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CODE FORMULA FOR THE FUNDAMENTAL PERIOD OF RC PRECAST BUILDINGS

Marianna ERCOLINO[1], Gennaro MAGLIULO[2], Orsola COPPOLA[3] and Gaetano MANFREDI[4]

ABSTRACT

Recent seismic events in Europe, as L'Aquila earthquake (2009) and Emilia earthquake (2012), seriously hit the precast concrete structures. Among the others, one of the most widespread damage is the collapse of the cladding panels system. The high vulnerability of precast panels connections motivate the need of an extended study on the behavior of precast panels and on their interaction with the structure. The first step of this study must be the investigation of the dynamic behavior (in particular, the vibration periods) of one-story precast structures with and without cladding panels.

In this paper a parametric study is performed in order to evaluate the first period of one-story precast buildings, without and with the cladding system. In particular, the aim of the work is to compare the results of the model with cladding panels to the dynamic properties of the bare model, in order to evaluate the cladding system influence on the stiffness and on the first period of this structural typology. Moreover, the results are compared with the code relationships that predict the first period of structures in linear static analysis.

INTRODUCTION

Precast structures have a very large diffusion and for some use categories represent a considerable estate. However, latest earthquakes, as L'Aquila (2009) and Emilia earthquakes (2012), pointed out some lacks in the design approach for precast buildings, among which the inadequacy of the panel–to-structure connection system design. Indeed, most of the numerous damaged precast buildings showed the collapse of cladding panels, caused by the connection systems failure, even in case of a good structural response (Faggiano et al., 2009; Magliulo et al., 2014c)

According to the design approach of the actual European and Italian codes, the precast structures are usually considered as bare systems and the cladding panels are separately designed for actions deriving by their weight and seismic or wind loads; no interaction between panels and structure is then considered. However, during a seismic event the panel-to-structure connections could let the panels collaborate with the structural system, increasing the structural stiffness and the seismic demand on the connection devices (Magliulo et al., 2014b).

The presented paper investigates the cladding panel influence on the first vibration period of typical precast industrial buildings by means of a parametric study. Both the bare model and the model with vertical panels are implemented in OpenSees (McKenna and Fenves, 2013) analysis code and modal analyses are carried out in order to record the first period of the analyzed precast structures. The

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[1] PhD, University of Naples Federico II , Naples (Italy), marianna.ercolino@unina.it
[2] PhD, Assistant Professor, University of Naples Federico II , Naples (Italy), gmagliul@unina.it
[3] PhD Candidate, University of Naples Federico II , Naples (Italy), orsola.coppola@unina.it
[4] PhD, Full Professor, University of Naples Federico II, Naples (Italy), gamanfre@unina.it

inadequacy of the simplified relationship, proposed by some codes to evaluate the first period for this typology of structures, is also demonstrated and more suitable formulas are proposed.

THE CASE STUDY: ONE-STORY PRECAST BUILDING

The benchmark structure is a one-story precast structure and it is schematically described in Fig. 1. The considered variable parameters are some geometrical characteristics: the columns height, H, (8 values), the length, $L_{bay,z}$, (3 values) and the number, $N_{bay,z}$, (2 values) of the transversal bays (Z direction) and, finally, the number of the longitudinal bays (X direction), $N_{bay,x}$, (6 values). The longitudinal bay width is assumed constant, i.e. equal to 12m for all the case studies. The structures are designed for a high seismicity Italian area (design peak ground acceleration at the bedrock equal to 0.27g) according to Eurocode 8 (CEN, 2005). For each structure all the columns have the same square cross-section, since this condition is widespread in industrial precast buildings.

The precast concrete panel must be anchored with efficient connecting devices. In the case of horizontal panels, these devices connect the panel to the columns, while, in the case of vertical panels, they connect the panels to the roof horizontal beams. This study refers to the case of vertical panels.

The investigated vertical panel connection system (Fig. 2a) consists of two steel profiles, embedded in the element to be fixed (panel) and in the fixed element (horizontal element, e.g. beam). The two profiles (Fig. 2b) are generally orthogonal in order to allow the adjustment of the panel in two directions. The connector (Fig. 2d) is a steel plate, which may be knurled to prevent sliding; it has a hammer-end for the attachment in the connected element, and a slot for adjustment in the assembly phase. The connector links the interlock (Fig. 2c) to the profile in the horizontal element. It follows that the connection yields three unrestrained, even though limited, translational degrees of freedom: one is ensured by the slot in the plate (typically displacement of 50 mm is allowed), and the other two are due to the channel bars (the allowable displacement depends on the profiles length). At the bottom, the panel connection can be ensured in different ways. Welded or bolted metal anchors are today widespread.

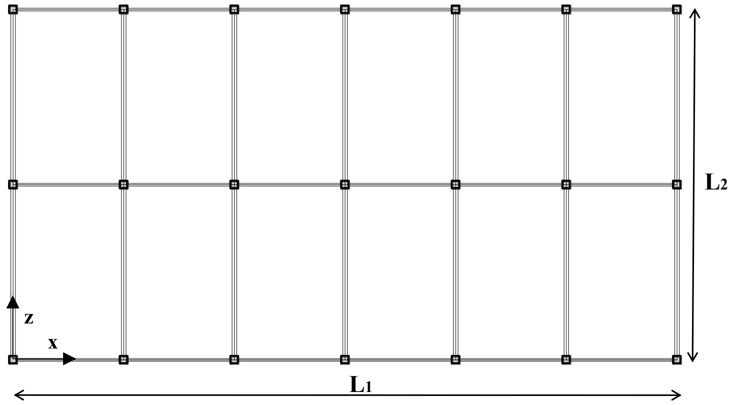
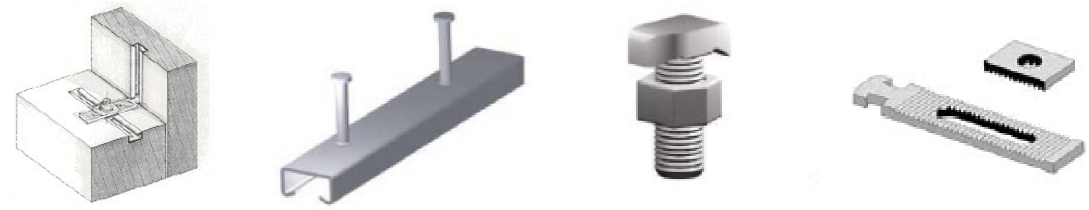


Figure 1 Plan view of the benchmark one-story precast building



(a) (b) (c) (d)

Figure 2 Investigated connection between vertical precast panel and resistant structure

MODAL ANALYSIS RESULTS OF THE BARE CASE STUDIES

The different case studies are modeled as bare three-dimensional structures in order to perform modal analyses.

The bare model consists of columns, girders (variable section beams) and secondary beams. Each of these elements is modeled as beam elastic element. For columns, halved inertia is considered due to the low values of axial loads in this type of structures. The structural model does not include roof elements, but they are considered in the mass evaluation.

The connection system of the column to the socket foundation is considered as a fixed joint (Osanai et al., 1996). The beam-to-column connection is a dowel connection (Magliulo et al., 2014a), that is modeled as a hinge, not able to transfer bending forces. The roof is designed according to the code provisions in order to satisfy the rigid diaphragm hypothesis, assumed in the model. As a consequence, the total mass of the structure is concentrated in the master node at the roof level.

In Fig. 3 the first vibrational periods are plotted versus the EC8 (CEN, 2005) and Italian code (D. M. 14/01/2008, 2008) relationship (1). This formula is proposed to simply evaluate the first period of structures in linear analyses and it is equal to:

$$T_1 = C_1 \cdot H^{3/4} \tag{1}$$

where H is the total height of the structure in meters and C_1 is a coefficient that depends on the structural system: for precast structures C_1 is assumed equal to the value used for concrete framed structures, that is equal to 0.075.

In Fig. 3 the gray line denotes the period values obtained by the code formula (1) and the black circles are the first periods from the performed linear modal analyses. The trend shows that the code relationship always returns lower values with respect to those obtained by modal analysis, considering stiffer structures.

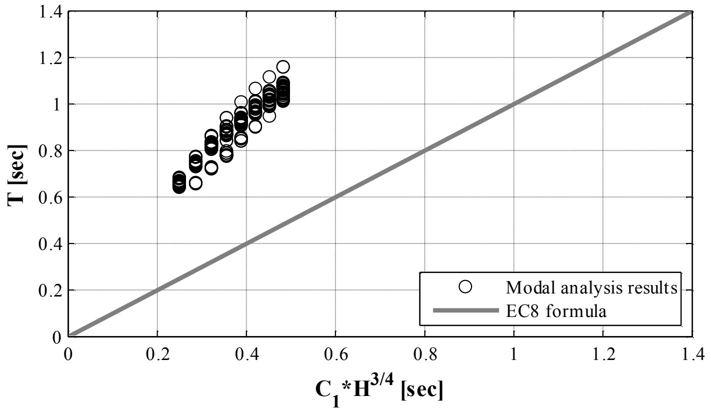


Figure 3 Values of the first period, T , obtained by modal analyses (black circles), versus the EC8 formula (1) (gray line) for bare structures

In order to propose a more effective formula, different regression analyses are performed on the results of the linear modal analyses. Hence, the period formula can be assumed equal to:

$$T = \alpha \cdot H^{\beta} \tag{2}$$

The best-fit equation can be found by determining the values of α and β for a linear regression problem, based on the following relationship:

$$\log(T) = \log(\alpha) + \beta \cdot \log(H) \tag{3}$$

Fig. 4 shows the regression formulas along with the first period values of the modal analyses.
In this Figure:

- the black solid curve represents the results of the regression analysis in which the β value is rounded off to the nearest 0.05 (unconstrained analysis), e.g. β=0.51 is rounded off to 0.50 and β=0.53 is rounded off to 0.55;
- the gray solid curve represents the results of the regression analysis (constrained analysis) in which β is assumed equal to the EC8 value (0.75).

Moreover, the same plot reports also the 16th percentile curve for the two regression formulas, since it could be proposed in a force-based design approach. Since the log(T) variable is assumed to be normal distributed and since the standard error approaches the standard deviation for large number of samples, the 16th percentile value is found with a value of α_r equal to:

$$\log(\alpha_r) = \log(\alpha) - s_e \tag{4}$$

In this equation s_e is the standard error of the analysis, equal to:

$$s_e = \sqrt{\frac{\sum_{i=1}^{n}\left[\log(T_i) - (\log(\alpha) + \beta \cdot \log(H))\right]^2}{(n-2)}} \tag{5}$$

The formulas obtained by the constrained regression analysis with the EC8 β value (gray lines) do not fit well the modal analysis results as the unconstrained formula. This evidence is also confirmed by the lower value of the correlation factor (R^2) in the case of the EC8 β value (0.78) with respect to the unconstrained problem (0.92).

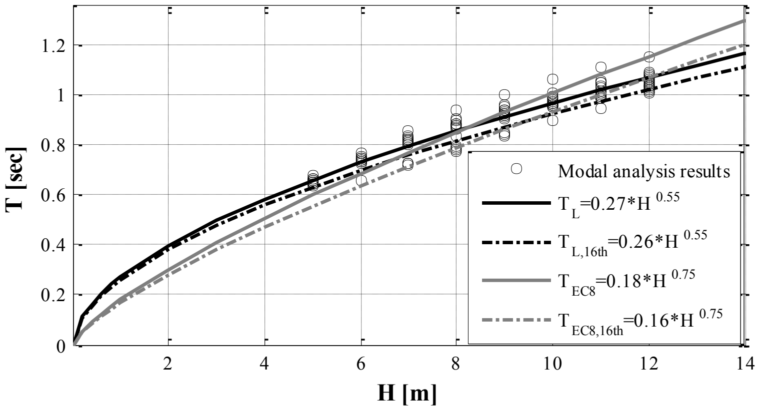


Figure 4 Values of the first period, T, obtained by modal analyses (black circles), versus the height of the structure, H, for bare buildings, along with the best fit curves (solid lines) from the linear regression analyses, and the 16th percentile curves (dash-dot lines)

The described parametric study has been performed on buildings designed for a single high seismic zone (I in Table 1). In order to cover a wider range of buildings other three seismic zones are considered. The same geometrical variables are assumed and the same 288 case studies are implemented in OpenSees program in order to perform linear modal analyses.

Table 1 shows the considered seismic zones, in terms of peak ground acceleration on rock soil for a return period equal to 50 years (a_g, 2nd column) and 475 years (a_g, 3rd column), and peak ground acceleration for a return period equal to 475 years and EC8 type B soil (PGA, 4th column).

Fig. 5 shows T_1 as a function of (1) for bare one-story precast buildings with floor rigid in its own plane, designed according to all the considered seismic zones. The results demonstrates again that the EC8 formula returns lower values than those obtained by modal analyses.

In order to give a common formula for the first periods of bare one-story precast buildings in different seismic zones, a regression analysis is performed on all the values of first period, providing α equal to 0.30 and β equal to 0.60 (black solid curve in Fig. 6). The matching of the regression curve is lower than in the case of the single seismic zone (Fig. 4). Then, a new parameter (PGA) is introduced in the period formula.

Table 1 Assumed seismic zones: peak ground acceleration on rock soil for a return period equal to 50yy (2nd column) and 475yy (3rd column), and peak ground acceleration for EC8 with type B soil (4th column)

Seismic zone	a_g $(T_R = 50yy)$	a_g $(T_R = 475yy)$	***PGA*** $(T_R = 475yy)$
[-]	*[g]*	*[g]*	*[g]*
I	0.108	0.270	0.324
II	0.078	0.196	0.235
III	0.062	0.154	0.185
IV	0.042	0.105	0.126

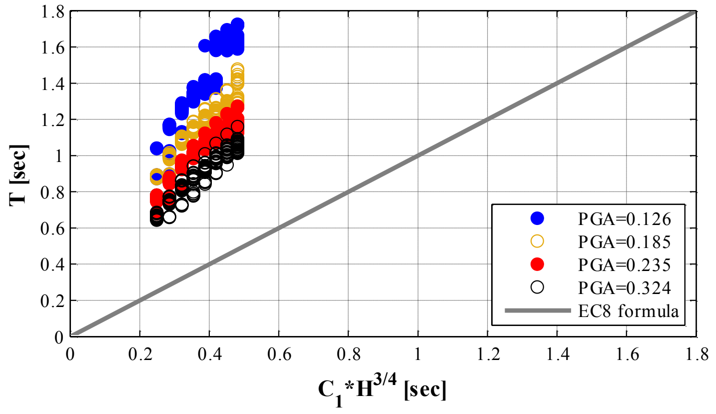


Figure 5 Values of the first periods, T, obtained by modal analyses (circles), versus the EC8 formula (1) for bare one-story precast buildings (gray line) in all the assumed seismic zones

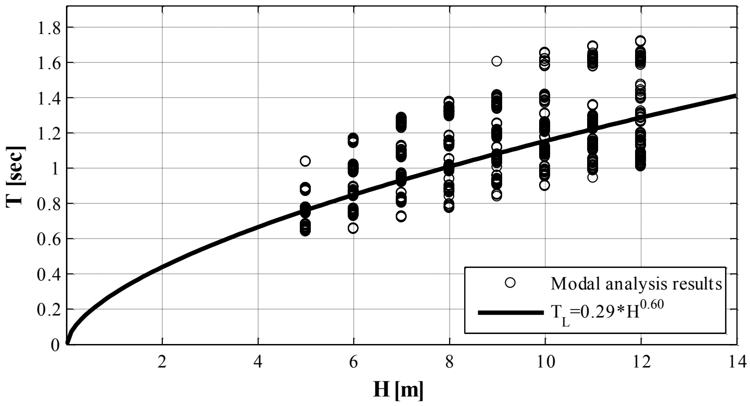


Figure 6 First periods, T, obtained by modal analyses (black circles), versus the height of the structure, H; along with the proposed formula (black line), obtained from the regression analysis on the bare buildings designed for all the seismic zones

In Fig. 7 the first periods of all the bare buildings (circles) obtained by modal analyses are reported along with the proposed period formula (PGA is in g):

$$T = 0.16^2 \cdot PGA^{-0.4} \cdot H^{0.6} \quad (6)$$

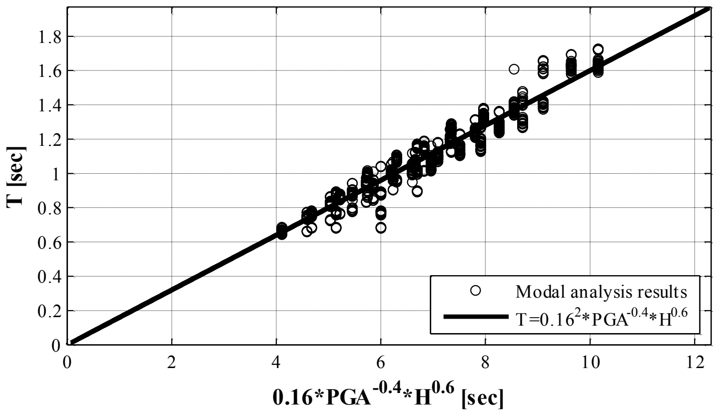


Figure 7 First periods, T, obtained by modal analyses (black circles), versus the proposed formula (6) for one-story precast bare buildings (black solid line)

MODAL ANALYSIS RESULTS OF THE CASE STUDIES WITH PANELS

According to the described design approach, the panel-to-beam connections should be designed in order to allow large interstory drifts expected under dynamic actions and the vertical panels could be modeled as vertical pendulums. However, the connections adopted in the last years in Europe for panel-to-beam connections of one-story precast industrial buildings do not actually accommodate interstory drift, causing interaction between structure and panels.

In order to take into account such an interaction the authors propose as model of the panel-to-structure connections:

- two hinge connections at the bottom of each panel;
- two constraints that allow rotations but avoid the sliding of the panel with respect to the beam, at the top of the panel.

The single panel is modeled as a two-dimensional frame (Fig. 8), as proposed in (Hunt and Stojadinovic, 2010), composed of four elastic one-dimensional elements:

- two vertical elements, characterized by area and moment of inertia equal to the half of area and moment of inertia of a single panel;
- two horizontal beams modeled as rigid bodies.

The vertical elements take into account the inertia properties of the panels and the two horizontal rigid elements give to the panel model the characteristics of a bi-dimensional element.

The seismic masses are assumed equal to the values of the bare models.

In all the models the rigid diaphragm hypothesis is used, assuming stiff and strong roof connections that allow a rigid behavior of the roof, also when the cladding panels interact with the structure.

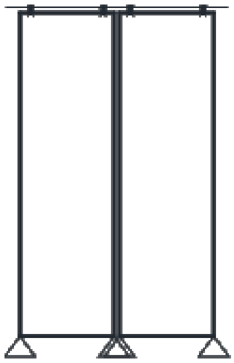


Figure 8 Linear elastic model of the structure with cladding system: model of two vertical panels with the bi-dimensional frame

Fig. 9 shows the first vibrational periods versus the EC8 formula (1), where C_1 is equal to 0.075. As first conclusion, it can be stated that the first vibration periods are significantly influenced by the presence of the cladding system, presenting large variations with respect to the case of bare frame (reduction up to 80%). As a consequence, the EC8 formula (gray line) overestimates the first period of the buildings with cladding system (black circles), considering more flexible structures.

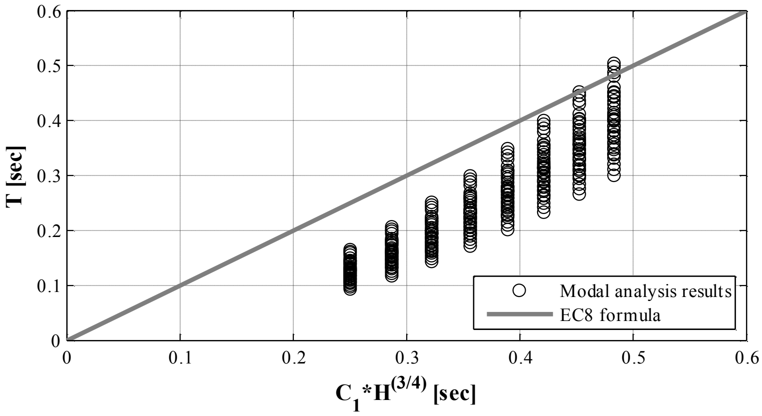


Figure 9 Values of the first periods, T, obtained by modal analyses (black circles), versus the EC8 formula (1) for one-story precast buildings with cladding system (gray line)

The extended parametric study is then carried out for buildings that include the external cladding system. In Fig. 10 the first periods of these buildings, obtained by the modal analysis, are plotted as a function of the EC8 first period formula, along with this formula itself.

Fig. 10 shows again that the trend of the periods from the modal analysis (circles) is opposite to that found for bare frames: the most of the points are arranged below the EC8 formula line (gray line).

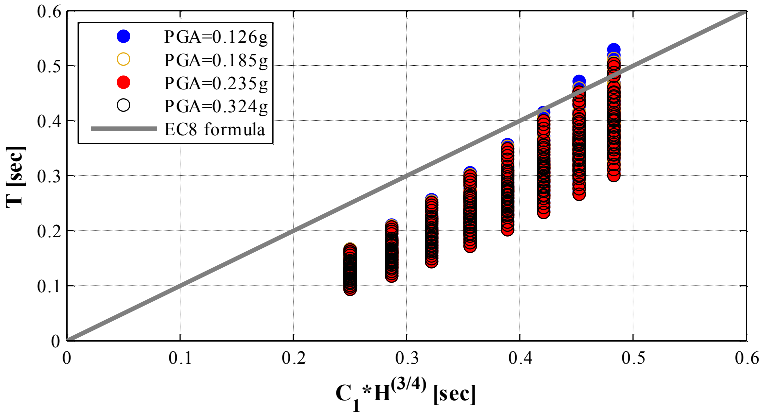


Figure 10 Values of the first periods, T, obtained by modal analyses (circles), versus the EC8 formula (1) for one-story precast buildings with cladding system (gray line) in all the assumed seismic zones

As for the bare case studies, different regression analyses are performed. Fig. 11 shows the best fit curve (solid lines) and 16th percentile curve (dash-dot lines) from the unconstrained regression analysis (black lines) and the constrained regression analysis with the EC8 value for β (gray lines). All the regression analyses give higher errors and lower correlation factors if compared to the bare buildings results: the relationship that includes only the height provides a worse fit of analytical results.

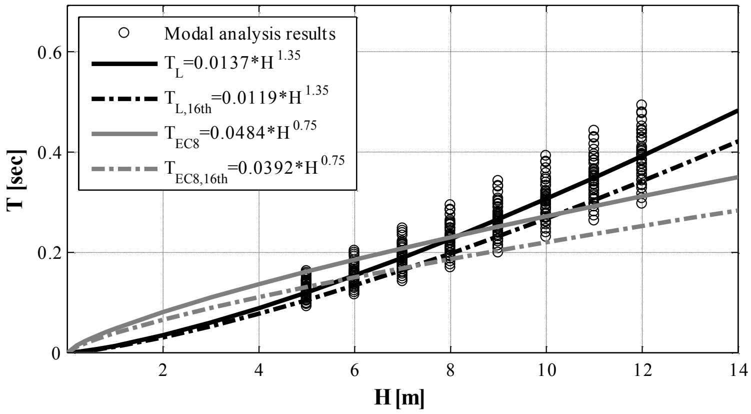


Figure 11 Values of the first periods, T, obtained by modal analyses (black circles), versus the height of the structure, H, for buildings with cladding panels, along with the best fit curves (solid lines) from the linear regression analyses, and the 16th percentile curves (dash-dot lines)

In order to find a better relationship, some geometrical characteristics, besides the building height, are considered (Goel and Chopra, 1998) and the following function is found to be the most suitable to fit the modal analysis results:

$$F_1 = \sqrt{L_x} \cdot H^{3/2} \tag{7}$$

where L_x represents the long side length (in meters) of the building and H is its total height (in meters). Then, the following new formula is proposed in order to evaluate the first vibration period of one-story precast buildings with floor rigid in its own plane and cladding system:

$$T_1 = 0.00088 \cdot H^{3/2} \cdot L_x^{1/2} \tag{8}$$

In formula (8) the intercept value is neglected in order to have a simpler relationship, obtaining anyway lower period values (red line in Fig. 12), which generally are on the safe side.

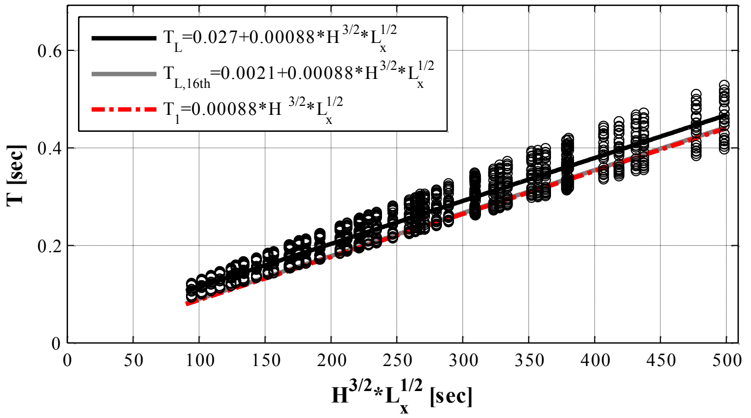


Figure 12 First periods, T, obtained by modal analyses (black circles), versus the F_1 factor (7), along with the best fit curve (solid black line) from the linear regression analysis, the 16th percentile curve (solid gray line) and the proposed formula (8) (dash-dot red line)

CONCLUSIONS

The main purpose of the described work is the investigation of the cladding system influence on the first vibration period of one-story precast buildings with floor rigid in its own plane.

A parametric study is performed in order to evaluate the dynamic properties (the first period) of 288 realistic buildings, designed according to EC8 and for different seismic zones. The considered variables are some geometrical characteristics of the structures.

According to the modal analyses results, the first vibration period is significantly influenced by the presence of the cladding system, presenting large variations with respect to the case of bare buildings (reduction up to 80%). Moreover, the simplified EC8 formula, that evaluates the first vibration period as a function of the height of the building, is not suitable either for the case of the bare building or for the case of building with cladding system. Hence, this relationship strongly underestimates the first periods of the analyzed bare one-story precast buildings, and overestimates the first periods of the same buildings with cladding system. With reference to the analyzed bare one-story precast buildings, a different relationship is found, considering four different seismic zones, the peak ground acceleration PGA is introduced as a new parameter in the period formula and a new relationship is found. In the case of one-story precast buildings with cladding system, a new relationship is found between the first period and a proposed parameter, that depends on a plan dimension of the building and on its height. This relationship has a very good correlation factor and a low standard error for all the four studied seismic zones.

ACKNOWLEDGEMENTS

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