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ANALYTICAL ASSESSMENT OF SEISMIC DAMAGE AND USABILITY OF RC RESIDENTIAL BUILDINGS BY PERIOD ELONGATION

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Abstract

During an earthquake, the progressive damage of structural and nonstructural components of a structure yields to the degradation of their stiffness, thus resulting in a progressive increase of the vibration period of the structure as a whole.
Also, the damage amount on structural and nonstructural elements, also known as Damage State (DS), can be determined by visual inspection or predicted, for a given earthquake scenario, by means of numerical analyses by relating the exceedance of a certain Engineering Demand Parameter (EDP) threshold to the attainment of a certain DS. Also, upon an earthquake, the observation of a certain DS in a building is the basis for the decision regarding its usability.
In this work, numerical incremental time-history analyses are performed on case-study reinforced concrete residential buildings. The analyses results are used to establish the expected DS attained by structural and nonstructural components and, so, by the considered building: this is also related to a certain usability judgment, as already mentioned. In tune, the analyses results are also used to evaluate the period elongation of the building at increasing intensity of the seismic demand.
The objective of the study is establishing a preliminary relationship between a) the DS attained by a certain building due to the occurrence of an earthquake with a certain intensity, and, so, the consequent usability judgment, with b) its period elongation. This is done in order to establish whether the vibration period elongation – which can be practically evaluated by means of ambient vibration tests – can be used for the assessment of structural usability after an earthquake as a tool for decision supporting in the aftermaths of a destructive event.

Keywords: Reinforced concrete, structure, vibration period, damage state, usability.

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1 INTRODUCTION

The vibration period of a building basically depends on its mass and on its lateral stiffness. The lateral stiffness of a building depends on the structural scheme and on the stiffness of the single members that, in turn, depend on the geometry of the member and on the elastic properties of the materials. This is true when a building is in its initial elastic condition. However, during the seismic event, damage spreads on building members, thus inducing a degradation of their stiffness. For example, in a reinforced concrete (RC) building, the seismic input may yield to cracking of members. As it is well known, a cracked RC members will undergo potential reloading with reduced stiffness with respect to an uncracked/undamaged one; hence, a cracked RC structure has a lower lateral stiffness and, so, a higher vibration period. In general, the heavier the seismic damage, the higher the increase of the period with respect to the initial/elastic/undamaged one: this phenomenon is referred to as “period elongation”. The vibration period of the damaged building is also named “inelastic period”, T_{in}, to highlight its difference from the “elastic period”, T_{el}, of the structure at its initial, elastic, undamaged state.

Based on the above discussion, it can be simply concluded that, in general, the measure of the period elongation can be assumed as a measure of the damage state of the building: the more the elongation, i.e., the higher the T_{in}/T_{el} ratio, the higher the damage state attained by the building. Despite many studies have been carried out on this topic ([1-12] among others), an explicit relation between the Damage State (DS) of 3D RC buildings modelled and analyzed as nonlinear multi-degree-of-freedom system and in presence of infill walls and their period elongation has never been derived. Note that this kind of relations may be also useful to assess, by means of ambient vibration tests, the usability of buildings for which the usability judgment after earthquake may be uncertain only based on visual inspection.

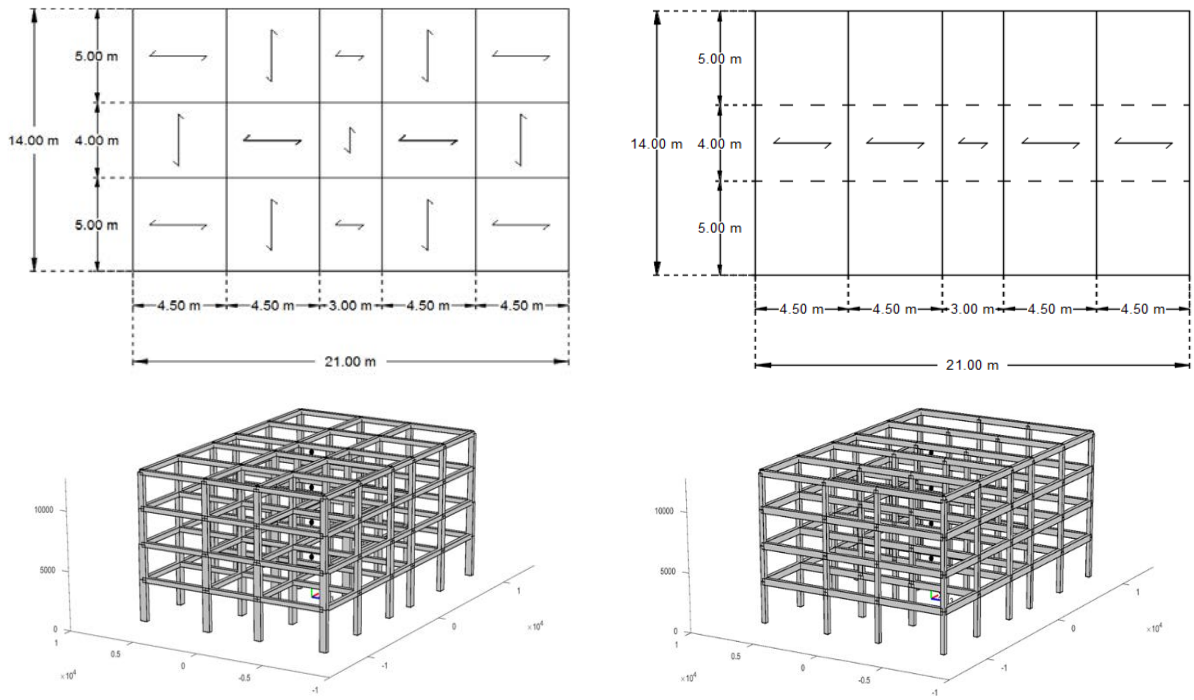
In this work, numerical incremental time-history analyses are performed on infilled case-study reinforced concrete residential buildings. The analyses results are used to establish the expected DS attained by structural and nonstructural components and, so, by the considered building, due to the occurrence of an earthquake characterized by a certain intensity measure: this is also related to a certain usability judgment, as already mentioned. In tune, the analyses results are also used to evaluate the period elongation of the building at increasing intensity of the seismic demand. This is done with the aim of establishing a preliminary relationship between a) the DS attained by a certain building due to the occurrence of an earthquake with a certain intensity, and, so, the consequent usability judgment, with b) its period elongation.

2 CASE-STUDY BUILDINGS

Two example buildings are considered for this study: a code-conforming new RC moment-resisting frame (labeled as “NEW” in the following) and an existing RC moment-resisting frame (labeled as “EX” in the following) designed only to gravity loads. The two buildings share the same site, Avellino, in southern Italy, and overall geometric features. More specifically, they have the same number of storeys, equal to four, the same interstorey height, equal to 3.50 m for the first storey and 3 m for the other storeys, the same number and dimensions of bays in both the planar directions (X and Y). Both buildings are regular in plan and in elevation according to the current Italian building code NTC2018 [13].

The NEW building is framed in both X and Y directions and is designed according to the current Italian building code NTC2018 [13] for the design seismic demand at Life Safety limit state (LS) for the site of Avellino, on a type B horizontal soil according to NTC2018 classification (PGA=0.23 g). It has been designed by adopting class C28/35 concrete (f_{cm} = 36 N/mm^2) and grade B450C deformed steel reinforcement (f_{ym} = 517.5 N/mm^2). The EX building is framed only in Y direction and is designed to gravity loads according to the old nonseismic Italian building code Regio Decreto 1939 [14]. It is assumed as realized by adopting concrete with f_{cm} = 16 N/mm^2 and grade AQ50 plain steel reinforcement (f_{ym} = 370 N/mm^2). Schematic pictures of the case-study structures are shown in Fig. 1.

Note that both buildings have been analyzed as uniformly-infilled (IF) frames. More specifically, NEW-IF building is provided, as typical of current construction practice of 30 cm-thick one-layer infill walls made with clay hollow bricks with vertical holes and good mechanical properties. On the other hand, EX-IF building is provided, as typical of old construction practice [15] of 12+8 cm-thin two-layer infill walls made with clay hollow brick with horizontal holes and poor mechanical properties.



NEW case-study building   EX case-study building

Figure 1: Geometry of the case-study buildings. For the sake of clarity, infill walls are not represented.

3 MODELING AND ANALYSIS PROCEDURE

The The potential non-linear response of both buildings is modelled in OpenSees software [16] by adopting a lumped-plasticity approach.

All structural members are classified as ductile as their plastic shear is lower than the minimum shear resistance according to NTC2018. So, they are modelled by assigning at both their ends plastic hinges with pre-determined moment-chord rotation response at fixed axial load (the one produced by gravity loads) and shear span length (assumed equal to one-half the member length). The assumed moment-chord rotation responses are multilinear and defined by the following characteristic points: first cracking, yielding, peak, conventional ultimate at 20% strength degradation with respect to peak load, collapse at zero moment resistance. Chord rotation values corresponding to these points are calculated according to [17] for the members with deformed bars of NEW building, according to [18] for the members with plain bars of EX buildings. Both studies also provide hysteretic rules to account for cyclic degradation phenomena.

Infill walls are modelled by adopting the equivalent strut approach with two equivalent no-tension struts whose axial load – deformation response is determined according to [19]. The material model adopted for numerical model is Concrete01 Uniaxial Material model in OpenSees. As shown in [20], the basic hysteretic rules included in this material model allow a quite satisfying reproduction of the cyclic degradation of reloading stiffness in infill walls under in-plane action, based on experimental data.

Beam-column joints nonlinear response, the out-of-plane response of infill walls and the potential frame-infill local shear interaction were not modelled.

Modal and pushover analyses were performed on the case-study buildings. Modal analyses allowed the assessment of the first vibration mode shape, participation factor, and period; pushover analyses under a first-mode force distribution and with bilinearization of the equivalent single-degree-of-freedom system according to NTC2018 allowed the assessment of the first effective period of the building. The pushover curves in the direction of the first vibration mode are shown in Fig. 2, together with the lines representative of the effective stiffness of the buildings. The elastic and effective first vibration period of the buildings are 0.37 s and 0.48 s for NEW-IF building, respectively, and 0.37 s and 0.54 s for EX-IF building, respectively.

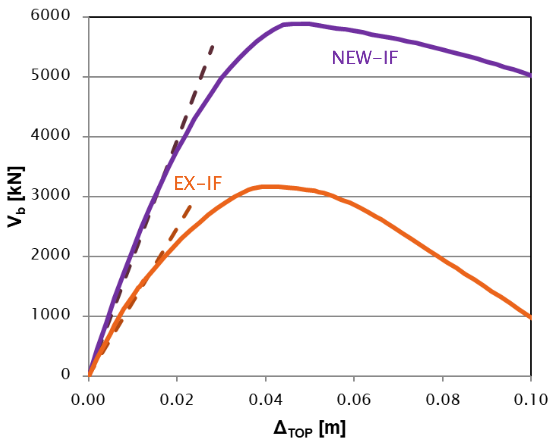


Figure 2: Pushover curves of the case-study buildings..

To perform Incremental Dynamic Analyses (IDAs) [21], seven bidirectional records were selected according to the indications provided by NTC2018 and by using the software Rexel [22]. The target spectrum adopted was the design spectrum at LS for Avellino city, horizontal soil type B. The spectra of the selected records are shown in Fig. 3a. A unique selection was performed for the two case-study buildings. However, the selected seven records were subjected to (limited) scaling for each case-study building, in order to have that for each selected and scaled record, Sa(Teff) was equal to Sa(Teff) of the target spectrum at LS, as shown for example purposes in Fig. 3b.

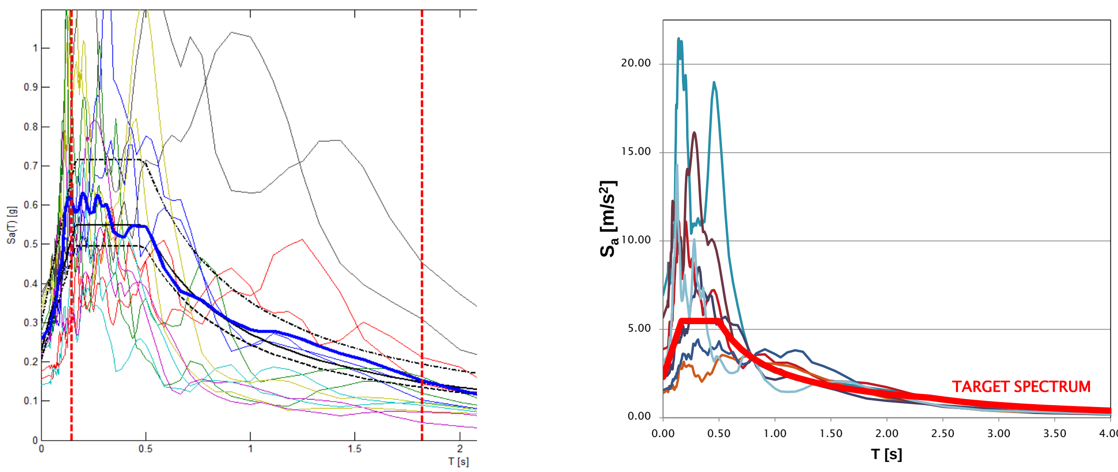
Once a set of seven records with the same Sa(Teff) at LS, i.e., at return period equal to 475 years, was determined for each case-study building, each set of records was furtherly scaled in order to perform IDAs. More specifically, given a certain case-study building, 15 different scale factors were applied in order to have Sa(Teff) equal to the Sa(Teff) value associated with the design response spectra defined by the code for return period equal to 30 (scale factor equal to 0.22), 50, 72, 101, 140 201, 475 (scale factor equal to 1), 975, and 2475 (scale factor equal to 1.73) years, plus 6 other scale factors (2, 2.25, …, up to 3) determined to investigate the incremental response of the buildings at very high seismic intensity measure (IM).

In other words, for each case-study building, the seismic performance is determined for 15 levels of the seismic intensity measure. For each level of seismic intensity measure, a total of

49 time-history analyses is performed: in fact, each of the seven scaled record is combined with the other six scaled record and with itself to generate a fictitious first-second event sequence with second event characterized by the same seismic intensity of the first event. For time history analyses, the accelerogram of the first event of the sequence is followed by ten seconds of null acceleration input (cf. [5]) and then by the accelerogram of the second event, as shown in Fig. 4. This has been done for reasons that will be cleared in the next section.

4 METHODOLOGY FOR THE ASSESSMENT OF DS, USABILITY, AND PERIOD ELONGATION

First, for the definition of DSs an approach based on the European Macroseismic Scale EMS98 [23] is adopted. Four DSs are defined: DS1 corresponding to light damage, DS2 corresponding to moderate damage, DS3 corresponding to severe damage, DS4 corresponding to collapse. The DS attained at increasing seismic demand by the case-study buildings has been determined at the end of each time-history analysis by comparing the maximum Interstorey Drift Ratio (IDR) demand with drift limits defined for both structural (STR) and nonstructural (NSTR) elements.



(a) (b)

Figure 3: Response spectra of the selected records (a) and preliminary scaling (b).

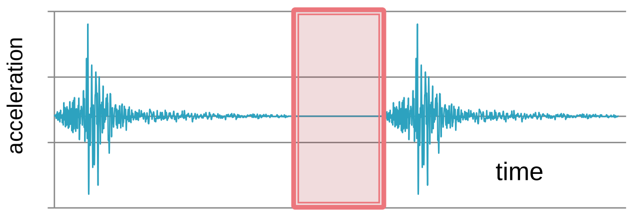


Figure 4: Example input for time-history analyses at given IM level. The red box highlights the presence of zero acceleration input between the first and the second event.

For STR, DS1 is attained at first cracking, i.e., when IDR demand makes at least one column attain a chord rotation demand equal to the chord rotation at cracking; DS2 is attained when at least one column yields; DS3 is attained when at least one column attains the peak moment point; DS4 is attained when at least one column attains the chord rotation at collapse (i.e., at zero moment capacity). This approach is based on [24].

Regarding NSTR, two sets of threshold IDR values are adopted. For NEW-IF building, the thresholds suggested in [25] for thick and strong infill walls are adopted: IDR=0.30% at the attainment of DS1; IDR=0.50% at the attainment of DS2; IDR=1.75% at the attainment of DS3. For EX-IF building, the thresholds suggested by [26] for thin and weak infill walls are adopted: IDR=0.05% at the attainment of DS1; IDR=0.30% at the attainment of DS2; IDR=0.73% at the attainment of DS3. DS4 is not defined for infill walls according to EMS98, which assumes that a building can attain DS4 (collapse) only due to structural damage.

So, for each time-history analysis, at the end of the first event, the attained STR and NSTR DSs are determined; for each level of the intensity measure, the median DSs are calculated based on the results of all the time-history analyses performed. In this way, an incremental curve showing the increase of the median DSs attained at increasing seismic intensity is obtained for both STR and NSTR. The final DS for the building is assigned considering both STR and NSTR, whichever occurs first.

After the first event, the free vibration of the building during the ten seconds of null acceleration input is investigated. More specifically, the acceleration response of the roof during this part of the record is considered and Fast Fourier Transform (FFT) is applied in order to evaluate the inelastic period of the structure after the first event. This allows the assessment, in median terms of each IM level, of the period elongation due to the damage achieved by the structure during the first event. This is done in terms of T_{in}/T_{el} ratio.

For the assessment of usability, two important statements must be considered. First, according to AeDES forms by Italian Department of Civil Protection [27], a building is usable after an earthquake (judgment “A”) if it has attained, at maximum, DS1; it is temporarily unusable, i.e., usable only provided that fast and non-invasive interventions are enforced (judgment “B”) if it has attained, at maximum, DS2; it is unusable if it has attained DS3 (judgment “E”). However, in addition, the AeDES handbook by the Italian Department of Civil Protection [27] states that, after an earthquake, a building can be deemed usable only if, after a potential second event with lower or equal intensity with respect to the first one, there is no significant increment of the DS.

Given both statements, to assess usability based on time-history analyses, both the response of each building during the first and the second event of the sequence are considered. The DS attained during the first event has already been considered. In addition, the response of the building is considered during the second event: this is done to potentially update the assessment of the attained STR and NSTR DSs during a second event with IM equal to that of the first event according to AeDES handbook.

In summary, if DS1 (or lower) is attained during the first or the second event of each sequence, judgment A (usability) is assigned to that time-history analysis; if DS2 is attained during the first or the second event of each sequence, judgment B (temporary unusability) is assigned to that time-history analysis; if DS3 is attained during the first or the second event of each sequence, judgment E (unusability) is assigned to that time-history analysis. The usability judgment associated with each IM level is assessed as the median usability judgment registered among the 49 time-history analyses performed for each IM level.

In this way, for each case-study building and for each IM level, three important results are obtained: the maximum DS induced by a single event; the period elongation after the first event; the usability judgment at the end of the first event also considering the effects of a potential second event with equal IM. In other words, the period elongation at given IM level is associated with the expected maximum DS and with the usability judgment of the building.

5 RESULTS AND DISCUSSION

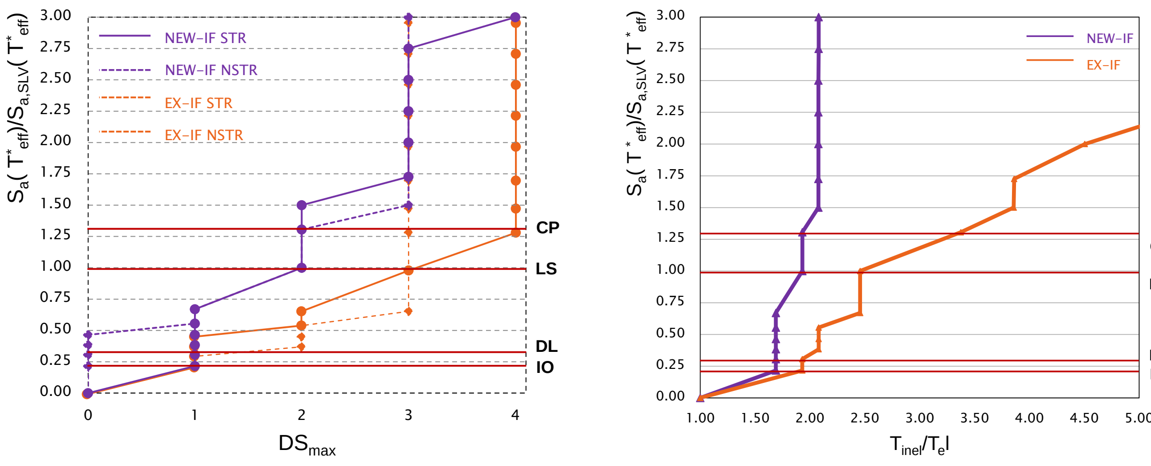
The results in terms of median maximum DS and period elongation evolution at increasing IM, with special reference to the IM levels set by NTC2018 for the “seismic” serviceability and ultimate limit states, are shown in Fig. 5. At IM corresponding to Immediate Occupancy limit state (IO), both buildings have attained DS1 and are judged usable. This is interesting, since EX-IF building is not designed to lateral actions, while NEW-IF building is explicitly designed to withstand Damage Limitation limit state (DL), while safety against IO is only implicitly assumed if DL is considered during design. Period elongation is already significant, roughly equal to 50% for NEW-IF and to 100% for EX-IF, due to members’ and infills’ cracking.

At IM corresponding to DL, both buildings are still usable, but EX-IF building is approaching DS2, corresponding to temporary unusability. Period elongation is stable with respect to the IM corresponding to IO.

At IM corresponding to LS, NEW-IF building attains DS2 due to both STR and NSTR and is temporarily unusable, with period elongation roughly equal to 100%; EX-IF building attains DS3 and should be deemed unusable, with period elongation roughly equal to 150%. It should be noted, however, that EX-IF building already attained that period elongation and DS3/unusability for IM equal to 0.67 times the IM corresponding to LS due to NSTR.

NEW-IF building attains DS3/unusability for IM equal to 1.50 times the IM at LS, which is higher than the IM corresponding to Collapse Prevention limit state (CP), due to NSTR, with period elongation roughly equal to 100%; DS4 is attained only for IM equal to 3 times the IM at LS. EX-IF building attains DS4 at IM corresponding to CP, with period elongation roughly equal to 250%.

In summary, based on the above results, a code-compliant infilled building attains temporarily unusability judgement (judgment “B”) for IM corresponding to LS with period elongation roughly equal to 100% (i.e., with period doubled with respect to the initial elastic one), while it attains unusability judgment (judgment “E”) for IM corresponding to 1.50 times the IM at LS with period elongation roughly equal to 100%. An existing infilled building designed only to gravity loads attains temporarily unusability judgment for IM equal to 0.67 times the IM at LS with period elongation roughly equal to 100%, while it attains unusability judgement for the IM corresponding to LS with period elongation roughly equal to 150%.



(a) (b)

Figure 5: Median maximum DS (a) and median period elongation (b) at increasing IM for the two case-study buildings.

6 CONCLUSIONS

In this paper, a methodology for correlating period elongation, damage state and usability judgment has been proposed. The methodology has been applied to two four-storey case-study RC buildings with infill walls, a code-conforming and an existing one. To apply the proposed methodology, nonlinear incremental time-history analyses have been performed on nonlinear models of the case-study buildings.

In summary, based on the above results, a code-compliant infilled building attains temporarily unusability judgement at IM corresponding to LS with period elongation roughly equal to 100%, while it attains unusability judgment for IM corresponding to 1.50 times the IM at LS with period elongation roughly equal to 100%. An existing infilled building designed only to gravity loads attains temporarily unusability judgment for IM equal to 0.67 times the IM at LS with period elongation roughly equal to 100%, while it attains unusability judgement for the IM corresponding to LS with period elongation roughly equal to 150%.

In other words, if the vibration period of an existing RC building has doubled after an earthquake, it should be considered, at least, temporarily unusable; if it has more than doubled, unusability judgment should be considered. If the vibration period of a code-compliant RC building has doubled after an earthquake, it should be considered, at least, temporarily unusable; unusability judgment should be considered only if the registered IM significantly overcame the design IM at LS and/or for higher period elongation.

Of course, these are only preliminary results. Future studies will consolidate/update them based on a larger number of numerical analyses on a larger number of case-study buildings and, potentially, with validation based on field evidence.

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