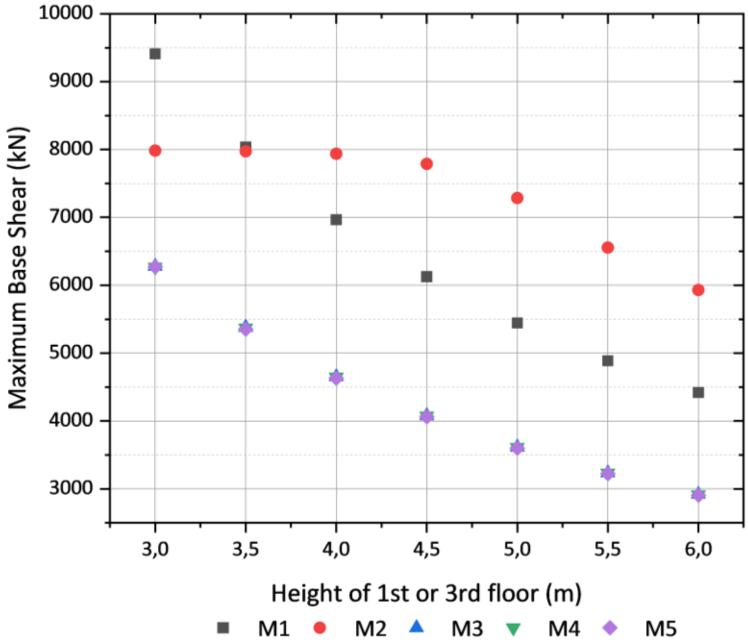
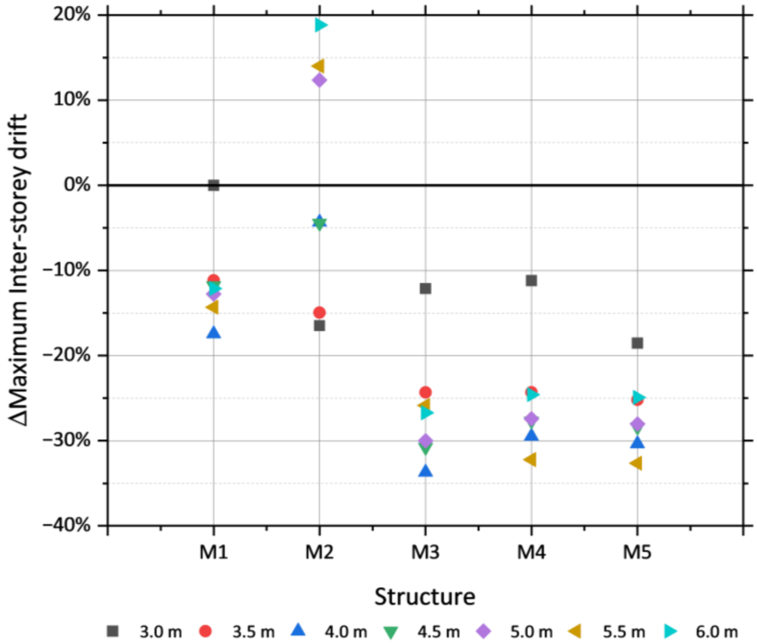


Figure 7 – % Variation of maximum inter-storey drift (%) in comparison with structures with 3,0m of height in all storeys



From Figure 4, 5, 6 and 7 and Table 5, we can draw several conclusions:

- The maximum displacement and storey drift are observed, respectively, in M2 structure (Height = 4.5m) and in M2 Structure (Height = 6.0 m).
- Compared to the regular structure (M1 with h = 3.0 m), it has been observed a maximum storey-drift increase of 18.8% and a maximum storey-drift decrease of -33.7%.
- M1 structure presents a considerable different Base Shear Value (50% higher) in comparison with M3, M4 and M5 structures.
- M2 structure (heights increasing in 3rd storey) presents 17.9% lower Base Shear Value in comparison with A1 structure.

5. Conclusions

The impact of elevation irregularity on structural seismic response was evaluated in this study using the guidelines provided by Eurocode 8. Robot Structural Analysis Professional® software was used to construct several structures to achieve this goal and SeismoStruct® software was used to conduct push-over analysis of these structures. The main conclusions and recommendations are outlined below:

- Despite the rise in height, the investigated buildings exhibit similar behavior in terms of natural frequency.
- The lateral stiffness is strongly and negatively impacted by height increases in the first or middle level, which generate soft and weak storeys. The last one produced worse structural response.
- The decrease in the column's cross-section has a negative effect on the lateral stiffness.
- The irregularity in elevation due to resistance variation between storeys, as prescribed on prEN 1998-1-2, didn't demonstrate a huge difference in lateral stiffness behavior, displacement nor storey drift. However, further structures must be assessed to generalize this conclusion.
- There is a maximum displacement and storey drift in M2 structure (height = 4.5 m) and M2 structure (height = 6.0 m), respectively. A weak-storey mechanism is presented by those structures.
- Compared to the regular structure (M1 with h = 3.0 m), it has been observed a maximum displacement increase of 97.40% and a maximum displacement decrease of -36.71%.
- M1 structure presents a considerable different Base Shear Value (50% higher) in comparison with M3, M4 and M5 structures.
- M2 structure (heights increasing in 3rd storey) presents 17.90% lower Base Shear Value in comparison with M1 structure.

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