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INFLUENCE FACTORS FOR THE ASSESSMENT OF MAXIMUM LATERAL SEISMIC DEFORMATIONS IN ITALIAN MULTISTOREY RC BUILDINGS

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Abstract. *In the aftermath of low-to-moderate earthquakes, simplified methods allowing fast estimate of maximum lateral deformations experienced in multistory building are particularly useful when estimating nonstructural damage on a large building inventory. In particular, Miranda [1] introduced a simplified method that adopts an equivalent continuum elastic structure to estimate both maximum roof displacement and maximum interstorey drift ratio for a given response spectrum. Based on a closed-form solution, this method was further extended [2] to account for higher vibration modes, different distributions of lateral forces and non-uniform stiffness along the height. However, the method assumes that building properties will continuously vary along the height, assumption that is not generally valid for the Italian building stock due to the presence of knee beams and infill panels. This paper investigates on the effect of variation of infill properties on the elastic lateral response of infilled RC buildings, assessing the influence of different characteristics, such as geometric and material properties or the opening percentage, on IDR_{max}. Plane Multi-degree-of-freedom elastic models including explicit modeling of infill panels are adopted and the effect of local discontinuities is included, while linear time-history analyses are performed considering several input ground motions. The effect on the interstorey drift ratio of different opening percentages and infill arrangements, both at the same storey and along the height, are considered to account for discontinuities caused by the presence of infills. Further, the influence of different types and thicknesses of the infill panels, level connection to the surrounding frame is analyzed.*

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1 INTRODUCTION

The inter-story drift ratio, IDR, defined as the difference in lateral displacements between two consecutive floors normalized by the inter-story height, has proven to be one of the best correlated parameters to damage in buildings ([3]-[8]), and this applies especially also for those part of the nonstructural system that are rigidly connected to the structure, such as masonry infill walls. There exist a number of proposals in literature for the simplified evaluation of lateral demands in multistory buildings ([9]-[12]). Among them, the approach by Miranda [1], successively corrected to account for the stiffness variation in elevation [2], allows a simplified estimation of maximum roof displacement and inter-story drift IDR_{max} that has proven to yield reliable results for multistory buildings in the USA, designed according to modern seismic standards. However, existing buildings that were not designed according to modern seismic design codes may be characterized by a non-uniform stiffness variation along the height and as a consequence these simplified methods may loose their effectiveness [13]. This may happen also for infilled RC buildings, whose lateral stiffness is largely influenced by the infill characteristics and on the efficacy of their casting with the surrounding frame.
This paper investigates on the effect of variation of infill properties on the elastic lateral response of infilled RC buildings, assessing the influence of different characteristics, such as geometric and material properties or the opening percentage, on IDR_{max}.
Adopting a single RC frame as the "reference" structure the consequence of variation of single parameters on IDR_{max} is studied, and their joint effect evaluated through the story level stiffness. The latter, that can be even computed in a simplified manner according to the proposal in [14], is used as a synthetic representative parameter for building elastic characteristics at the story level. Also, the story level stiffness variation (at the lower or upper stories of a building) is used to investigate on its influence on the elastic response, also in comparison with the results of simplified approaches.

2 ELASTIC MODEL OF UNIFORMLY INFILLED RC FRAME

Reference structure
The reference structure is a six-story gravity load designed RC frame with three bays, with length equal to 6.0m and an interstorey height equal to 3.0m. The analyzed planar frame is the perimeter longitudinal frame extracted from a 3D structure symmetric in plane, in both longitudinal and transverse directions, with three bays in both the longitudinal and the transverse direction and with a floor area equal to 216 m^2. The slab way is parallel to the transverse direction, as typical for existing gravity load designed GLD buildings [15]-[16]; the dead load is equal to 5.95 kN/m^2 for all stories and the live load is equal to 2 kN/m^2. The element dimensions of the analyzed frame were obtained via a simulated design procedure applied for a GLD building [17], assuming a mean concrete strength equal to 20MPa. Beams are 25cm wide and 55cm high; columns are 25cm wide and 25cm high except for interior columns from first to third story that are 40cm-35cm-30cm high, respectively. The model geometry for the reference frame is sketched in Fig. 1. In the reference frame, infill panels are realized with hollow clay brick panels and are uniformly distributed along the height. Panel thickness is assumed equal to t_w=20 cm (corresponding to a double layer brick infill -12+8) and elastic shear modulus G_w= 1350 MPa. Height h_w and length l_w of infill panels take into account the beam and column dimensions, i.e. are clear dimensions.

Analytical model

The building model is a two-dimensional finite element multi-degree of freedom system developed using OpenSees [18]. The response of beams and columns is represented by axially rigid elastic elements. Both beams and columns are assumed cracked and the element stiffness is evaluated according to [19]. Rigid beam-columns joints of finite size are adopted in the model.

The presence of infill panels is simulated through a simplified macro-model adopting equivalent struts acting only in compression, as sketched in Figure 1. The numerical model of the infill panels adopts the relationship proposed in [20]). In particular, the parameters defining the force-displacement relationship depend on mechanical and geometric properties of the masonry panel and of the surrounding frame. Referring to the infill behavior, only the first (elastic) branch, which corresponds to initial shear behavior of the un-cracked panel, is employed. The parameter defining first branch of the force-displacement curve is the initial stiffness of the un-cracked initial tract K_w:

$$K_w = \frac{G_w t_w l_w}{h_w} \tag{1}$$

Where G_w is the elastic shear modulus of the infill material; l_w and h_w are the clear length and height of the infill panel, respectively; and t_w is the thickness of the infill panel.

The compression strut is modeled as a truss element employing a uniaxial elastic-no tension material.

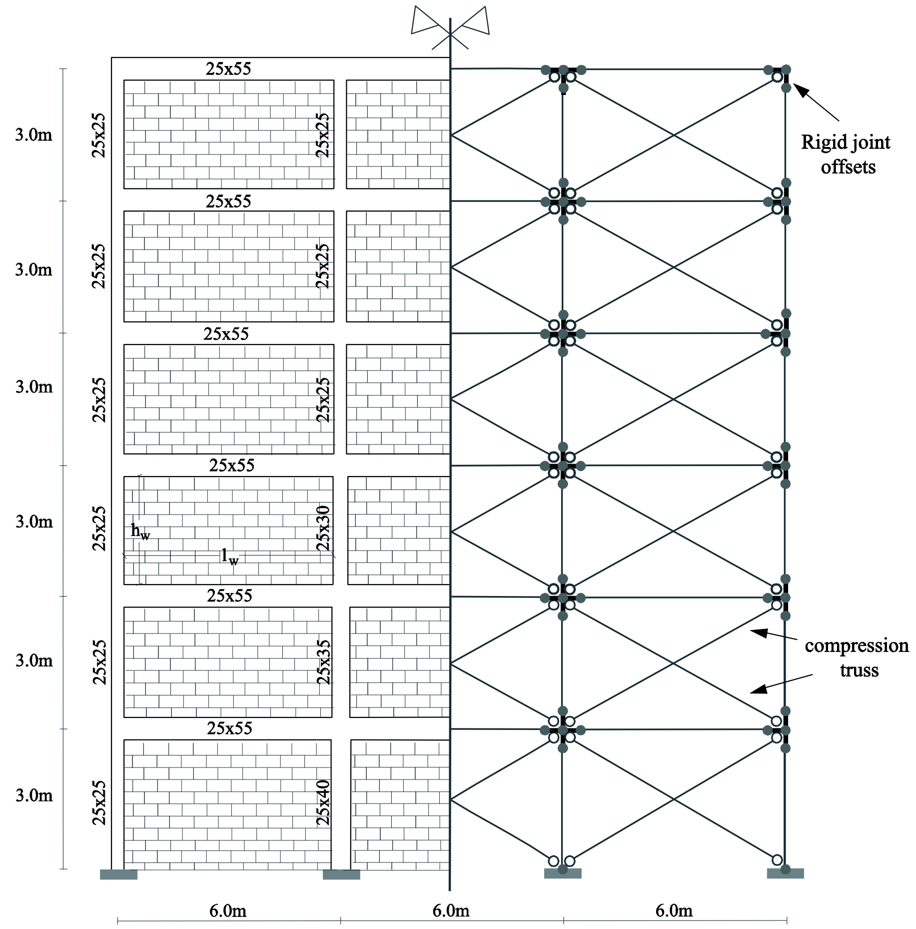


Figure 1: "Reference" structure geometry and analytical model.

Noticeably, when openings are present in the infill panel, a reduction of lateral stiffness has to be expected. In order to take into account the effect of infill openings, a reduction of the envelope forces in the load-displacement relationship of the panel is obtained by multiplying it by $\lambda_{openings}$, as suggested in [21]:

$$\lambda_{openings} = \max\left(0;1-1.8\cdot\frac{A_{openings}}{A_{panel}}\right) \tag{2}$$

where $A_{openings}$ and A_{panel} represents the area of the openings and of the infill panel, respectively.
Finally, both structural and nonstructural masses are considered as acting only in the horizontal direction. In order to include the influence of infill walls on structural damping, a 10% Rayleigh damping is assumed according to [22].

2.1 Influence of infill characteristics on elastic periods and modes

In this study, we refer to infill panels realised with clay-holed bricks disposed in double arrays. The definition of mechanical characteristics of the panels is affected by high uncertainties. With the aim of considering the possible variability of such characteristics and to investigate its effect, the minimum and maximum values of the elastic tangential modulus G_w suggested for masonry formed by clay bricks, with hole percentage less than 45% in the actual Italian seismic code [23], are considered, namely 1080 and 1620 MPa; the "reference" value G_w= 1350 MPa corresponds to the mean. For what concerns the geometric characteristics, three possible values for the infill thickness are assumed, t_{w1}= 16 cm and t_{w2}=20 cm and t_{w3}=24 cm, first case corresponding to double layer brick infill 8+8, second one to 12+8 and third to 12+12. Moreover, the effect of opening is considered; in particular, the ratio $\alpha_{openings}=A_{openings}/A_{panel}$ is varied from 0% (the reference case) to 20% and 40%.

A parameter that that could be used to synthetically represent the effect of variation of the aforementioned parameters on the structural model and response is the story lateral stiffness. A simplified approach for its evaluation was proposed in [14]; it defines the storey lateral stiffness of MRFs through equivalent simple systems that consists of sub-modules of one-bay/one-story frames. The method allows to account for the influence on lateral stiffness of both columns and beams and infill panels (considered as an equivalent concentrically braced frame).

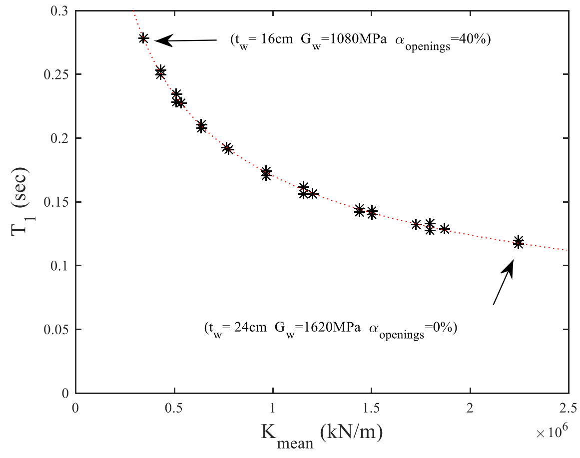


Figure 2: Variation of T_1 as a function of mean story lateral stiffness K_{mean}.

Fig. 2 synthetically shows the effect of the three parameters G_w, t_w and $\alpha_{openings}$ on the mean story lateral stiffness (K_{mean}) and the associated fundamental period of the frame (T_1). K_{mean} is here defined as the mean lateral stiffness of the all the frame stories, with storey stiffness evaluated according to [14]. In particular, combining the possible variations for the three considered parameters (G_w, t_w and $\alpha_{openings}$) a total number of 27 configurations is obtained. The K_{mean}-T_1 points representing the different configurations are shown in figure. It can be noted that T_1 varies proportionally to 1 versus the square root of K_{mean}, with slight deviations due to the variation of seismic masses among the different configurations (depending on the the variation of t_w and $\alpha_{openings}$). In the figure, it is also evidenced that the lower and the upper bounds for K_{mean} are represented by the case in which the triplet (G_w, t_w, $\alpha_{openings}$) assumes minimum and maximum values, respectively.

3 ELASTIC ANALYSIS OF THE INFILLED FRAME

The elastic response of the RC infilled frames is studied using the set of accelerograms (two components from 21 earthquakes of the far field record set) included in ATC 63 [24]. All the accelerograms are scaled to the same intensity level and elastic analysis is performed. Adopting the peak ground acceleration a_g as Intensity Measure IM, and scaling all accelerograms to a_g=0.1 g, the IDR profiles shown in Figure 3 (a) are obtained. Black profile represents median results while red profiles represent the results obtained for each accelerogram. As it can be noted a high dispersion of maximum IDR at the various stories is obtained; this dispersion is mainly due to the variation of displacement spectrum value $S_d(T_1)$ for the different accelerograms when scaled to the same a_g; notably, the logarithmic dispersion is not constant along the height and varies between 0.23 and 0.27.

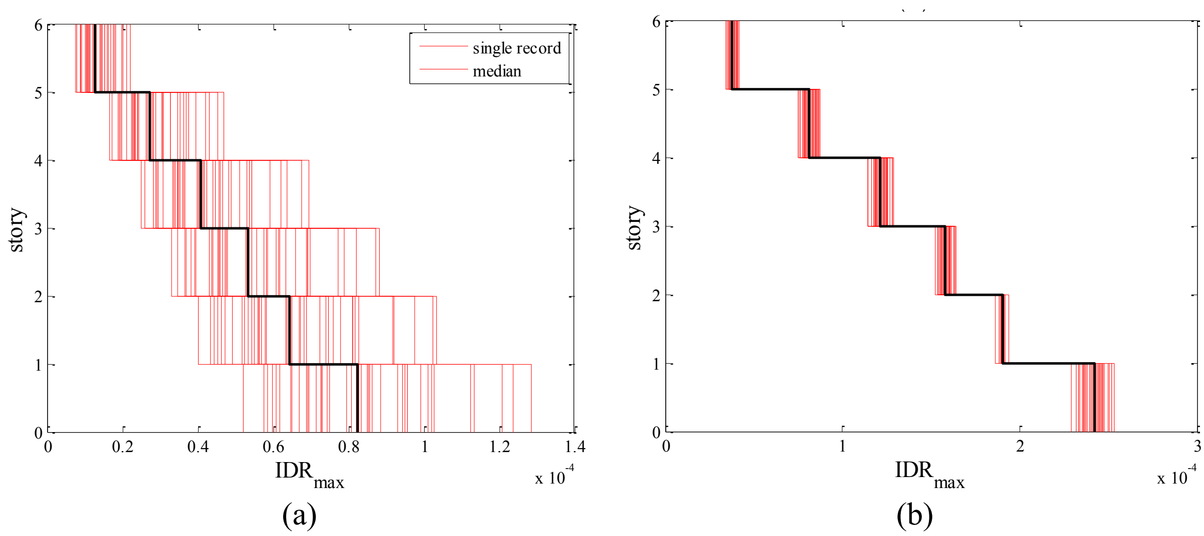


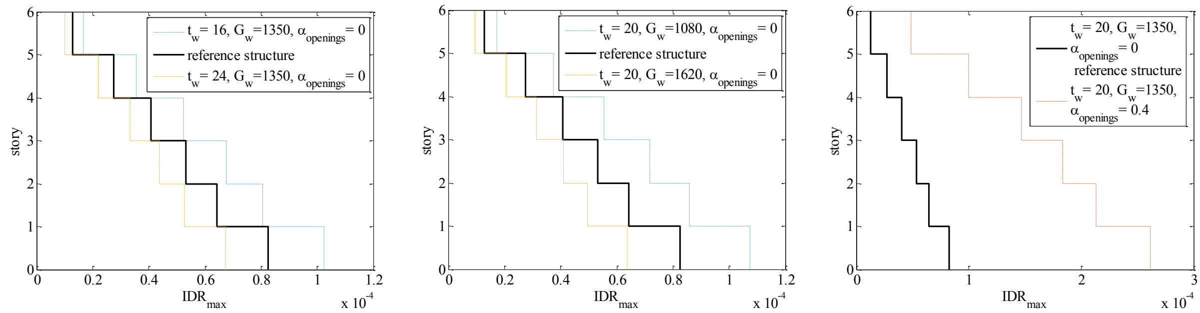
Figure 3: IDR profiles obtained for the "reference" structure after scaling the accelerograms to a_g=0.1 g (a) or to $S_d(T_1)$ =0.02 m (b).

Adopting $S_d(T_1)$ as IM and scaling all the accelerograms to $S_d(T_1)$=0.02m a lower dispersion is obtained, as shown in Figure 3 (b). The latter dispersion is due to the variation of displacement spectrum ordinates, with respect to period higher than the first, for the different accelerograms. In particular, the logarithmic dispersion decreases from a mean of 0.26 to 0.03.
Although the use of $S_d(T_1)$ as IM is appealing for the significant reduction of dispersion, in the following analyses it is chosen to scale accelerograms with respect to a_g in order to allow comparison of results among RC frames characterized by a different period T_1. Indeed, as

shown in § 2.1, the variation of infills characteristics determines the variation of K_{mean} and of the period T_1.

3.1 Variation of IDR_{max} depending on infill characteristics

Figure 4 (a)-(c) show the influence of the different parameters on the expected lateral IDR profiles for the 27 configurations obtained varying G_w, t_w and $\alpha_{openings}$. In particular, Figure 4 (a) shows the effect of variation of infills thickness t_w, Figure 4 (b) the effect of variation of G_w while Figure 4 (c) the effect of variation of $\alpha_{openings}$. As it could be expected, the increase (lowering) of thickness t_w and infill stiffness G_w, shown in Figure 4 (a) and (b), leads to an increase (decrease) in the system lateral stiffness and to the consequent lowering (increasing) of the expected lateral IDR with respect to the reference structure of about 22% and 29% (24% and 30%), respectively.

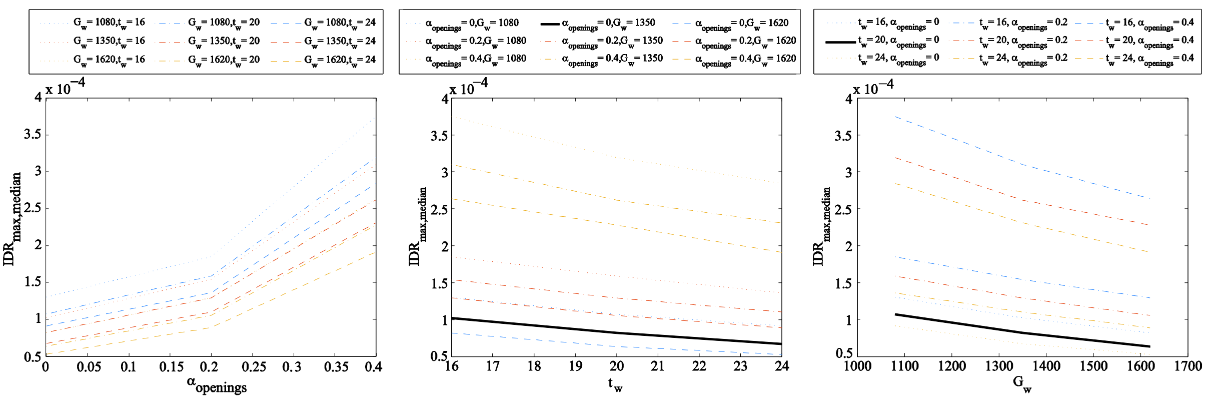


(a) (b) (c)

Figure 4: IDR profiles along building height considering the variation of t_w (a), G_W (b) and $\alpha_{openings}$ (c).

Opposite effect is observed for $\alpha_{openings}$; its higher value corresponding to more flexible structures and therefore to higher IDR (320% higher than that for the reference structure).

Figure 5 (a)-(c) show the variation of IDR_{max} for the different configurations as a function of $\alpha_{openings}$ (Figure 5 (a)), t_w (Figure 5 (b)) and G_w (Figure 5 (c)). Comparing results with respect to the ones obtained for the reference structure it can be observed that a maximum decrease of IDR_{max} of about 40% can be expected for the case of the stiffer structures considered (G_W=1620 MPa and t_w=24 cm), while maximum expected increase of IDR_{max} is nearly 500% for the case of more deformable structures (G_W=1080 MPa, t_w=16 cm and $\alpha_{openings}$=0.4).



(a) (b) (c)

Figure 5: IDR_{max} variation as a function of $\alpha_{openings}$ (a), t_w (b) and G_W (c)

As evidenced in section 2.1 the variation of infill properties has a direct influence on system's lateral stiffness and consequently on the elastic period and modes. The period is clearly connected to maximum system's elastic displacement response through $S_d(T_1)$ and modal participation factor, while also mode shapes influence the inter-storey drift profile. Figure 6 shows the variation of IDR_{max} as a function of T_1 (median values among the 42 records scaled to a_g=0.1 g). In figure, square markers of different colors refer to the case of frames with different infill characteristics, namely black squares (t_w=16 cm, $\alpha_{openings}=0$); magenta squares (t_w=20 cm, $\alpha_{openings}=0$); cyan squares (t_w=24 cm, $\alpha_{openings}=0$); red squares (t_w=16 cm, $\alpha_{openings}\neq 0$); green squares (t_w=20 cm, $\alpha_{openings}\neq 0$); blue squares (t_w=24 cm, $\alpha_{openings}\neq 0$).

For comparison, also the IDR_{max} obtained with the approach proposed in [1] are considered. In [1] a multistory building is modeled as equivalent continuum structure consisting of a combination of a flexural cantilever beam and a shear cantilever beam. The response of this equivalent system depends on a dimensionless parameter α, that controls the degree of participation of overall flexural and shear deformations in the simplified model of multistory buildings, on the period T_1 of the fundamental mode and on the damping. A value of α approximately equal to zero represents a pure flexural model while for $\alpha \rightarrow \infty$ a pure shear model is obtained. Generally, larger α (e.g. 30) correspond to shear-type buildings, while intermediate values correspond to a multistory building that combines shear and flexural deformations. In [1] a simplified formulation for estimation of IDR_{max} is proposed:

$$IDR_{max} = \beta_1 \beta_2 \frac{S_d(T)_1}{H} \tag{3}$$

In Eq. (3) β_1 can be considered as an amplification factor acting on the spectral displacement in order to obtain an estimate of the maximum roof displacement (similar to first mode participation factor) while β_2 as an amplification factor acting on roof drift ratio in order to obtain the maximum IDR for a building of height H. β_2 takes into account that usually the distribution of interstory drifts along the height of the building is not uniform. The authors have studied the relationship of β_1 and β_2 with α, number of storeys and the shape of the vector of horizontal loads applied to the equivalent system in the simplified formulation (a=0.01 triangular loads; a=2000 uniform loads). β_2 is significantly larger for buildings where shear deformations dominate over flexural deformations ($\alpha > 20$) with respect to the one obtained for flexure dominated buildings ($\alpha \approx 0$); this evidences that shear-type buildings have larger concentrations of interstory drifts than flexural-type ones.

In Figure 6 the IDR_{max} calculated with Eq. (3) for each configuration obtained varying infill parameters are also shown (circle markers of the same color as previously explained). The α of these buildings ranges between 18 and 22 when considering a=2000, and it is constant and equal to 710 when considering a=0.1.

In Figure 6 it is also reported IDR_{max} calculated with Eq. (3) when considering an approximate formulation for the fundamental period T_1 (triangles) and adopting α=20 as suggested in [11] for RC frames (diamond markers of the same color as previously explained). In particular, the expression for T_1 proposed in [25] is employed. It accounts for the effect of infill panels on the fundamental period and relays on the infill area in each story, normalized with respect to the story area, the building height and the presence of openings, while not accounting explicitly for the effect of G_w and the opening percentage on T_1. In this case, the difference in the estimate of IDR_{max} can be significant, mainly due to the variation of $S_d(T_1)$. For instance, for the reference frame the difference between T_1 from analysis and simplified formula is about 35%, that entail a difference in S_d (thus, in IDR_{max} according to eq. (3)) of about 60%.

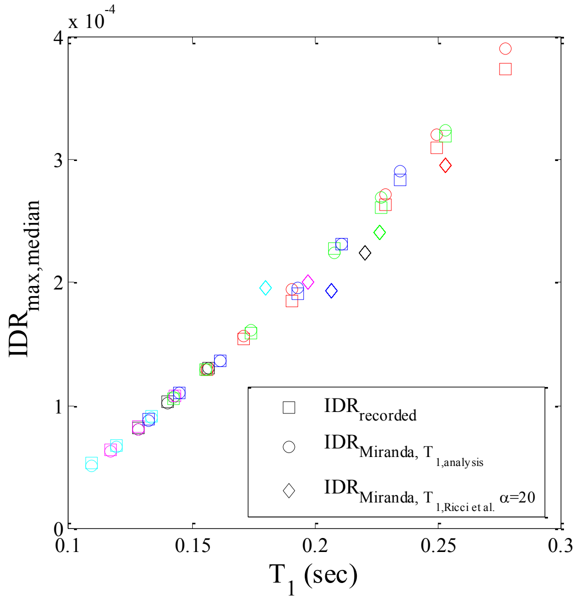


Figure 6: IDR_{max} variation as a function of T_1 (squares). IDR_{max} from Eq. (3) are also shown: (circles) uniform load distribution (a=2000) for calibration of α and T_1 from analyses; (diamonds) α =20 and T_1 from [25].

3.2 Preliminary evaluation of the influence of stiffness variation in elevation on IDR_{max}

In addition to uniform lateral stiffness variation along the height due to the variability of material properties (G_w) as well as the infill geometry (t_w, $\alpha_{openings}$), non-uniform stiffness variations along the height may occur in one or more stories due to the lacking of efficacy of the infill casting with the surrounding frame (i.e. participation to the lateral stiffness of the frame), to the presence of large openings (i.e., $\lambda_{openings}$=0) or even to the lacking infills in one or more spans at the same story.

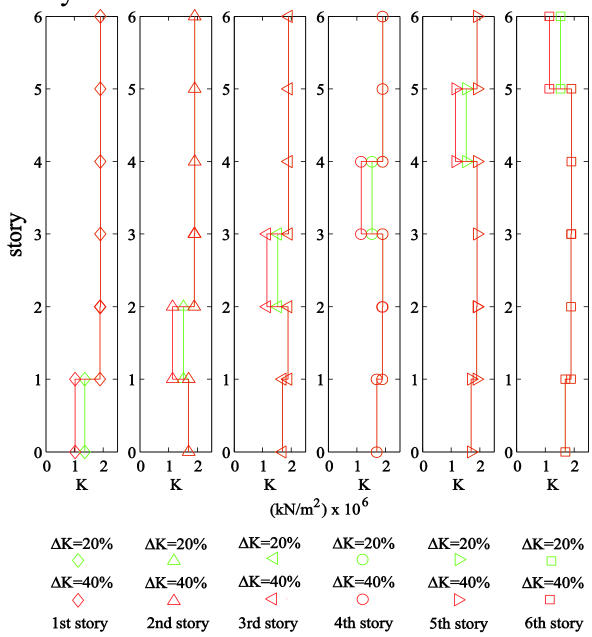


Figure 7: Local story lateral stiffness variation (K) of 20% (green) and 40% (red) applied to different storeys

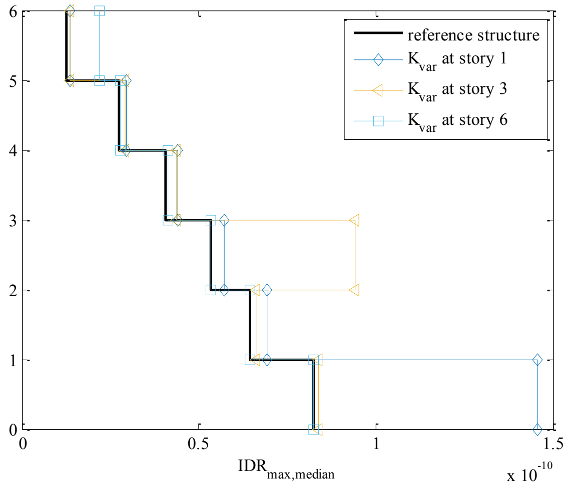


Figure 8: Median IDR_{max} profile for 40% reduction of story lateral stiffness considered at 1st, 3rd,6th story and for reference structure.

In order to investigate the effect of local variations in story lateral stiffness, in this paragraph two different values of stiffness reduction, namely 20% and 40%, are in each different story, see Figure 7.

Figure 8 shows the effect on IDR_{max} of the 40%-reduction of lateral stiffness in 1st, 3rd and 6th story with respect to the reference structure. It is possible to note that in the story in which the reduction of lateral stiffness is considered lateral deformation is generally 70-80% higher than the one recorded in the reference structure at the same story.

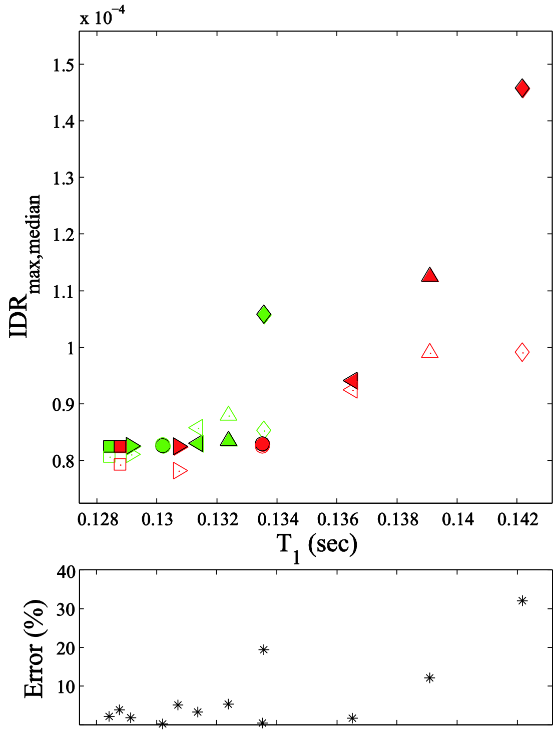


Figure 9: IDR_{max} (median) as a function of T_1, for 20% and 40% of reduction in lateral stiffness considered in different storeys (see Figure 7 for Markers). Filled markers represent IDR as recorded, empty markers are obtained adopting Eq. (3). For each period also the error between predicted and calculated IDR_{max} are reported.

In particular, when the reduction is applied to 1^{st} story, deformation concentrates in that story determining an increase of IDR_{max}, while the deformation demand slightly increases in upper stories with respect to the one of the reference structure and the increase is almost constant along the height. Instead, the influence of lateral stiffness variation on other stories reduces when it is considered in upper stories. In fact, when 40% variation of stiffness is considered in 3^{rd} story, the deviation in other stories with respect to the IDR profile for the reference structure decreases, and when the variation is considered in the 6^{th} story the effect in other stories in terms of lateral deformations is negligible.

In Figure 9 the median IDR_{max} from analyses of the configurations obtained varying story lateral stiffness are shown; green is adopted for 20% and red for 40%. Also, IDR_{max} calculated with Eq. (3), considering uniform load pattern, are represented with hollow markers. The α of these buildings show a significant scatter being equal to 710 when stiffness variations it is applied to 1^{st} story, 34 to 2^{nd}, 14 to 3^{rd} and 6^{th} story, and 10 to 4^{th} and 5^{th}. In Figure 9, filled markers represent the median results obtained from analyses, while hollow markers are obtained adopting Eq. (3) (for application of Eq. (3) T_1 from eigen analysis and α calibrated on the analytical models were adopted).

From Figure 9 it is possible to note that when lateral stiffness reductions are considered in first two storeys a larger error in the prediction of IDR_{max} with the method proposed in [1] is obtained (about 30% and 10% error when considering 40% of variation of stiffness in 1^{st} and 2^{nd} story, respectively). Despite T_1 and α are explicitly calibrated on the analytical model significantly reducing the error between predicted and calculated values, the high error in these cases is mainly ascribable to the basic hypothesis of the model that assumes continuous systems (i.e., no local variation in system properties such as lateral stiffness). When the reduction in lateral stiffness is considered in upper stories, the prediction error is generally lower than 10% since, as evidenced above for the 40% reduction in upper three stories, the maximum IDR still occurs at the 1^{st} story and it is quite similar to the one calculated for the reference structure.

4 CONCLUSIONS AND FUTURE STUDIES

The study presented in this paper investigates on the influence of relevant factors for the assessment of maximum elastic lateral deformations in typical Italian RC multistory buildings and on the effect of their variation along building height.

The response of a six-story gravity load designed RC frame with three bays, obtained via a simulated design procedure, was simulated by means of a 2D nonlinear multi-degree-of freedom finite element model that properly simulates the effect of infill panels on the seismic behavior of the frames in the elastic range.

The analytical model of building was subjected to multiple records scaled to the same intensity measure to account for record-to-record variability.

A sensitivity analysis was carried out to evidence the influence of different parameters on the expected lateral deformations. In particular, the effect of uncertainties in the definition of mechanical characteristics of the panels (G_w, t_w) and the effect of different openings percentages ($\alpha_{openings}$) is considered.

The results show that, assuming boundary values of G_W and t_W, the variation of maximum lateral deformations with respect to a reference structure with "mean" properties of infill panel properties, are of about 23% and 30%, respectively. When the effect of infill openings is accounted for, a variation of 320% of lateral deformation with respect to the reference structure may occur.

Further, comparing results with respect to those obtained for the reference structure it can be observed that a maximum decrease of maximum lateral deformations of about 40% can be expected for the case of the stiffer structures (G_w=1620 MPa and t_w=24 cm), while maximum expected increase is nearly 500% for the case of more deformable structures (G_w=1080 MPa, t_w=16 cm and $\alpha_{openings}$=0.4).

For comparison, also the maximum Interstorey drift ratio (IDR_{max}) obtained with a simplified approach proposed in [1] is calculated. The method efficiently predicts IDR_{max} when the main parameters (T_1, α) are calibrated on the analytical model, while it may lead to substantial error (nearly to 60% with respect to a reference structure with mean values of the considered parameters) when simplified expression are adopted to calculate T_1 and α.

The effect of non-uniform stiffness variations along the height is also considered. In particular, two values of stiffness reduction, namely 20% and 40%, were considered in different stories. The results show that, for a storey lateral stiffness reduction of 40%, a lateral deformation about 70-80% higher with respect to the one of the reference structure is obtained at the story in which the reduction of lateral stiffness is considered. The stiffness variation also slightly increases the deformation demand in other stories with respect to that of the reference structure, while this increase is almost constant along the height.

It is possible to note that when the simplified method proposed in [1] is applied, even considering T_1 and α calibrated on the analytical model, it fails to predict IDR_{max} when lateral stiffness reductions are considered in first two stories. In particular, the error is about 30% and 10% when considering a stiffness variation of 40% in 1st and 2nd story, respectively. The high error is mainly ascribable to the basic hypothesis of the model that assumes continuous systems. When the reduction in lateral stiffness is considered in upper stories, the prediction error is generally lower than 10%; this happens because, in spite of an increasing of IDR at the upper stories, the maximum IDR still occurs at the 1st story and it is quite similar to that recorded for the reference structure.

In this study, the effect of aspect ratio of infill panels and number of spans on maximum lateral deformations was not investigated. Further studies are required to address this topic.

Based on previous observations, further studies are required to extend the validity of simplified methods to the assessment of RC frame structures considering infills with both uniform and non-uniform stiffness along the height.

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