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Mariani, V.; Tanganelli, M.; Viti, S.; De Stefano, M.

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Mariani, V., Tanganelli, M., Viti, S., De Stefano, M.

Department of Architecture (DiDA), University of Florence, Italy

Summary

It is well known that the axial load plays an important role in the evaluation of the structural capacity of RC columns. In existing buildings this problem can be even more significant than in new ones, since the material can easily present poor mechanical properties. The paper is aimed at the investigation of the role of the axial load variation on the seismic performance of RC columns of a case-study, i.e. a doubly symmetric 4-storey RC building. The effects of the axial load variation have been checked on the 1st storey columns, by comparing the seismic response, measured in terms of chord rotation and shear force, with the corresponding capacity. The sensitivity of the seismic performance to the axial load is evaluated with special attention on the type of analysis adopted to determine the seismic response and on considering a wide range of values for the concrete strength. The study points out a non-negligible effect of the axial load variation on the seismic response of the case-study building, especially when combined to concrete strength variability.

Keywords: RC framed structures, axial load sensitivity, concrete strength, concrete mechanical properties.

1. INTRODUCTION

It's common knowledge that the axial load plays an important role in the evaluation of the structural performance of RC buildings. The axial load amount, indeed, affects both the seismic response and the capacity of RC members, (Saadeghvaziri 1997, ElMandooh Galal and Ghobarah 2003, Ousalem et al. 2004, Abbasnia et al. 2011, Kim et al. 2007, Kenneth et al. 2007). Moreover, the axial load variation can induce a dangerous reduction in ductility in the joints of RC buildings, (Akguzel and Pampanin 2010, Masi et al. 2014), especially when they have been designed without specific confinement provisions.

Concerning the seismic response, when the structure is subjected to horizontal loading, e.g. a seismic action, it necessary experiences an axial load variation in its vertical elements. At the occurring of severe ground motion, in particular, some columns can be subjected to significant axial load reduction - with a possible presence of tension in extreme cases - or conversely, they can experience a large increase in compression. Nevertheless, since the current European technical legislation, Eurocode 8 (EC8) does not assume the axial load as response quantity, the axial load variation affects the seismic performance only through the capacity of the members.

For axial load values higher than the "balanced" value, i.e the one corresponding to the maximum bending capacity of the section, in fact, the ultimate bending moment, as well as the limit shear force, progressively decreases. If the section is subjected to tension, its flexural and shear capacity is largely reduced, as well as in case of high levels of compression.

The seismic performance should therefore be carefully checked at the axial load variation, while, according to the current practice and legislation, the capacity of the structural sections can be determined referring to the static axial load only, i.e. the axial load due to vertical loads. Furthermore, in existing buildings the sensitivity of the seismic performance to axial load variation can be even more significant than in new ones, since the material can easily present poor and uncertain mechanical properties.

In this framework, this paper is aimed at investigating the influence of the axial load variation on the seismic performance of RC structures. The study is carried out with reference to a case-study, i.e. a doubly symmetric 4-storey RC building (De Stefano et al. 2014a, 2015), representing a typical example of pre-seismic code structure. The seismic performance, expressed as the ratio between demand (D) and capacity (C), has been checked at the 1st storey columns only, since they resulted the most affected by the axial load variation.

The seismic demand has been found by performing two alternative nonlinear one-directional analyses, i.e. the nonlinear static and time-history ones. As regards the nonlinear static analysis, despite interesting improvements introduced in recent years (Elnashai 2001, Antoniou and Pinho 2004, Bosco et al. 2009, 2013) in the current work the standard N2 method (Fajfar 2000), as provided by EC8, has been applied.

The capacity of the columns have been evaluated with reference to two limit states, respectively a serviceability (Damage Limitation, *DL*) and an ultimate (Significant Damage, *SD*) one. Chord rotation and shear force have been assumed as control parameters. The limit domains of the response parameters have been found as a function of the axial load assuming the concrete strength *i*) in accordance with the EC8 conventional approach, which prescribes to scale the *mean* compressive strength by proper reduction factors (Confidence Factors, *CF*) depending on the knowledge level of the building, and *ii*) as a variable quantity, described by a Gaussian distribution, with a *mean* strength and three different Coefficients of Variation (*CoV*), respectively equal to 15%, 30% and 45%. This probabilistic model has been set up according to a large database of experimental values of compressive strength (Cristofaro et al. 2012, 2014, De Stefano et al. 2013a,b, 2014b). Each strength distribution has been discretized into seven percentile values, respectively equal to 5%, 10%, 20%, 50%, 80%, 90% and 95%.

For each PGA, the seismic performance of all 1st storey columns has been found, as the ratio between one value of seismic response for each analysis type (static and dynamic) and a range of capacities, depending on the axial load variation and the assumed concrete strength variability. The range obtained for each seismic performance has been compared to the corresponding value found by assuming the static axial load.

In the discussion of the results the sensitivity of the seismic performance to the axial load variation has been checked, and special attention has been paid to the effects of the type of analysis (static vs dynamic) on the axial load evaluation in the columns and to the role played by the assumed concrete strength on their sensitivity to axial load variation.

2. THE ANALYSIS

2.1 The case-study

The sample structure (De Stefano et al. 2015) is a 4-story 3D reinforced concrete frame, symmetric along both *x* and y directions, with two 4.5 m long bays in the *y*-direction and 5 bays 3.5 m long in the *x*-direction, as shown in Fig. 1.

All the columns have cross section dimensions of 30x30 cm, with 8 ϕ14 rebars as longitudinal reinforcement and ϕ6 stirrups with a spacing of 20 cm. Longitudinal beams have constant cross section dimensions of 30x50 cm in both directions. The concrete has been assumed to have a *mean* strength equal to 19.36 MPa, while for the reinforcement the Italian FeB38k steel has been assumed, with a stress value equal to 380 MPa assumed for analysis. The building is designed for vertical loads only (dead load equal to 5.9 KN/m^2, live load equal to 2.0 KN/m^2), without considering any seismic load.

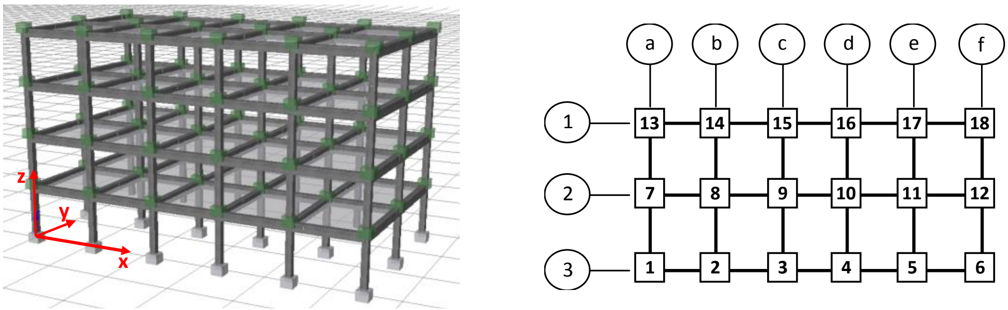


Fig. 1 Case-study: 3D view and plan configuration.

The *mean* values of concrete and steel strength have been assumed in the analysis for seismic response assessment, while the capacity of the case study has been evaluated considering two different assumptions for the concrete strength: the first one refers to the conventional EC8 approach, which requires to reduce the *mean* strength value by a *CF*, equal to 1.00, 1.20 and 1.35 (Italian Annex, NTC 2008) respectively, depending on the knowledge level (KL3, KL2 and KL1) of the structure; the second one provides for a Gaussian representation of the probabilistic distribution of the concrete strength. In the Gaussian representation, exhaustively explained in De Stefano et al. (2014, 2015) the strength domain is defined with reference to an extensive experimental campaign carried out by the Tuscan Regional Government (Cristofaro 2009, Cristofaro et al. 2012); a single *mean* strength, i.e. the EC8 value for CF=1.00 has been assumed, while three different *CoV*, respectively equal to 15%, 30% and 45% have been considered. For each *CoV*, a sample of seven concrete strength values, corresponding to the percentiles of 5%, 10%, 20%, 50%, 80%, 90% and 95% has been assumed for the definition of columns capacity. Table 1 resumes the strength values assumed for the concrete strength.

Table 1. Assumed concrete strength values (in MPa)

	assumed distribution							EC8	
	K05	K10	K20	K50	K80	K90	K95		
CoV = 15%	14.68	15.63	16.92	19.36	21.80	23.08	24.13	KL1	14.34
CoV = 30%	9.80	11.91	14.47	19.36	24.24	26.80	28.91	KL2	16.13
CoV = 45%	5.03	8.19	12.02	19.36	26.69	30,52	33,68	KL3	19.36

2.2 The finite element model

The seismic response of the case-study has been found by performing two different analyses, i.e. a nonlinear static (pushover) analysis and a nonlinear dynamic (time history) one, by using the computer program Seismostruct (Seismosoft 2013). A fiber model has been adopted to describe the cross sections, and each member has been subdivided into four segments. The Mander et al. model (Mander et al. 1988) has been assumed for the core concrete, a three-linear model has been assumed for the unconfined concrete, and a bilinear model has been assumed for the reinforcement steel. The stiffness of floor slabs has been considered by introducing a rigid diaphragm.

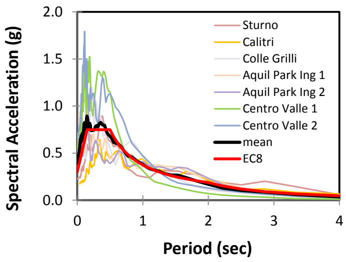
2.3 The seismic input

The seismic analysis has been performed along the *y*-direction only. For the pushover analysis the elastic spectrum provided by EC8 for a soil-type B has been assumed, while for the dynamic analysis the seismic input has been defined by a set of 7 ground motions whose mean spectrum closely fits the EC8 one.

The records, described in Table 2, have been selected from the Italian Accelerometric Archive (Itaca 2008) through the adoption of the software REXEL (Iervolino et al. 2009a,b; Smerzini e al. 2013), on the basis of a PGA equal to 0.25g, a nominal life of the structure of 50 years and a magnitude between 5.5 and 6.5.

Table 2. Ground motions data.

Name	Location	Date dd/mm/yyyy	PGA (g)	Duration (sec)
Irpinia	Sturno	23/11/1980	0.225	70.75
Irpinia	Calitri	23/11/1980	0.174	85.99
L'Aquila	Colle Grilli	06/04/2009	0.446	100.00
L'Aquila	Aquil Park Ing 1	06/04/2009	0.353	100.00
L'Aquila	Aquil Park Ing 2	06/04/2009	0.330	100.00
L'Aquila	Centro Valle 1	06/04/2009	0.545	100.00
L'Aquila	Centro Valle 2	06/04/2009	0.657	100.00



2.4 The assumed limit states

Two different limit states have been assumed in the present paper: the Damage Limitation (*DL*) and the Significant Damage (*SD*) limit states. According to EC8 provisions, the response parameter to be checked for the serviceability limit states is the chord rotation only, while both chord rotation and shear force must be checked for ultimate limit states. Therefore, in the present paper, a limit value corresponding to the yield chord rotation has been assumed for the *DL* limit state, while two limit values, based respectively on the ultimate chord rotation and ultimate shear force, have been assumed for the *SD* limit state. All limit values are strictly dependent on the axial load level in the RC members. In fact the yield chord rotation and the ultimate shear, quantified according to the EC8 prescriptions, (equations A10b and A12 of the Annex A, respectively) are a function of the yield curvature of the cross section, which in turn depend on the neutral axis depth, while the *SD* limit chord rotation, assumed as ¾ of the ultimate chord rotation defined by eq. A1 (EC8, Annex A), is a function of the normalized axial load ν, defined as N/(b h f_c).

3. THE SEISMIC PERFORMANCE OF THE 1ST STOREY COLUMNS

3.1 The seismic demand

Fig. 2 shows the global response of the case study found by performing the two analyses in terms of top displacement (*TD*), maximum drift, maximum shear force and maximum axial load variation (ΔN). All local results refer to the 1st storey columns, since they are the most affected by ΔN.

As regards the time-history analysis, both the mean response and the responses to each single record are shown. It should be reminded that the dynamic analysis has been performed by applying the assumed ground motions in one way only, so providing a seismic response not perfectly symmetric. Therefore the axial load increase and decrease are not coincident. When the nonlinear static analysis is performed, instead, the same force patterns are applied in the two ways, so obtaining the same axial load variation in terms of increase and decrease.

Fig. 3 shows the amount of axial load in each column of the case-study. Since, in each frame, the internal columns (column lines *b*, *c*, *d* and *e*) and the side ones (column lines *a* and *f*) respectively experience almost the same ΔN (see De Stefano et al. 2014c), in Fig. 3 only the results of two columns for each frame have been shown, together to the static axial load of the two (side and internal) columns.

It can be noted that the two types of analysis provide similar trends for the maximum and minimum axial load in the side frames (1 and 3), while they provide substantially different results for the central frame. In the frame 2, in fact, ΔN is almost negligible when the static analysis is performed, while it achieves 40% when the dynamic analysis is adopted.

It should be noted that, despite the building is symmetric along both main axes, the axial load variation, when the dynamic analysis is performed, is not exactly the same in the two side frames (frames 1 and 3). This occurrence is expectable, since the assumed ground motions have not equal positive and negative peak acceleration values.

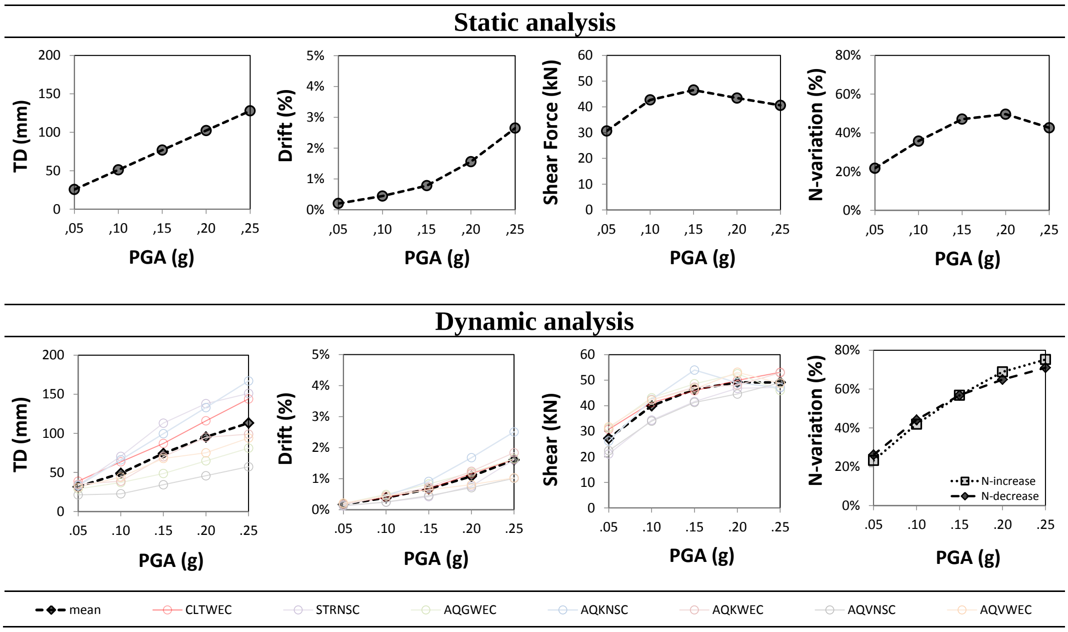


Figure 2. Seismic response of the case study.

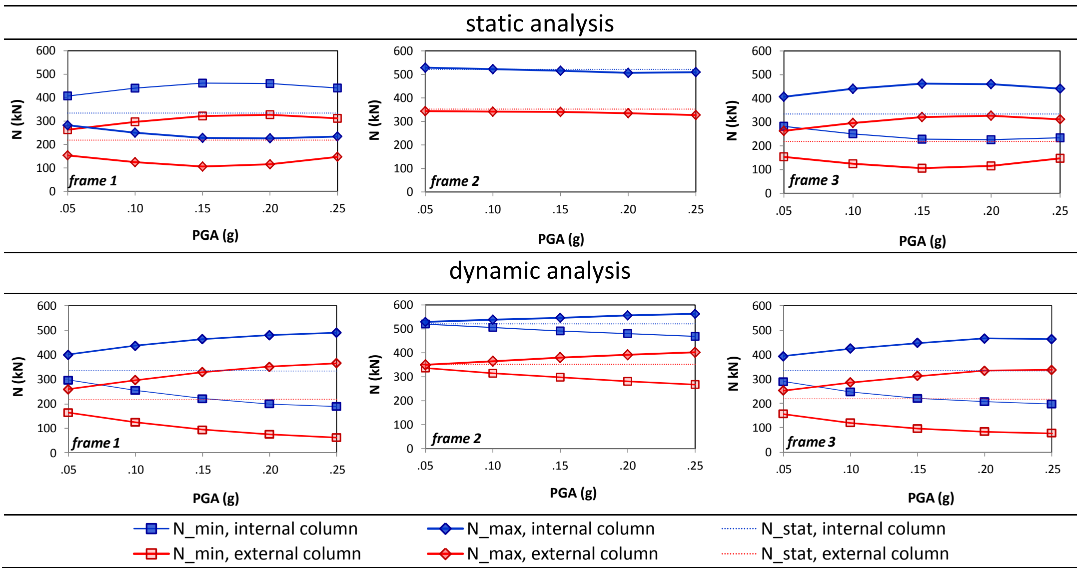


Figure 3. Axial load variation in the columns.

3.2 The seismic capacity

The structural capacity of existing structures is measured with reference to chord rotation and shear force, depending on the considered – ductile or brittle – mechanisms.

In this section, columns structural capacity is evaluated as a function of the normalized axial load, i.e. the ratio between the axial load in the column and its maximum axial force, equal to product of the cross area and the concrete strength.

Fig. 4 shows the sensitivity of the chord rotation capacity to the axial load variation for *DL* and *SD* limit states, while Fig. 5 shows the sensitivity of shear force capacity for the *SD* limit state only.

In each graph, the colored lines represent the domains related to the percentile values describing the assumed strength distribution related to the three different *CoV* values, while the the dashed gray lines represent the capacities provided by EC8. As can be noted, the range of capacities provided by EC8 is much smaller than the one obtained when the probabilistic strength variability is considered, even for the lowest assumed *CoV* (*CoV* = 15%). For higher values of *CoV*, more likely to be found in existing buildings (Cristofaro 2009, De Stefano et al. 2013a,b), the difference between the two ranges is even more significant.

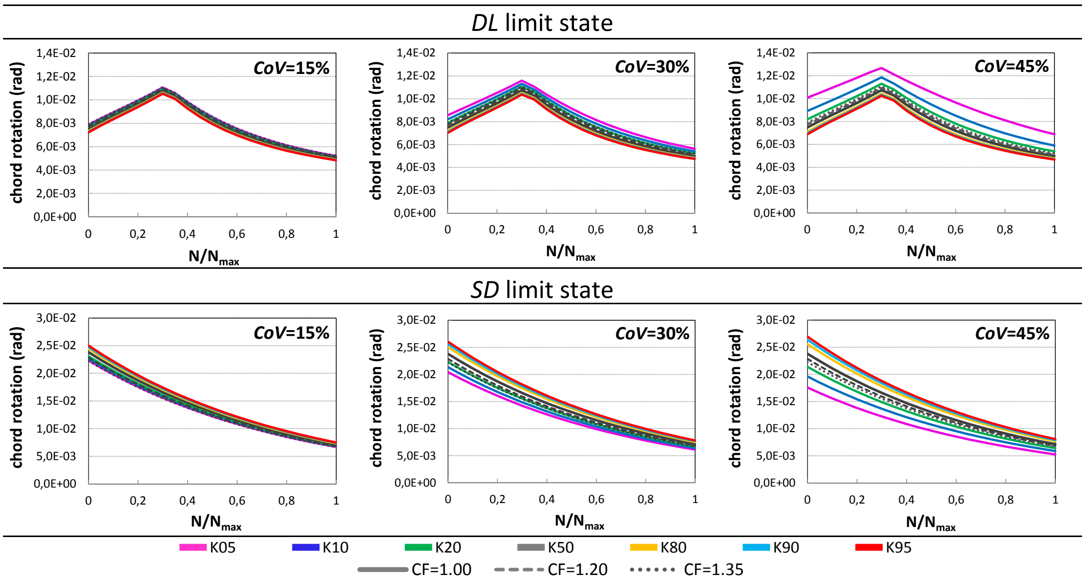


Figure 4: Sensitivity of the chord rotation capacity of columns to the axial load variation for the *DL* and *SD* limit states.

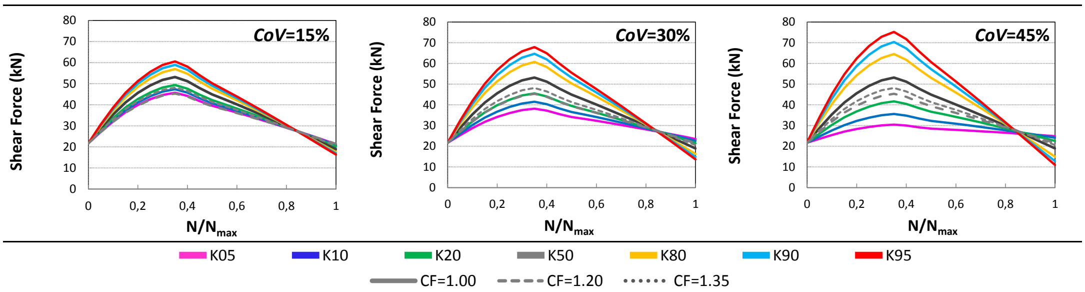


Figure 5: Sensitivity of the Shear Force capacity of columns to the axial load variation for the *SD* limit state.

3.3 The seismic performance

The seismic performance has been quantified as the ratio between the demand (D) and the capacity (C) of each column at the first storey. The sensitivity of the seismic performance to the axial load variation has been investigated with reference to both *DL* and *SD* limit states. *DL* limit state has been verified for PGAs up to 0.15g, while *SD* limit state has been checked for PGA values higher or equal to 015g.

For each column the actual range of axial load has been considered in the capacity only, while the seismic demand (chord rotation and shear force, respectively) has been assumed with its maximum value. Consequently, for each PGA, a range of values is found for the seismic performance; the amplitude of the range, therefore, can be read as an index of the sensitivity of the seismic performance to ΔN. The ranges found for the seismic performance of each column at the varying of the axial load have been compared to the ones found by assuming the static axial load, as commonly done according to EC8. This comparison has been measured in non-dimensional terms, by the *variation range*, found

by normalizing the difference between the maximum and minimum D/C values related to *ΔN*, to the D/C value corresponding to the static axial load.
In this section, for sake of brevity, only results referred to four columns have been shown, i.e. columns No. 1, 2 of the frame 1, and No. 7 and 8, of the frame 2; therefore, a side and an internal column have been considered for a side and the central frame, so covering the most significant axial load distribution.

3.3.1 DL limit state

Figure 6 shows the D/C percentage variation of the seismic performance referred to the *DL* limit state. The variation has been found for all considered PGAs and *CoV*s. The strength value provided by EC8 for the KL3 coincides to the *mean* strength value, so it is indicated as the K_{50} percentile.
Fig. 6 evidences that *ΔN* plays an important role especially in the side frame, where it is larger, while in most cases *ΔN* is negligible in the central frame (columns No. 7 and 8), except in the case of time-history analysis with low strength values.

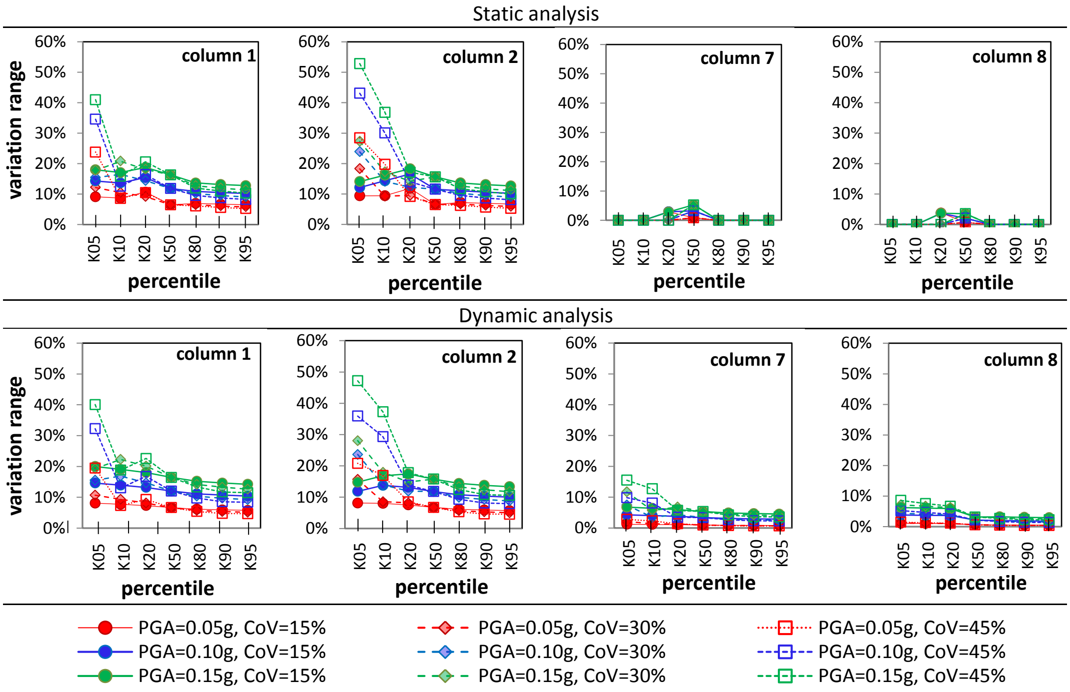


Figure 6. *DL* limit state: D/C percentage variation related to of chord rotation.

In Figure 7 the D/C ranges found for each assumed strength value by performing the two types of analysis have been compared. For sake of brevity, only the results referred to the higher PGA (PGA=0.15g) have been shown. The ranges found for each assumed strength percentile have been represented by a colored histogram, while the D/C value found for the static axial load is represented by a black line. It should be noted that the two types of analysis evidence a similar sensitivity to the axial load variation (D/C ranges of similar width) in the columns belonging to the side frame, while the results related to columns of the internal frame seem to be more sensitive to the type of performed analysis.

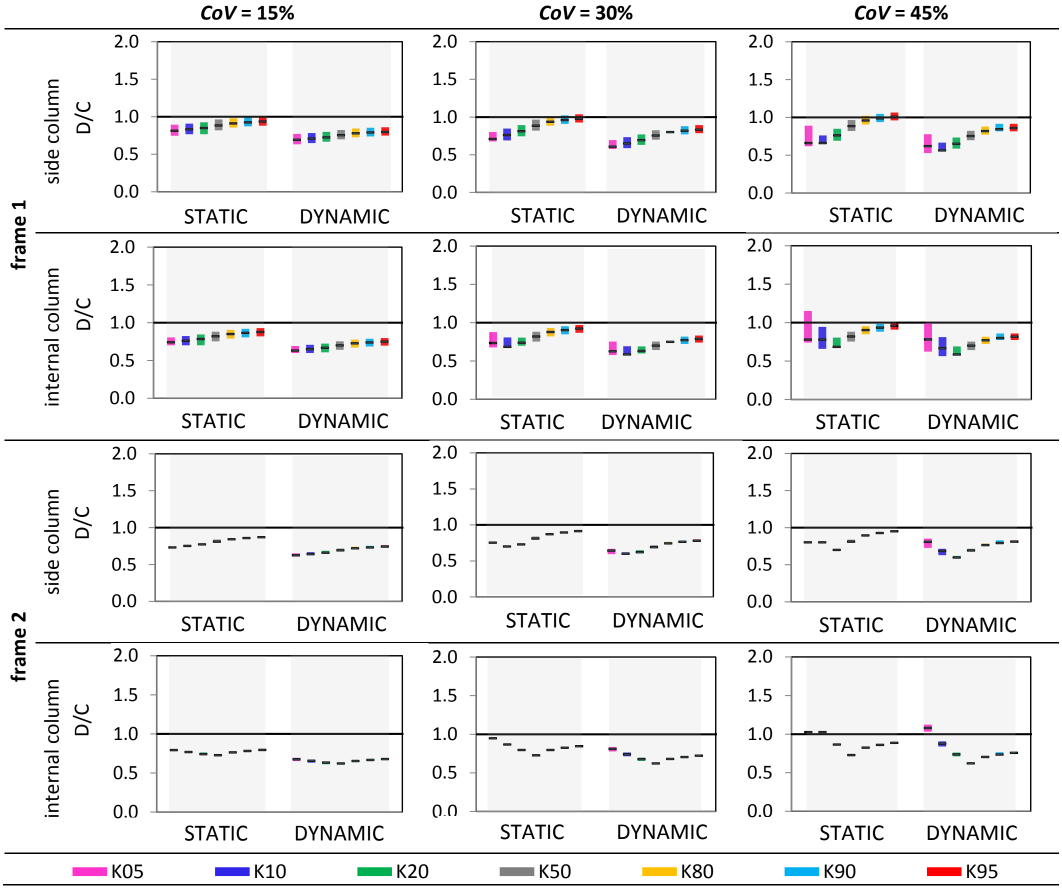


Figure 7. *DL* limit state: performance in terms of chord rotation, PGA= 0.15g.

3.3.2 SD limit state

The Significant Damage limit state has been investigated in terms of both chord rotation and shear force. Fig. 8 shows the D/C percentage variation due to ΔN related to chord rotation. ΔN affects the *SD* limit state much more than the *DL* one. When the dynamic analysis is performed, in fact, the D/C variation reaches 80%, when the higher PGA and *CoV* are considered. The ranges found by performing the static analysis are lower even in the side columns, while they are equal to zero in the internal columns.

Fig. 9 shows the ranges of D/C found for the *SD* limit state in terms of chord rotation.

The ranges between minimum and maximum D/C values related to ΔN are much larger than in the *DL* limit state, so showing a higher sensitivity of the seismic performance to the axial load variation. Such sensitivity, in fact, is significant especially in the side frames (frames 1 and 3) for both types of analysis, and it increases when low values of concrete strength are assumed.

With reference to the current case-study, when a low concrete strength is assumed, i.e. for high variability and low percentiles (K_{05}, K_{10}), ΔN plays an important role in the seismic performance of the structure, inducing an increase of the D/C ratio which overcomes the required limit with both static and dynamic analysis. In the central frame (frame 2) the dynamic analysis results to be more sensitive to the axial load variation than the pushover one. For low strength values, i.e. for high variability and low percentiles (K_{05}, K_{10}), the axial load variation plays a crucial role in the seismic performance of the structure, inducing an increase of the D/C ratio up to four times the one obtained adopting the *mean* strength value, i.e. by assuming EC8 procedure. In the internal columns, where the amount of axial load is higher, the D/C ratio varies between 0.7 and 4.0, depending on the assumed concrete strength percentage and the axial load amount.

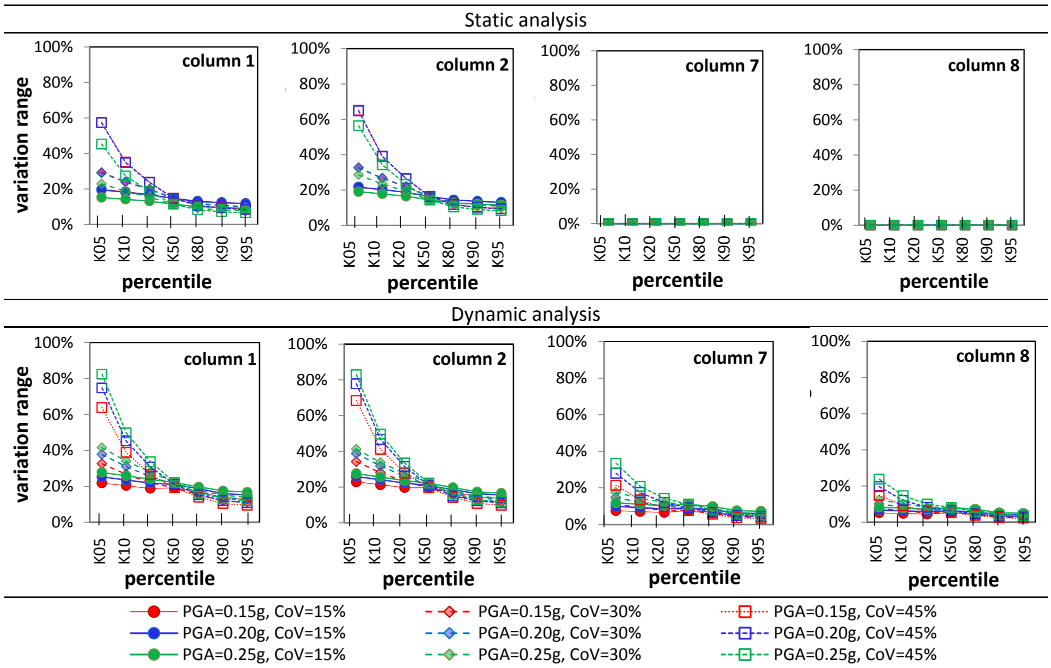


Figure 8. ***SD*** **limit state: D/C percentage variation related to chord rotation.**

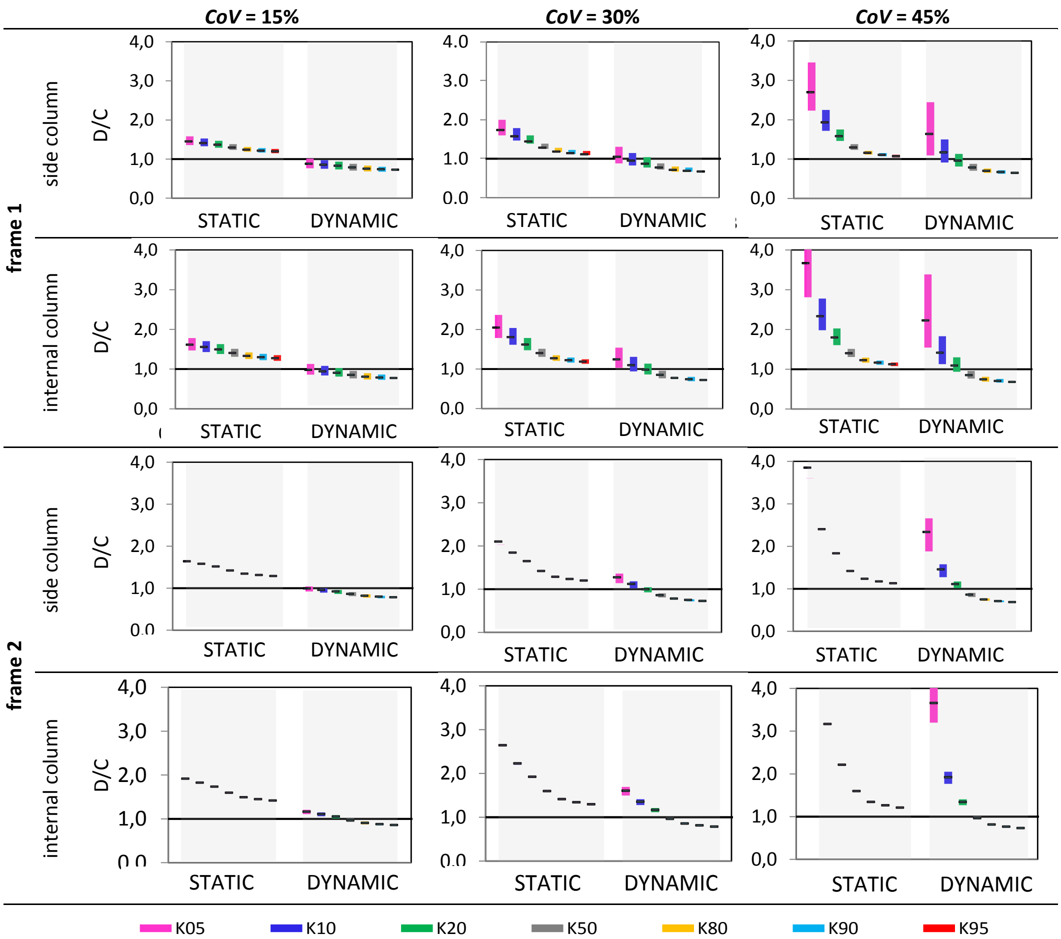


Figure 9. ***SD*** **limit state: performance in terms of chord rotation, PGA= 0.25g.**

Fig 10 shows the D/C percentage variation with respect to the static axial load for the *SD* limit state in terms of shear force. As can be noted, for high values of axial load, i.e. in the internal columns, the trends of D/C percentage variation is not monotonic, due to the shape of the corresponding capacity domain (see Fig. 5). The variation range found by performing the dynamic analysis is higher than the one coming from the static analysis even for the side columns, reaching a maximum value of 55%.

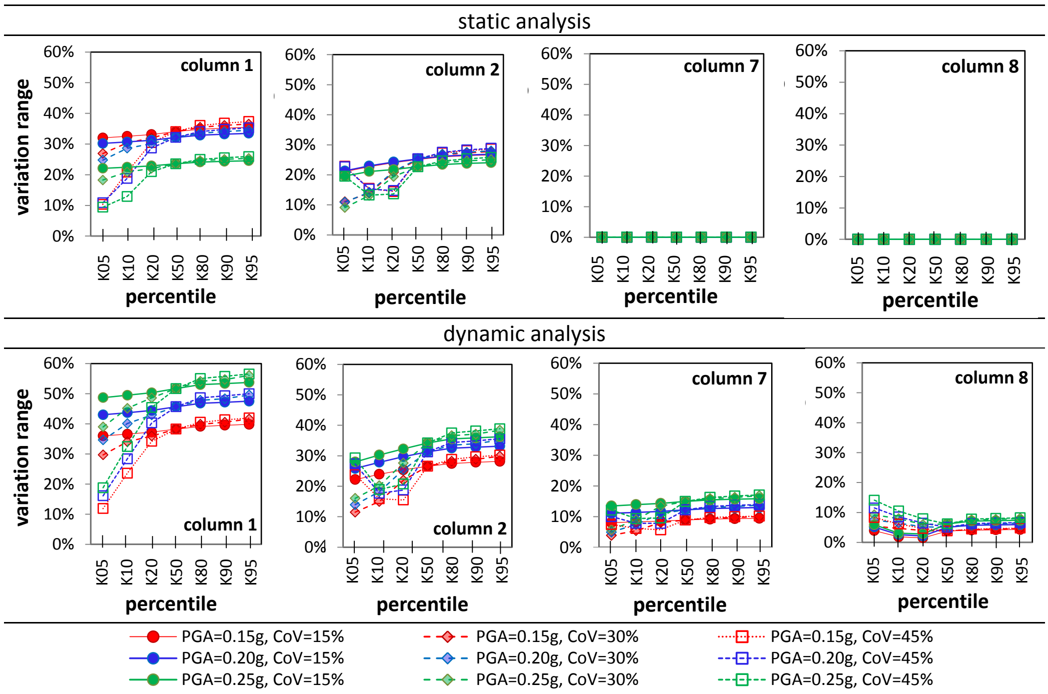


Figure 10. ***SD*** **limit state: D/C percentage variation related to shear force.**

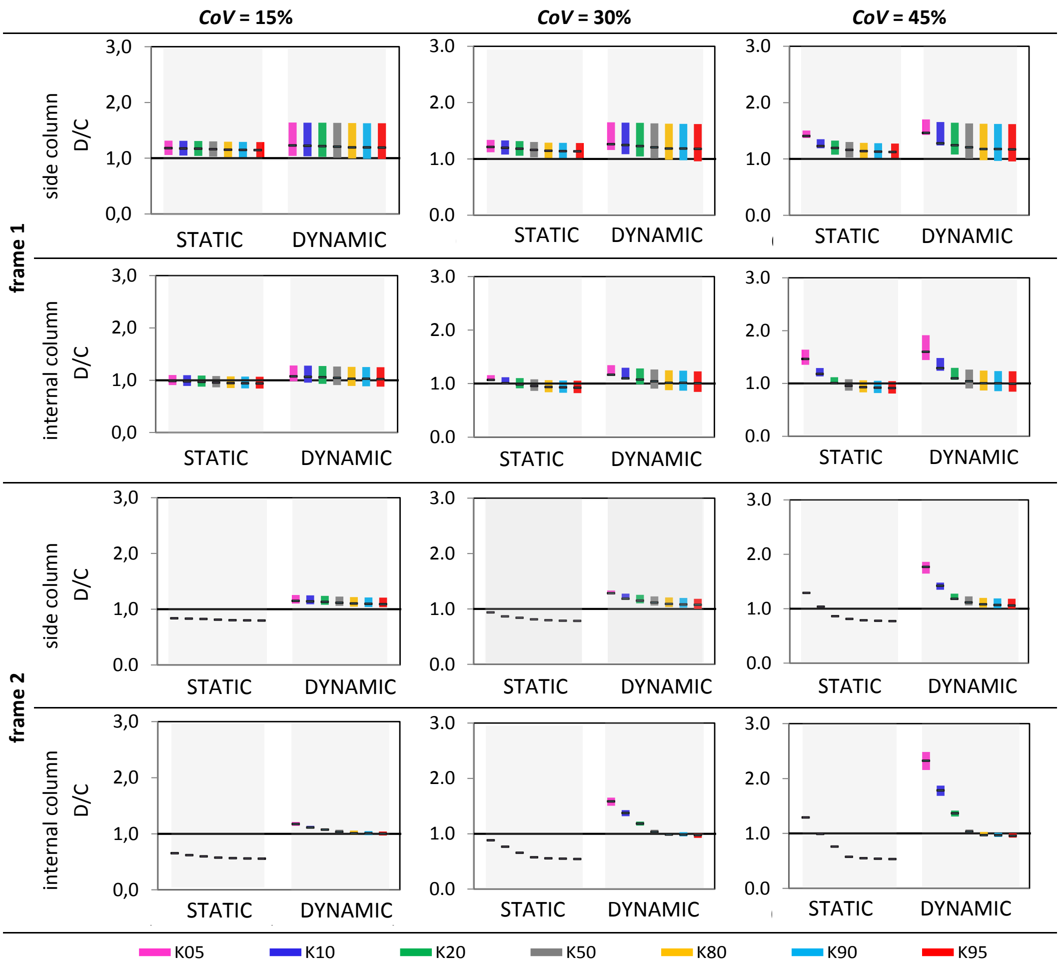


Figure 11. ***SD*** **limit state: performance in terms of shear force, PGA= 0.25g.**

Fig. 11 shows the D/C ranges found for the *SD* limit state in terms of shear force. In this case, for the highest PGA value (PGA=0.25g), the results provided by the static analysis are lower than the ones coming from the dynamic analysis. As can be observed by the diagram in Fig. 2, the maximum shear force found by performing the static analysis occurs for PGA=0.20g; for PGA equal to 0.25, the dynamic analysis provides more conservative results than the static one. Additionally the dynamic analysis shows a higher sensitivity to the axial load variation. Indeed, the ranges between minimum and maximum D/C values are higher in the dynamic analysis than in the static one in all frames (not only in the frame 2, as observed for the chord rotation). When the lower concrete stength values are assumed, i.e. for the higher *CoV* and low percentiles, the seismic performance provided by the dynamic analysis is more conservative than the one obained by the pushover analysis. With reference to the case-study, the axial load variation has a significant role in the performance assessment related to shear force capacity, expecially for internal columns, where double values of D/C ratio can be observed.

CONCLUSIONS

In this paper the effects of the axial load variation on the seismic performance of RC structures have been investigated with reference to a case-study, i.e. a 4-storey RC framed building, symmetric about both main directions. In order to investigate the sensitivity of the performance to the axial load variation, the range of the Demand over the Capacity (D/C) ratios, related to minimum and maximum axial loads observed in the columns, has been found, so that the width of the range expresses how sensitive the seismic performance is to the axial load variation. D/C percentage variation with respect to the D/C related to the static axial load has been also assessed to investigate the potential error associated to the use of the static axial load instead of the real one. Results found by the two types of analysis have been compared, in order to additionally evaluate the role of the analysis type in the investigated sensitivity of the case-study.
As regards the *DL* limit state the two analysis provide very similar results, despite the pushover analysis proves to be more conservative. The sensitivity of the seismic performance to the axial load variation is significant only in the side frames for the higher considered PGA (equal to 0.15g), while the value of the concrete strength has a significant effect in most cases. The case-study complies the EC8 requirements in almost all cases; only when the highest value of *CoV* (*CoV* = 45%) is assumed together with lowest strength percentile (5%), for PGA=0.15g the internal columns belonging to the three frames may present D/C values higher than unity.
Concerning the *SD* limit state expressed in terms of chord rotation, the ranges between minimum and maximum D/C values related to the amount of axial load are much wider than in the *DL* limit state, so showing a higher sensitivity of the seismic performance to the axial load variation. Such sensitivity, larger in the side frames, increases for low values of concrete strength. The columns belonging to the central frame (frame 2), subjected to higher axial loads, are less sensitive to ΔN; but the difference between the two analysis in terms of axial load sensitivity is maximum just in these members, being the dynamic analysis much more sensitive than the pushover one. This difference is larger for low strength values, i.e. for high variability and low percentiles (K_{05}, K_{10}), with a D/C ratio up to four times the one obtained adopting the *mean* strength value, i.e. by assuming EC8 procedure. In the internal columns, where the amount of axial load is higher, the D/C ratio varies between 0.7 and 4.0, depending on the assumed concrete strength percentage and the axial load amount.
As regards the *SD* limit state expressed in terms of shear force capacity, no differences have been observed in the performance sensitivity for the two types of analysis.

The ranges between minimum and maximum D/C values are higher in the dynamic analysis than in the static one in all frames (not only in the frame 2, as observed for the chord rotation). When the lower concrete strength values are considered, the seismic performance provided by the dynamic analysis is more conservative than the one obtained by the pushover analysis. With reference to the case-study, the axial load variation has a significant role in the seismic performance measured in terms of shear force especially for internal columns, where double values of D/C ratio are observed.
The obtained results underline the relationship between the effects of axial load variation and the effective concrete strength, which in existing buildings can be much lower than mean one, due to high variability of experimental results. The study also highlights the need for further investigation on a wider range of structures aimed at defining specific provisions to account for the combined effect of axial load and concrete strength variability. Both factors, i.e. the effective amount of axial load during the seismic response of the structure, and a more realistic description of the concrete strength distribution should be carefully evaluated in order to assess the seismic performance of existing buildings.

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