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Fundamental period of infilled RC frame structures with vertical irregularity

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Abstract. The determination of the fundamental period of vibration of a structure is essential to earthquake design. Current codes provide formulas for the approximate estimation of the fundamental period of earthquake-resistant building systems. These formulas are dependent only on the height of the structure or number of storeys without taking into account the presence of infill walls into the structure, despite the fact that infill walls increase the stiffness and mass of the structure leading to significant changes in the fundamental period. Furthermore, such a formulation is overly conservative and unable to account for structures with geometric irregularities. In this study, which comprises the companion paper of previous published research by the authors, the effect of the vertical geometric irregularities on the fundamental periods of masonry infilled structures has been investigated, through a large set of infilled frame structure cases. Based on these results, an attempt to quantify the reduction of the fundamental period due to the vertical geometric irregularities has been made through a proposal of properly reduction factor.

Keywords: fundamental period; infilled frames; masonry; modal analysis; reinforced concrete buildings; vertical setback irregularity

1. Introduction

The fundamental period of vibration is a critical parameter for the seismic design of structures according to the modal superposition method. Nevertheless, the so far available in the literature proposals for its estimation are often conflicting one another making their use uncertain. The majority of these proposals do not take into account the presence of infill walls, with or without opening, into the structure, although infill walls increase the stiffness and mass of structure leading to significant changes in the fundamental period. Furthermore, the majority of these proposals do not also take into account the vertical geometric irregularity such as the setback irregularity.

The presence of masonry infill walls significantly influences the seismic behaviour of the building. While infill walls regularly distributed improve the seismic behaviour of the building, non-uniformly distributed infills may cause soft-storeys (discontinuous walls) or torsion (plan irregularity) to the building. Moreover, infill walls may cause an increase of the shear at the adjoining columns.

The most common type of irregularity in modern buildings is that of setback irregularity. The functional, aesthetic and architectural code requirements are the main reasons that these buildings are preferred. These setback buildings are very useful in urban areas, where the buildings are closely spaced. Buildings with setback irregularity provide adequate sunlight and ventilation for the lower storeys. The presence of vertical geometric irregularities leads in the reduction of mass and stiffness of the structure in relation to the corresponding regular/normal structure. These two parameters and their distribution across the height of the structure are the ones that define and value the fundamental period of the structure.

Despite the extensive experimental efforts in the last six decades (Smith 1966, Smith and Carter 1969, Page *et al*. 1985, Mehrabi *et al*. 1966, Buonopane and White 1999, Santhi *et al*. 2005a, b, Cavaleri *et al*. 2005) and analytical investigations (Liauw and Kwan 1984, Dhanasekar and Page 1986, Chrysostomou 1991, Saneinejad and Hobbs 1995, Chrysostomou and Asteris 2012, Asteris 2003, 2005, 2008, Cavaleri and Papia 2003 , 2014, Moghaddam 2004, Zeris *et al*. 2005, Repapis *et al*. 2006, Lee and Ko 2007, Kakaletsis and and Karayannis 2009, Anagnwstopoulou *et al*. 2012, Tanganelli *et al*. 2013, Young and Adeli 2014a, b, 2016, Varadharajan *et al*. 2014a, b, Tesfamariam *et al*. 2015, Syrmakezis and Asteris 2001), the rationale behind neglecting infill walls as well as vertical geometric irregularity is partly attributed to: a) incomplete knowledge of the behaviour of quasi-brittle materials, such as unreinforced masonry; b) the composite behaviour of the frame and the infill; and c) the lack of conclusive experimental and analytical results to substantiate a reliable design procedure for this type of structures. For this reason, a reliable estimation of the fundamental period by simple

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and at the same time reliable expressions is not easy and still constitutes a task of major interest.

In this study, which serves as a companion paper of previous published research by the authors (Asteris *et al*. 2015a, b, 2016a, b) the effect of the vertical geometric irregularities on the fundamental period of masonry infilled structures has been investigated. In particular, the effect of vertical geometric irregularities including the setback irregularity has been investigated through a large set of infilled frame structure cases taking into account the influence of the number of storeys, the number of spans, the span length, the infill wall panel stiffness and the percentage of openings within the infill panel. Based on these results, a simple reduction factor for the fundamental period is proposed.

2. Estimation of fundamental period for RC buildings with and without infills

Worldwide codes provide simple empirical formulas for the estimation of the fundamental period of vibration (T) of constructions. In most of the cases these expressions are simply related to the overall height of the buildings. Among these, a large number of technical codes refer to the following

$$T = C_{\mathrm{t}} \cdot H^{3/4} \tag{1}$$

where H is the total height of the building (in meters) and C_{t} is a numerical coefficient depending on the structural typology. Such relationship originates by the application of Rayleigh's method by assuming a linear distribution of lateral forces and a constant distribution of mass and stiffness. The above expression was adopted for the first time in 1978 by ATC3-06 (1978) for RC framed structures. The European seismic design regulations (Eurocode 8 2004) and the Uniform Building Code (UBC 1997), among others, adopt the same expression as ATC3-06 for the evaluation of fundamental period of vibration. EC8 suggest a value of C_{t}=0.075 for reinforced concrete constructions and 0.085 for steel, while a value 0.05 is suggested for all other structural typologies.

In a similar way other codes report the same formula presenting small variations of the coefficient Ct. An update of the previous expression, calibrated on the observations of Californian earthquakes, can be found in the Federal Emergency Management Agency (FEMA-450 2003). The fundamental period is calculated as follows

$$T = C_{\mathrm{r}} H_{\mathrm{n}}^{\mathrm{x}} \tag{2}$$

H_{n} being overall height (in meters) and C_{r} and x take the values 0.0466 and 0.9 respectively.

Other codes provide expressions of the fundamental period related to the number of storeys of buildings rather than their height. It is the case of the National Building Code of Canada (NBCC 1995) which for a RC building of N storeys above the ground states the following relationship

$$T = 0.1N \tag{3}$$

Further height-related formulas for the estimation of the fundamental period of masonry infilled RC frames have been proposed by several researchers. Among them, Chopra and Goel (2000) suggest the following expression:

$$T = 0.067H^{0.9} \tag{4}$$

As previously shown (Asteris *et al*. 2015a, 2015b), the values of the fundamental period based on the expressions proposed by researchers have a spread that is larger than the one obtained by the use of code formulas and reveal the need for further investigations and refinements. Some researchers take into account other parameters apart from the height of the building. Amanat & Hoque (2006) recognized that the span length, the number of spans and the amount of infills significantly influence the fundamental period. More complex expressions have been derived by other researchers. Hatzigeorgiou & Kanapitsas (2013) take into account the soil flexibility, the influence of shear walls, and the external and internal infill walls. Kose (2009) proposed an expression considering the effects of building height, frame type and the presence of infill walls.

Asteris *et al*. (2016b) proposed an empirical expression that takes into account the number of storeys, the number of spans, the span length, the infill wall panel stiffness and the percentage of openings within the infill panel. More than 700 analyses were performed and from regression analysis Eq (5) was proposed. This equation was shown to fit better the data than others available in the literature, having a high correlation factor R^2 and a low Mean Square Error and can adequately estimate the fundamental period of masonry infilled RC buildings.

$$\begin{aligned} T = \big(&0.55407 + 0.05679 \cdot \sqrt{H} - 0.00048 \cdot L \\ &-0.00027 \cdot a_W - 0.00425 \cdot Et + 0.00202 \cdot \sqrt{H} \cdot L \\ &+0.00016 \cdot \sqrt{H} \cdot a_W - 0.00032 \cdot \sqrt{H} \cdot Et + 0.00013 \\ &\cdot L \cdot a_W - 0.00017 \cdot L \cdot Et + 0.00010 \cdot a_W \cdot Et\big)^5 \end{aligned} \tag{5}$$

where H is the height (in meters), L is the span length (in meters), α_{w} is the opening percentage (100%: bare frame, 0%: fully infilled) (in %) and Et is the infill wall stiffness (which is the product of the masonry modulus of elasticity and the masonry thickness (in 10^5 kN/m).

Details for expressions of other codes and researchers are presented extensively in previous studies (Asteris *et al*. 2015a, b, 2016b).

Varadharajan *et al*. (2014b) proposed Eq. (6), based on the results of time history analysis of 305 different building frames, for the estimation of the fundamental period of buildings with setback irregularity.

$$T = \lambda \cdot 0.075 \cdot H^{0.75} \tag{6}$$

where λ is a correction factor proposed for the setback irregularity.

3. Description of the structures

3.1 Building forms and infill walls parameters

In this study, the influence of vertical geometric irregularity on the fundamental period of infilled RC plane frame structures is investigated. For this reason, building frames with different geometrical configurations of setbacks

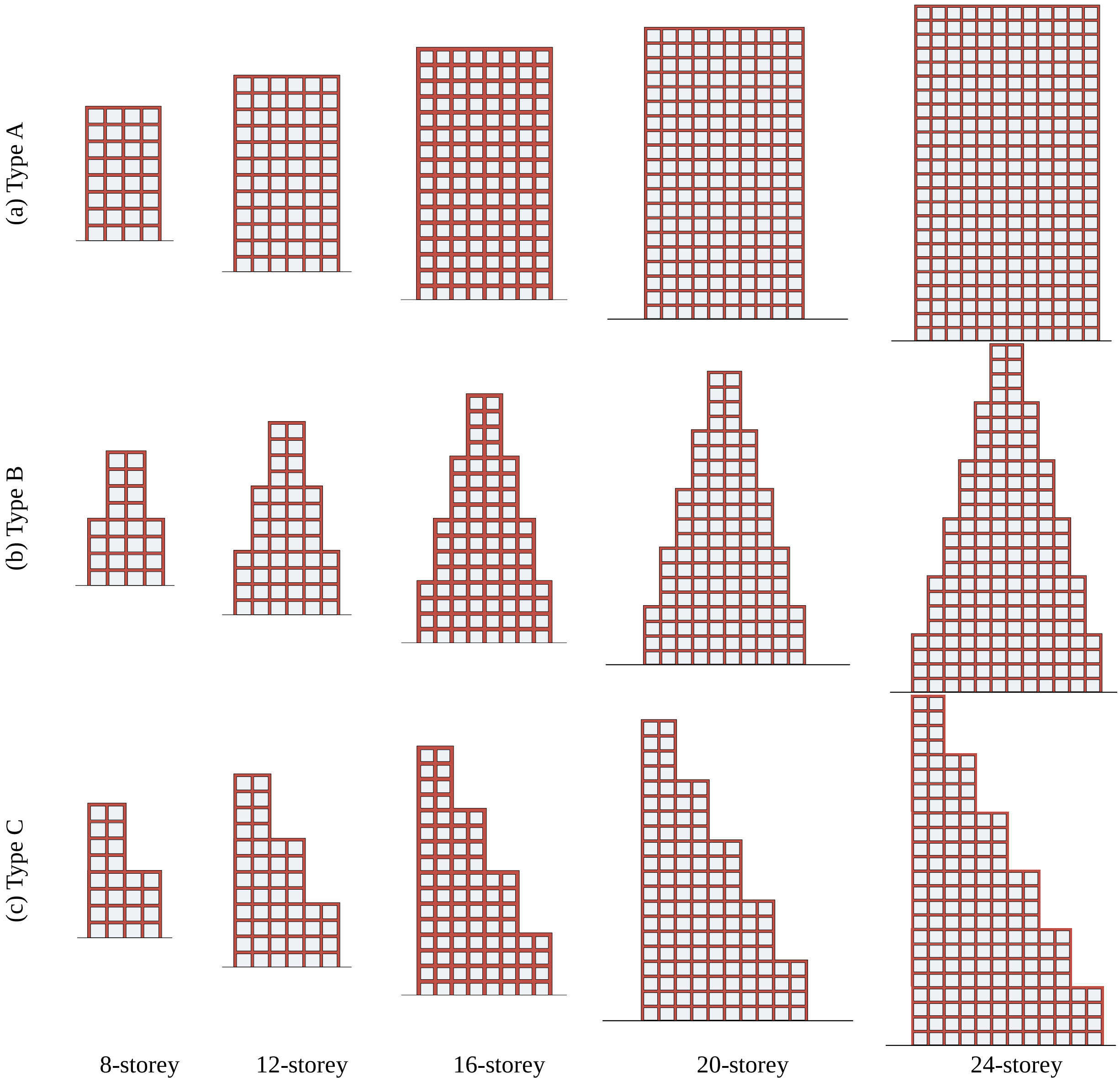


Fig. 1 (a) Regular RC frame (Type A), (b) Irregular RC frame (Type B) (c) Irregular RC frame (Type C).

are analysed. Buildings analysed have 8, 12, 16, 20 and 24 storeys. Apart from the regular building frames (Type A), two types of vertical setback irregularities have been investigated, as shown in Fig. 1. For the first type of irregularity (Type B) the building frame has one setback on both sides every 4 storeys. For the second type of irregularity (Type C) the building frame has two setbacks on one side every 4 storeys.

The storey height for all buildings is kept constant and equal to 3.0 m. The number of spans varied between 4, 6, 8, 10 and 12 depending on the number of storeys, so that for both types of vertical setback irregularity, the frame ends to two spans at the upper storey. For each case, two different span lengths were considered, namely 3.0 m and 6.0 m. In the perpendicular direction the span length has been considered constant and equal to 5 m for all cases.

For the 8-storey building frame, the same vertical setback irregularity has been analysed for 6 spans (Fig. 2) and the results were compared with the results of the 4 spans building frames, in order to examine this parameter.

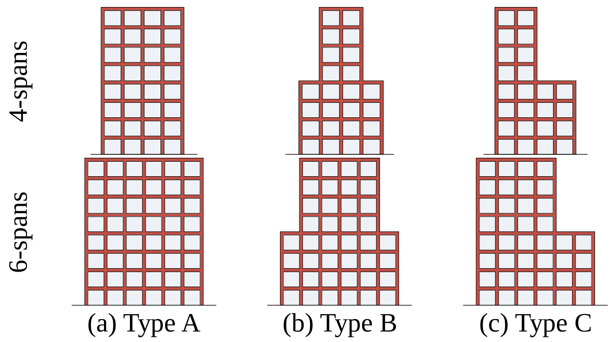


Fig. 2 Geometrical configurations of setbacks for the 8-storey building frame with 4 and 6 spans. (a) Regular RC frame (Type A), (b) Irregular RC frame (Type B) (c) Irregular RC frame (Type C)

For the 12-storey building frame, additional geometrical configurations of setbacks are analysed, as shown in Fig. 3.

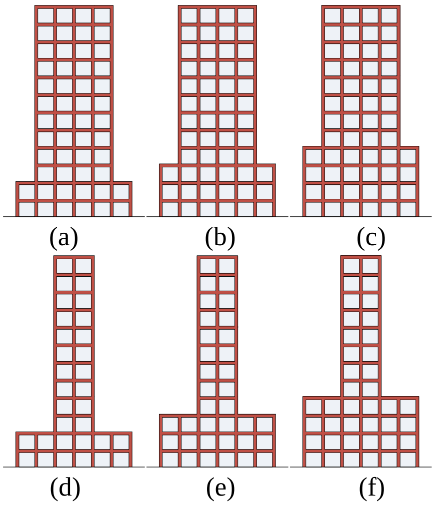


Fig. 3 Types of irregularities examined for 12-storey building frame

Table 1 Building parameters

Concrete strength	25 MPa
Modulus of elasticity of concrete, E_c	31 GPa
Steel tensile yield strength	500 MPa
Size of beams	250/600 mm
Slab thickness	150 mm
Dead loads	1.50 kN/m^2+0.90 kN/m^2
Live loads	3.50 kN/m^2
Number of storeys	8, 12, 16, 20, 24
Building height	24 m, 36 m, 48 m, 60 m, 72 m
Span length	3.0 m, 6.0 m
Number of spans	4, 6, 8, 10, 12 (depending on the number of storeys, see Fig. 1)
Masonry compressive strength, f_{m}	1.5 MPa, 3.0 MPa, 4.5 MPa, 8.0 MPa, 10.0 MPa
Modulus of elasticity of masonry, E_m	1.5 GPa, 3.0 GPa, 4.5 GPa, 8.0 GPa, 10.0 GPa
Thickness of infill panel, t_w	150 mm, 250 mm
Infill wall opening percentage	0% (fully infilled), 25%, 50%, 75%, 100% (bare frame)

The first three geometrical configurations have one setback on both sides with 33% reduction of the width (one span are missing on both sides), starting at the 3rd, 4th or 5th storey (at 16.7%, 33.3% or 41.7% of the total height, respectively) and the number of spans remains the same until the roof (Figs. 3(a)-(c)). The next geometrical configurations have also one setback on both sides with 66% reduction of the width (two spans are missing on both sides) at the 3rd, 4th or 5th storey (Figs. 3(d)-(f)).

Both bare frame structures and structures with fully or partially unreinforced masonry infilled frames with or without openings are analysed. Various parameters are considered for each case. Infill panels are either 0.15 or 0.25 m thick, following the conventional construction of single and two leaf walls. The influence of infill wall openings is also examined. Infill wall openings are given as a percentage of the panel area. Five different cases for infill wall openings are studied. These are: fully infilled walls (0% openings), infill walls with small and large openings (25%, 50% and 75% openings) and bare frames (100% openings). The opening is the same for all the infill panels of the building.

Moreover, five different values for the masonry panel strength were adopted to represent weak, medium and strong masonry, namely 1.5 MPa, 3.0 MPa, 4.5 MPa, 8.0 MPa and 10.0 MPa. These values are assumed to cover the most common cases for masonry infill condition in Europe.

The building parameters used for the development of the model are listed in Table 1. In total, 1031 different cases of infilled RC frames were analysed in order to investigate the influence of vertical irregularities on the fundamental period of infilled frame structures.

3.2 Design of structures

The frames are designed according to Eurocode standards using the software FESPA (LH Logismiki 2013). Modal response spectrum analysis was also performed. The frames designed for seismic zone I with reference peak ground acceleration on type A ground, a_{gR}=0.16 g. The importance factor γ_{I} was taken as 1.0 and the ground type as B with soil factor S equal to 1.2, according to Eurocode 8. Frames designed for medium ductility class (DCM) and the behaviour factor, q assumed to be 3.45. Concrete strength class C25/30 was used for beams and columns, while steel grade B500c was used for the reinforcement steel bars. The dead load was 1.50 kN/m^2 plus 0.90 kN/m^2 to include interior partition walls in the mass of the building. Live load is 3.5 kN/m^2.

Slabs were 150 mm thick for all cases. Beams were 250/600 mm for all frames. Square column sections were used for all frames. For the 24-storey frame with 6.0 m span length, columns had dimensions ranging from 800x800 [mm] at the ground floor to 500×500 [mm] at the roof. For the 8-storey frame with 3.0 m span length, column dimensions range from 500×500 [mm] to 350×350 [mm]. Column dimensions for all frames are shown in detail in Table 2. Column longitudinal reinforcement ratio was kept low and ranged between 1.0% and 1.5%, with most cases being under 1.15%.

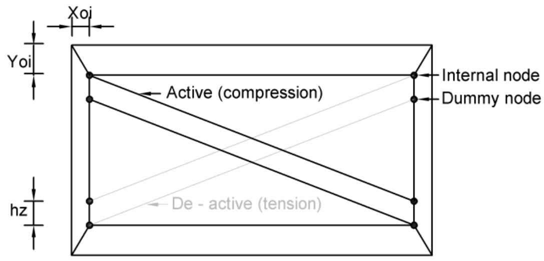
3.3 Modelling of structures

All buildings were modelled as plane frames using Seismostruct (Seismosoft 2013). Concrete compressive strength was equal to 25 MPa and the yield strength of the steel equal to 500 MPa. Mass was calculated using the seismic load combination, namely dead loads plus 30% of the live loads.

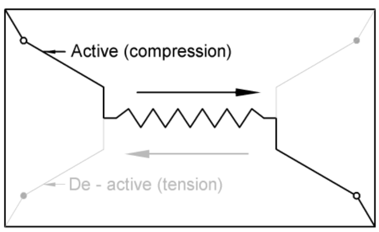
Masonry is modelled using the inelastic infill panel element. This is an equivalent strut nonlinear cyclic model proposed by Crisafulli (1997) for the modelling of the nonlinear response of infill panels in framed structures. Each panel is represented by six strut members. Each diagonal direction features two parallel struts to carry axial loads only in compression across two opposite diagonal corners and a third one to carry the shear from the top to the

Table 2 Side dimension (mm) of square columns

Storey	Column's Dimensions (mm)									
	6.0 m span length					6.0 m span length				
	Storeys									
	24	20	16	12	8	24	20	16	12	8
24	450					500				
23	450					550				
22	450					550				
21	450					550				
20	450	400				550	500			
19	450	450				600	550			
18	450	450				600	550			
17	450	450				650	550			
16	450	450	400			650	600	500		
15	500	450	450			700	600	500		
14	500	450	450			700	600	550		
13	500	450	450			750	650	550		
12	550	450	450	400		750	650	550	500	
11	550	500	500	450		750	650	600	550	
10	550	500	500	450		750	700	600	550	
9	550	500	500	450		750	700	600	550	
8	550	550	500	500	400	750	700	600	550	500
7	600	550	500	500	450	750	750	650	600	550
6	600	550	500	500	450	750	750	650	600	550
5	600	550	500	500	500	750	750	650	600	550
4	650	600	550	500	500	800	750	700	650	600
3	650	600	550	500	500	800	750	700	650	650
2	650	600	550	550	500	800	750	700	650	650
1	650	600	550	550	500	800	750	700	650	650



(a)



(b)

Fig. 4 Infill panel element proposed by Crisafulli (1997). (a) Compression/Tension Struts, (b) Shear Strut

bottom of the panel (Fig. 4).

The equivalent diagonal strut width is evaluated with Eq. (7) proposed by Mainstone (1971) and included in

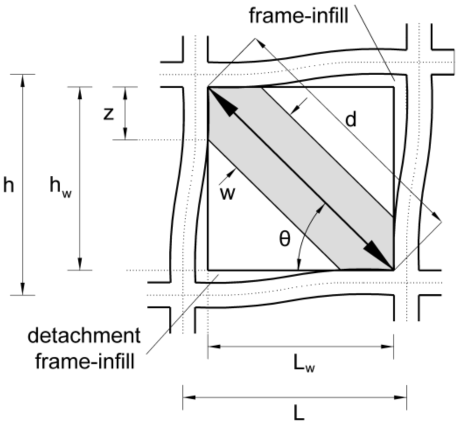


Fig. 5 Masonry infill frame sub-assemblage

FEMA-274 (Federal Emergency Management Agency 1997) for the analysis and rehabilitation of buildings as well as in FEMA-306 (Federal Emergency Management Agency 1998), as it has been proven to be the most popular over the years.

$$\frac{w}{d} = 0.175\,\lambda_h^{-0.4} \tag{7}$$

where, w is the width of the diagonal strut and d is the diagonal length of the masonry panel. λ_h is given by Eq. (8).

$$\lambda_h = h\sqrt[4]{\frac{E_w\, t_w\, sin2\theta}{4\,E\,I\,h_w}} \tag{8}$$

where E_w is the modulus of elasticity of the masonry panel, EI is the flexural rigidity of the columns, t_w the thickness of the infill panel and equivalent strut, h the column height between centerlines of beams, h_w the height of infill panel, and θ the angle, whose tangent is the infill height-to-length aspect ratio, being equal to

$$\theta = tan^{-1}\left(\frac{h_w}{L_w}\right) \tag{9}$$

where L_w is the length of infill panel. All the above parameters are explained in Fig. 5.

Infill walls with openings are modelled with the same element but reduced stiffness, according to Eq. (10) proposed by Asteris (2003).

$$\lambda = 1 - 2\,a_w^{0.54} + a_w^{1.14} \tag{10}$$

where α_w is the ratio of the area of opening to the area of infill wall. The above coefficient is used to find the equivalent width of a strut for the case of an infill with opening by multiplying the width obtained using Eq. (7) by the relevant reduction factor.

The model was previously validated by Asteris *et al.* (2011) employing a reinforced concrete frame with infill walls. In that study the infill walls of a reinforced concrete frame were modelled using either the double-strut model proposed by Crisafulli (1997). The accuracy of the modes was assessed through comparison with experimental results obtained from pseudo-dynamic tests of a full-scale, four-storey, three-bay, reinforced concrete infilled frame, which was tested at the European Laboratory for Structural

Table 3 Fundamental period for building frames with 3 m span length

Opening percentage (%)	Masonry wall Stiffeness Et (kN/m)	24-storey			20-storey			16-storey			12-storey			8-storey		
		Irregularity type														
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
0	2.25	1.278	0.911	0.928	1.091	0.791	0.806	0.883	0.657	0.668	0.647	0.506	0.513	0.463	0.386	0.390
0	4.50	1.050	0.752	0.764	0.894	0.651	0.662	0.725	0.541	0.550	0.532	0.417	0.422	0.380	0.317	0.321
0	7.50	0.892	0.640	0.651	0.758	0.553	0.562	0.615	0.460	0.467	0.453	0.355	0.360	0.322	0.270	0.272
0	11.25	0.778	0.559	0.569	0.661	0.483	0.491	0.536	0.401	0.408	0.396	0.311	0.315	0.280	0.235	0.238
0	15.00	0.704	0.506	0.515	0.597	0.437	0.445	0.484	0.363	0.369	0.359	0.282	0.286	0.254	0.213	0.215
0	20.00	0.636	0.458	0.466	0.539	0.395	0.402	0.437	0.328	0.334	0.325	0.255	0.259	0.229	0.192	0.195
0	25.00	0.587	0.423	0.431	0.498	0.365	0.372	0.404	0.303	0.309	0.300	0.236	0.240	0.212	0.178	0.180
25	2.25	1.765	1.246	1.281	1.510	1.085	1.115	1.209	0.891	0.914	0.894	0.690	0.704	0.634	0.524	0.532
25	4.50	1.578	1.118	1.145	1.346	0.971	0.994	1.083	0.801	0.818	0.799	0.618	0.629	0.567	0.470	0.477
25	7.50	1.417	1.007	1.029	1.206	0.873	0.891	0.972	0.721	0.736	0.716	0.556	0.565	0.508	0.423	0.428
25	11.25	1.281	0.913	0.931	1.089	0.790	0.805	0.879	0.654	0.665	0.647	0.504	0.511	0.459	0.383	0.387
25	15.00	1.184	0.845	0.861	1.004	0.730	0.743	0.811	0.605	0.615	0.598	0.466	0.472	0.424	0.354	0.358
25	20.00	1.087	0.777	0.791	0.922	0.671	0.683	0.745	0.556	0.565	0.549	0.428	0.434	0.389	0.325	0.328
25	25.00	1.014	0.726	0.739	0.860	0.626	0.637	0.694	0.519	0.527	0.512	0.400	0.405	0.362	0.303	0.306
50	2.25	2.014	1.412	1.465	1.725	1.231	1.276	1.371	1.003	1.036	0.991	0.781	0.800	0.719	0.592	0.603
50	4.50	1.919	1.349	1.395	1.642	1.175	1.213	1.308	0.960	0.988	0.970	0.746	0.763	0.685	0.565	0.576
50	7.50	1.820	1.283	1.322	1.555	1.116	1.149	1.242	0.914	0.939	0.919	0.709	0.723	0.650	0.537	0.546
50	11.25	1.724	1.218	1.252	1.470	1.057	1.086	1.177	0.868	0.889	0.870	0.672	0.685	0.615	0.510	0.517
50	15.00	1.645	1.164	1.194	1.401	1.010	1.035	1.124	0.830	0.849	0.829	0.642	0.653	0.587	0.487	0.494
50	20.00	1.559	1.105	1.132	1.327	0.958	0.980	1.065	0.788	0.805	0.786	0.609	0.619	0.556	0.462	0.468
50	25.00	1.488	1.057	1.081	1.265	0.915	0.935	1.017	0.753	0.769	0.749	0.581	0.591	0.531	0.441	0.447
75	2.25	2.146	1.498	1.564	1.840	1.308	1.363	1.454	1.061	1.099	1.083	0.829	0.851	0.764	0.627	0.641
75	4.50	2.133	1.490	1.555	1.828	1.300	1.354	1.446	1.055	1.093	1.076	0.824	0.846	0.759	0.623	0.637
75	7.50	2.117	1.480	1.543	1.814	1.291	1.344	1.436	1.048	1.085	1.069	0.818	0.840	0.753	0.619	0.632
75	11.25	2.099	1.468	1.529	1.799	1.281	1.332	1.424	1.040	1.076	1.060	0.812	0.833	0.747	0.614	0.627
75	15.00	2.083	1.457	1.517	1.784	1.271	1.321	1.413	1.033	1.068	1.051	0.805	0.826	0.741	0.609	0.622
75	20.00	2.062	1.444	1.502	1.766	1.259	1.307	1.400	1.024	1.058	1.041	0.798	0.818	0.734	0.604	0.616
75	25.00	2.043	1.431	1.488	1.749	1.247	1.294	1.387	1.015	1.048	1.031	0.791	0.810	0.727	0.598	0.610
100	-	2.036	1.428	1.493	1.748	1.248	1.302	1.383	1.013	1.051	1.022	0.795	0.817	0.732	0.604	0.617
Average		1.522	1.075	1.108	1.300	0.934	0.962	1.039	0.766	0.786	0.768	0.594	0.607	0.544	0.450	0.458
Average reduction %			29.15	27.16		27.88	25.93		26.05	24.24		22.42	20.95		17.04	15.75

Assessment (ELSA), reaction-wall laboratory, within the framework of the Innovative Seismic Design Concepts for New and Existing Structures (ICONS) research program (Pinto *et al.* 2002). From the comparison of experimental and numerical results, it was shown that the double-strut model by Crisafulli (1997) provided a very good fit to the experimental results, thus, it was chosen for modelling the infill walls in the present study.

4. Results and discussion

Two types of vertical irregularity, as described in the previous paragraph, were analysed for the 8, 12, 16, 20 and 24-storey building frames, in order to examine the influence of the vertical setback irregularity on the fundamental period. Two span lengths were considered, namely 3.0 m, 6.0 m and the values of the fundamental period of vibration for all the building frames analysed are shown in Tables 3 and 4 for the two different spans, respectively. Masonry wall stiffness *Et* is the product of masonry wall modulus of elasticity *E* with masonry infill wall thickness *t*.

Fig. 6 shows the relationship between the fundamental periods of vibration of the 24-storey regular building frames versus the corresponding values of period for the 24-storey irregular building frames, for two types of setback irregularity and for two different span lengths. It is shown that the period of the irregular building frames are consistently smaller than the period of the regular building with the same parameters. The same occurs for the 8, 12, 16 and 20-storey building frames, as shown in Fig. 7. The values of the fundamental period for building frames with 3 m and 6 m span length are shown in Tables 3 and 4, respectively.

For the 24-storey building frame with 6 m span length, the values of the fundamental period vary from 0.607 s for the fully infilled frame with the maximum stiffness to 3.113 s for the bare building frame. The reduction of the fundamental period for the vertical setback irregularity type B varies from 27.5% to 29.1% with an average value of 28.3%. The average reduction of the fundamental period for the vertical irregularity type C is equal to 27.3%.

The average reduction of the period of vibration between the regular and the vertical irregular type B building frame is equal to 16.7%, 22.2%, 25.5%, 27.2% and 28.3%, for the 8, 12, 16, 20 and 24-storey building frames,

Table 4 Fundamental period for building frames with 6 m span length

Opening percentage (%)	Masonry wall Stiffeness Et (kN/m)	24-storey			20-storey			16-storey			12-storey			8-storey		
		Irregularity type														
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
0	2.25	1.538	1.107	1.120	1.296	0.947	0.958	1.046	0.783	0.791	0.804	0.625	0.632	0.537	0.451	0.454
0	4.50	1.192	0.860	0.872	1.006	0.737	0.748	0.814	0.611	0.619	0.628	0.490	0.496	0.423	0.354	0.358
0	7.50	0.977	0.706	0.718	0.826	0.607	0.617	0.670	0.504	0.512	0.517	0.405	0.410	0.350	0.294	0.298
0	11.25	0.833	0.602	0.614	0.705	0.518	0.528	0.573	0.431	0.439	0.444	0.347	0.353	0.300	0.253	0.256
0	15.00	0.743	0.538	0.549	0.629	0.463	0.473	0.512	0.386	0.393	0.397	0.309	0.317	0.269	0.227	0.230
0	20.00	0.663	0.480	0.492	0.562	0.414	0.424	0.458	0.345	0.353	0.356	0.279	0.286	0.242	0.204	0.207
0	25.00	0.607	0.440	0.451	0.516	0.380	0.389	0.421	0.317	0.325	0.327	0.256	0.263	0.223	0.188	0.191
25	2.25	2.362	1.690	1.707	1.983	1.441	1.455	1.595	1.186	1.199	1.196	0.930	0.939	0.806	0.669	0.674
25	4.50	1.979	1.420	1.435	1.664	1.213	1.226	1.342	1.000	1.011	1.010	0.780	0.795	0.684	0.570	0.574
25	7.50	1.692	1.216	1.230	1.424	1.041	1.052	1.150	0.859	0.869	0.869	0.678	0.687	0.590	0.493	0.502
25	11.25	1.474	1.061	1.074	1.242	0.909	0.920	1.005	0.752	0.761	0.780	0.594	0.604	0.518	0.433	0.436
25	15.00	1.330	0.958	0.971	1.121	0.821	0.832	0.907	0.680	0.689	0.688	0.538	0.544	0.470	0.393	0.397
25	20.00	1.195	0.862	0.875	1.008	0.739	0.750	0.817	0.613	0.621	0.620	0.486	0.492	0.424	0.356	0.359
25	25.00	1.098	0.792	0.805	0.927	0.680	0.691	0.751	0.564	0.572	0.571	0.447	0.454	0.391	0.328	0.332
50	2.25	2.912	2.074	2.096	2.439	1.763	1.782	1.958	1.448	1.466	1.439	1.117	1.128	0.976	0.806	0.813
50	4.50	2.660	1.899	1.919	2.231	1.617	1.634	1.793	1.329	1.345	1.322	1.013	1.043	0.899	0.745	0.750
50	7.50	2.423	1.733	1.751	2.034	1.477	1.492	1.637	1.216	1.230	1.210	0.941	0.951	0.825	0.685	0.690
50	11.25	2.211	1.583	1.600	1.857	1.351	1.365	1.496	1.113	1.126	1.108	0.863	0.872	0.758	0.631	0.632
50	15.00	2.052	1.471	1.487	1.725	1.257	1.270	1.391	1.036	1.048	1.032	0.804	0.812	0.707	0.589	0.593
50	20.00	1.891	1.357	1.372	1.591	1.160	1.173	1.283	0.957	0.968	0.954	0.744	0.752	0.655	0.546	0.550
50	25.00	1.766	1.269	1.283	1.487	1.085	1.097	1.200	0.896	0.906	0.893	0.697	0.704	0.614	0.513	0.517
75	2.25	3.262	2.314	2.342	2.727	1.964	1.987	2.187	1.611	1.635	1.584	1.227	1.241	1.080	0.889	0.897
75	4.50	3.220	2.285	2.313	2.693	1.940	1.963	2.160	1.591	1.615	1.560	1.209	1.222	1.068	0.879	0.887
75	7.50	3.170	2.251	2.277	2.652	1.911	1.934	2.127	1.568	1.591	1.536	1.192	1.205	1.053	0.868	0.875
75	11.25	3.113	2.212	2.237	2.605	1.879	1.900	2.090	1.542	1.564	1.510	1.172	1.185	1.036	0.854	0.861
75	15.00	3.061	2.176	2.201	2.562	1.849	1.870	2.056	1.518	1.539	1.487	1.154	1.167	1.021	0.842	0.849
75	20.00	2.998	2.133	2.156	2.510	1.813	1.833	2.015	1.488	1.508	1.467	1.139	1.151	1.002	0.827	0.834
75	25.00	2.940	2.093	2.116	2.462	1.779	1.799	1.977	1.461	1.481	1.432	1.112	1.124	0.984	0.813	0.819
100	-	3.113	2.216	2.244	2.604	1.883	1.906	2.089	1.545	1.563	1.577	1.223	1.238	1.040	0.860	0.867
Average period		2.016	1.441	1.459	1.693	1.229	1.244	1.363	1.012	1.025	1.011	0.785	0.795	0.688	0.571	0.576
Average reduction%			28.30	27.34		27.17	26.20		25.49	24.45		22.23	21.15		16.73	15.92

respectively. Similarly, the average reduction of the period is equal to 15.9%, 21.2%, 24.5%, 26.2% and 27.3% for the vertical irregularity type C, for the 8, 12, 16, 20 and 24-storey building frames, respectively (Fig. 8(b)). Similar values for the average reduction of the fundamental period for the irregular buildings with 3 m span length for the two types of vertical setback irregularity are shown in Table 3 and Fig. 8(a).

Fig. 9 shows the fundamental period versus the infill masonry panel stiffness *Et* (*E*: modulus of elasticity, *t*: thickness of the masonry panel) for 12-storey infilled RC frames with 25% infill opening percentage and 6.0 m span length. In Fig. 9 it can be seen that the period is highly sensitive to the infill wall panel stiffness, as also shown in detail in previous studies (Asteris *et al*. 2015a, 2015b, 2016b). An increase to the infill wall panel stiffness results to a decrease of the fundamental period. In the same figure it can also be seen that the influence of infill masonry panel stiffness is the same for both regular frame buildings and buildings with vertical setback irregularities.

Fig. 10 shows the influence of the height on the fundamental period of RC frames. Fig. 10(a) refers to bare RC frames while Fig. 10(b) refers to fully infilled RC frame with wall stiffness equal to $7.50 \cdot 10^{5}$ kN/m. For all cases, it can be seen that the period of RC frames with vertical setback irregularity is consistently smaller than the period

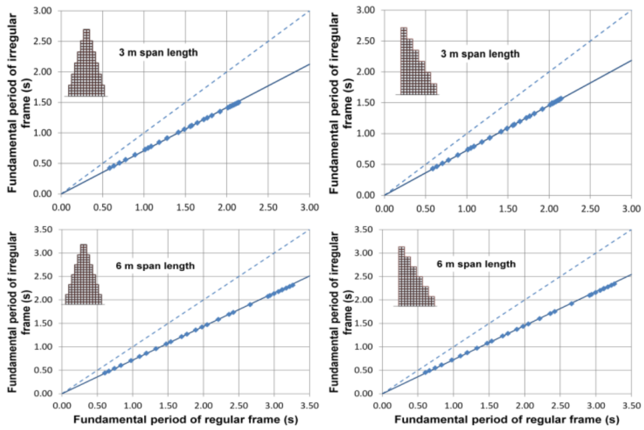


Fig. 6 Comparison of the fundamental period for the 24-storey regular and irregular building frame with 3 m and 6 m span

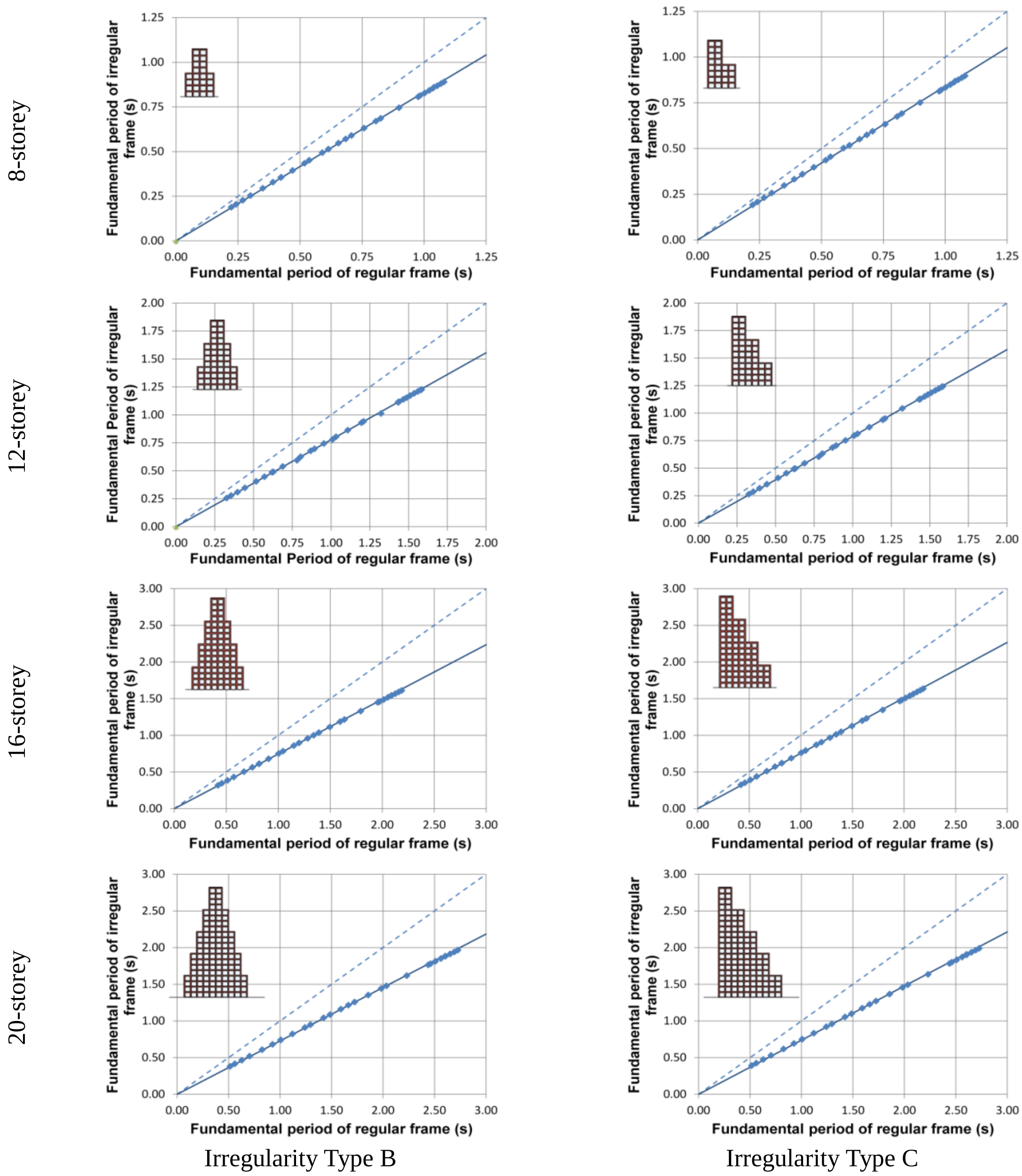


Fig. 7 Comparison of the fundamental period for the 8, 12, 16 and 20-storey regular and irregular building frames with 6 m span length

of the regular RC frames. Moreover, the period is almost the same for both types of vertical setback irregularity. From the same figure it can be seen that the reduction of the period is smaller for lower frames and larger for taller frames.

In Fig. 11 the relationship between the fundamental periods of vibration of the 8-storey regular building frames with 6 m span length versus the corresponding values of period for the 8-storey irregular building frames, is presented for the case of frame with 4 spans and 6 spans. The average reduction factor of the fundamental period of the 8-storey frame with vertical irregularity type B is 16.7% for the frame with 4 spans and 10.0% for the frame with 6 spans. Similarly, the reduction factors are 15.9% and 9.4% for the 8-storey frame with vertical irregularity type C with 4 and 6 spans, respectively. It can be seen that the reduction of the period is smaller for frames with more spans. This could be explained due to the fact that in the case of the frame with 4 spans, the setback is 50%, while for the case of the frame with 6 spans, it is 33%.

Additional types of vertical setback irregularity are considered only for the 12-storey RC building frame, as described in section 3.1 and shown in Fig. 3, in order to examine their influence. Fig. 12 shows the relationship between the fundamental periods of vibration of the 12-storey regular building frames with 6 m span length versus the corresponding values of period for the 12-storey irregular building frames, for the additional six types of setback irregularity. For the first geometrical configuration with one setback on both sides (25% reduction of the width)

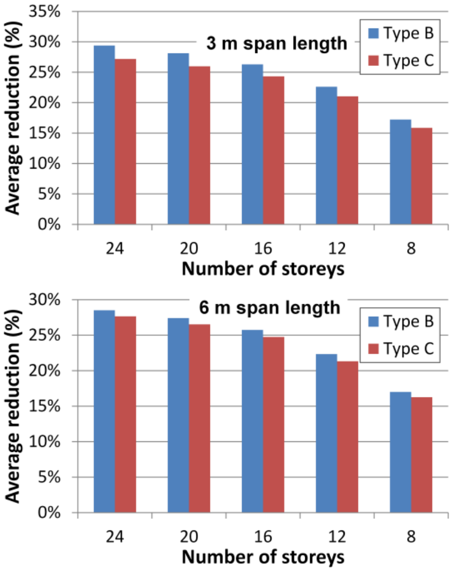


Fig. 8 Average reduction of the fundamental period, between the regular building frame and the frame with the vertical irregularity (types B and C), for (a) 3 m span length and (b) 6 m span length

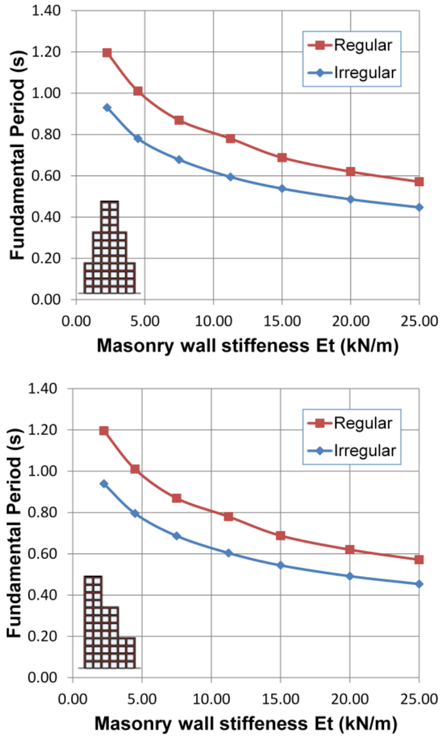


Fig. 9 Influence of masonry stiffness on the fundamental period of the 12-storey RC building frame with 6 m span length and 25% infill opening percentage

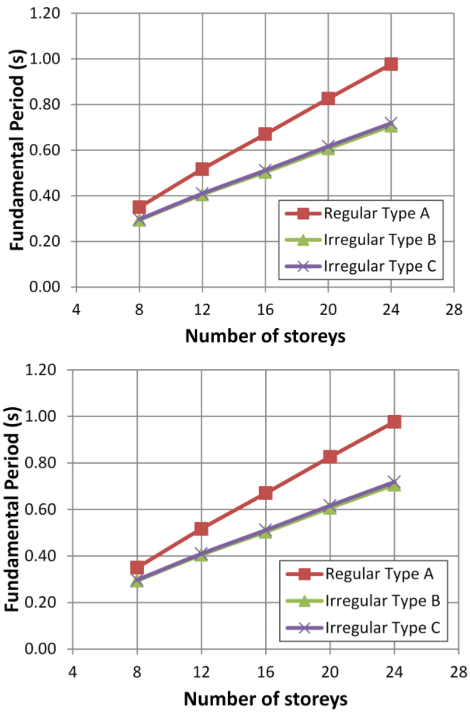


Fig.10 Influence of height on the fundamental period of a RC building frame with 6.0 m span length, (a) bare frame and (b) fully infilled with $7.50 \cdot 10^5$ kN/m stiffness

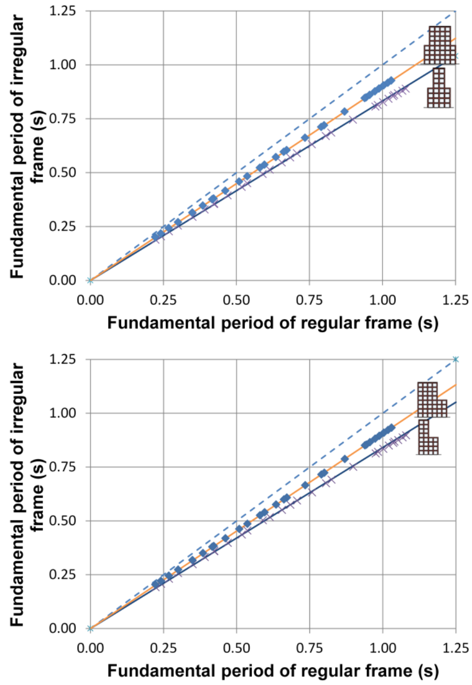


Fig. 11 Comparison of the fundamental period for the 8-storey regular and irregular building frames with 6 m span length, with 4 spans and 6 spans for (a) irregularity type B and (b) irregularity type C

at the 3rd storey (at 16.7% of the total height), the fundamental period of the regular building reduces by 2.6% for the irregular building. The reduction is equal to 6.3% for the second geometrical configuration which has two setbacks on both sides (50% reduction of the width) at the 3rd storey. If these setbacks occur at the 4th storey (at 25% of the total height), the reduction of the period is equal to 5.0% and 11.5%, respectively. Finally, if these setbacks occur at the 5th storey (at 33% of the total height), the reduction of the period is equal to 8.3% and 16.9%, respectively. From these results it can be clearly seen that if the setback occurs

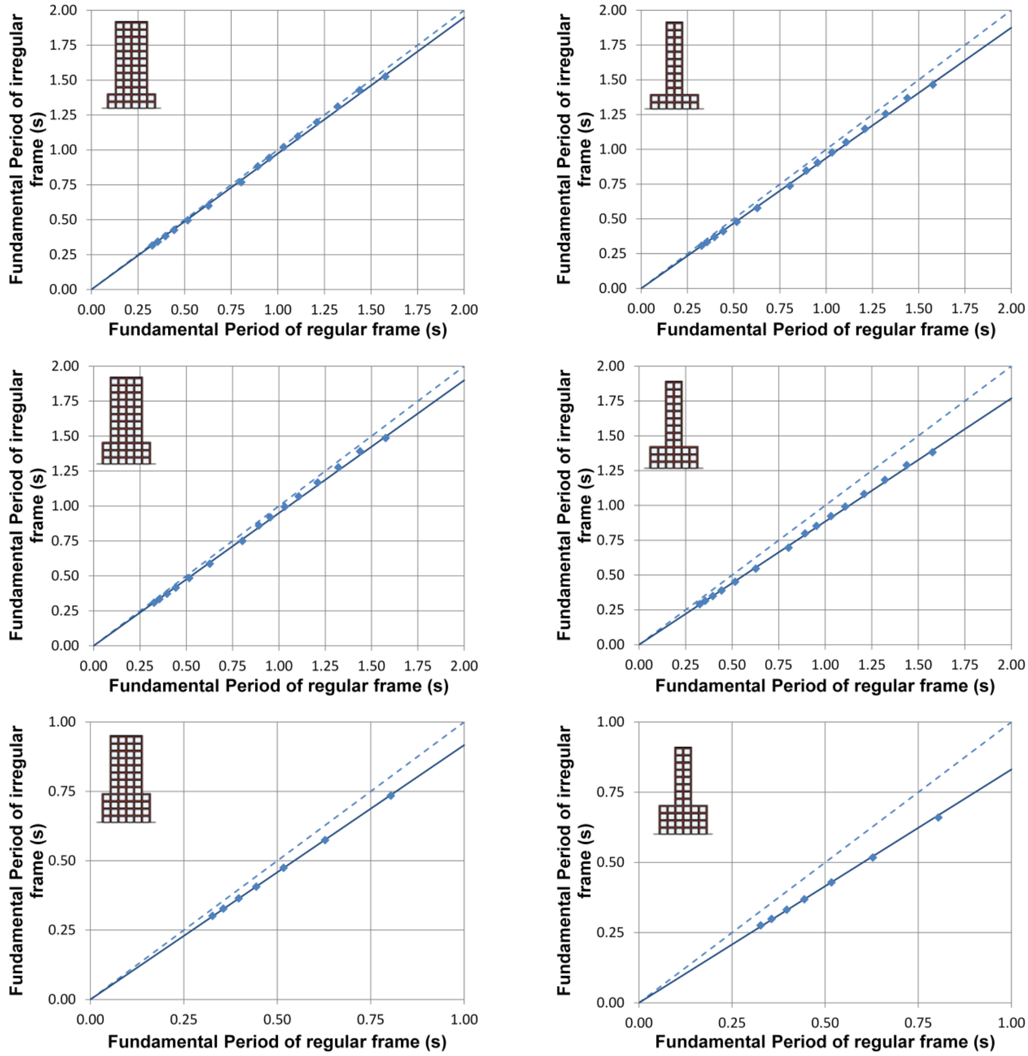


Fig. 12 Comparison of the fundamental period for the 12-storey regular and irregular building frames with 6 m span length

at a higher storey then the reduction of the fundamental period is higher. Moreover, if the reduction of the width of the frame at the setback is larger, the reduction of the fundamental period is also higher.

From the above results it is clear that the reduction of the period depends on the height of the building and is larger for the taller building frames. For the two types of vertical setback irregularity considered in this study (Fig. 1), the average reduction can be expressed with the following equation

$$1-\frac{1}{N^{0.1}} \tag{11}$$

where N is the number of storeys.

Every proposed equation for the estimation of the fundamental period of vibration can be multiplied by the reduction factor λ, expressed with Eq. (12), in order to take into account the vertical setback irregularity.

$$\lambda=\frac{1}{N^{0.1}} \tag{12}$$

5. Conclusions

Although the fundamental period of vibration is a critical parameter for the seismic design of structures, the available methods for its estimation do not take into account crucial parameters and very often conflict with each other, thus making their use uncertain. In the present study, which is a companion paper of previous research by the authors, the influence of the vertical setback irregularity on the fundamental period masonry infilled RC structures is investigated.

From the present study the following conclusions can be drawn:

- The vertical setback irregularity influence the fundamental period of vibration of RC frames.
- The fundamental period of the irregular building frames are consistently smaller than the period of the regular building frames with the same parameters.
- For the two main types of vertical setback irregularity considered in the current study, the reduction was similar.

• The reduction of the fundamental period is smaller for lower frames and larger for taller frames.

• The significant influence of span length, the presence of infill walls, their stiffness and the percentage of openings within the infill panel on the fundamental period of vibration, shown in previous papers, is also confirmed with analyses of irregular frame buildings.

Based on the above results, a reduction factor for the fundamental period of RC frame buildings with vertical setback irregularity is proposed. This factor depends on the number of storeys and can be used as a multiplier factor in any available equation for the estimation of the fundamental period of vibration.

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