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Procedia Structural Integrity 44 (2023) 99–106

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XIX ANIDIS Conference, Seismic Engineering in Italy

Assessment of the effect of seismic sequences on steel X-CBF for industrial buildings

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Abstract

This work concerns about the study of the effect of the seismic sequences on steel mono-storey industrial buildings equipped with X-CBFs, with the aim to evaluate a code change to adequately consider this issue. Indeed, current technical regulations (CEN, 2004; MIT, 2018) do not take into account this phenomenon, thus the structure are designed only to withstand a single main-shock, without considering the possible accumulation of damage due to the after-shocks. In this work it is instead shown how this effect has to be properly considered and evaluated. First, a mono-storey industrial building is analysed as preliminary case study. Fragility curves are built for both sequences and single main events, thus obtaining an important comparison. Then the study focuses on a single X-CBF, validated through an experimental test from literature. The calibrated system is subjected to both seismic sequences and corresponding mainshocks. Analyses are carried out also by varying brace profiles. The results show a significant influence of the seismic sequences on the increase of the ductility request of the structure. Therefore, with the aim to properly represent the effect of the sequences, it is considered necessary to require a reduction of the available behavior factor, providing a precautionary estimate. This operation wants to give a first preliminary estimate of the increase of the seismic risk only on the seismic vulnerability side of this kind of structures.

Keywords: *X - concentrically braced frames, seismic sequences, nonlinear dynamic analyses, elastic response spectrum.*

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10.1016/j.prostr.2023.01.014

1. Introduction

The present work concerns about the study of the effects of the seismic sequences on the design of mono-storey industrial buildings equipped with X – concentrically braced frames (X-CBFs). Usually, earthquakes are not isolated events; in fact, they can be followed by several after-shocks with intensity comparable to the main-shock. Ruiz Garcia (2014) underlined that, while the main-shock is always the event with the maximum magnitude, in a specific site an after-shock could have a higher PGA. This fact may cause a progressive accumulation of damage, if the time between the shocks is not enough to repair the structure. Current technical regulations (CEN, 2004; MIT, 2018) do not take into account the possible effects of the seismic sequences, which means that the structures are designed only to resist a single event. The aim of this work is to properly evaluate code modifications to adequately keep into account this issue.

Several past studies have already investigated on the effect of the seismic sequences on steel structures. The effects of repeated earthquake ground motions on the response of single-degree-of-freedom systems (SDOF) with non-linear behaviour and on moment resisting frames were analyzed by Amadio et al. (2003), in which it has been underlined how multiple events can lead to a significant accumulation of damage and a consequent reduction in the behavior factor. Hatzigeorgiou (2010) presented a ductility demand-spectra for SDOF systems under multiple near- and far-fault seismic ground motions, by examining artificial sequences, generated by combinations of real single events. Fragiacomo et al. (2004) evaluated the response of SDOF systems and real steel structures under seismic sequences: moment resisting frames with rigid joints, moment resisting frames with semi-rigid joints and concentrically braced frames were evaluated. A simplified design criterion for the damage control limit state verification of steel frames under repeated shakings was presented, consisting of an elastic analysis by using a reduced q-factor with respect to the case of one event only. The maximum reduction needed was observed for the CBF case. Ruiz Garcia et al. (2011) investigated on the influence of after-shocks on drift demands of MRF existing buildings. Rinaldin et al. (2017) analyzed SDOF systems with different hysteretical behavior; it was underlined too that mainshock-aftershocks sequences should be considered in earthquake-prone regions, with a higher probability of sequences occurrence. The use of viscous dampers or the reduction of behavior factor were two modes proposed to withstand the multiple shakings. Rinaldin et al. (2020) addressed the study on the evaluation of CBF system, by considering both MDOF and equivalent SDOF models. As the probability of damage accumulation increases under the effect of seismic sequences (therefore the vulnerability/fragility of the structure), so the probability of exceeding a certain threshold of spectral acceleration or PGA increases, therefore the seismic sequences also affect the seismic hazard. Several studies, like in (Iervolino et al., 2014; Lolli and Gasperini, 2003), are focused on the influence of the seismic sequences on the seismic hazard evaluation.

The work is focused on the influence of seismic sequences on the fragility of the structures. A typical mono-story industrial building (Section 2), subjected to natural seismic sequences is analyzed. Fragility curves are built to evaluate the behavior of both moment resisting portal frames and braced frames. Then the study is focused on the behavior of X – concentrically braced frames (Section 3) with the aim to evaluate the maximum possible effects of the seismic sequences. Analyses are carried out on a X-CBF validated through experimental tests from literature and by varying the section of the brace. A proper reduction of the available behavior factor is then proposed, representative of the seismic sequences effects. It is stressed that this approach addresses only the increment of vulnerability due to the effect of seismic sequences. The influence on the hazard is not considered here and is left to other studies.

2. Preliminary case study

The industrial steel building with X-CBFs designed by Scozzese et. al (ReLUIS et al., 2018; Scozzese et al., 2017), according to italian code (Ministero delle infrastrutture e dei trasporti, 2008) and located in L'Aquila (Italy), has been analyzed as case study (Fig. 1). The structure has been modeled with Seismostruct (Seismosoft, 2020), that considers a fiber approach to model the inelastic behaviour of the elements, according to a force-based finite element formulation. The Menegotto-Pinto model (1973) has been chosen to represent the uniaxial stress-strain relationship of steel. With the aim to validate the model, a series of pushover analysis on the whole structure have been carried out and calculation of the braces buckling strength has been done (according to the relationships given in the Eurocode 8), showing a great correspondence.

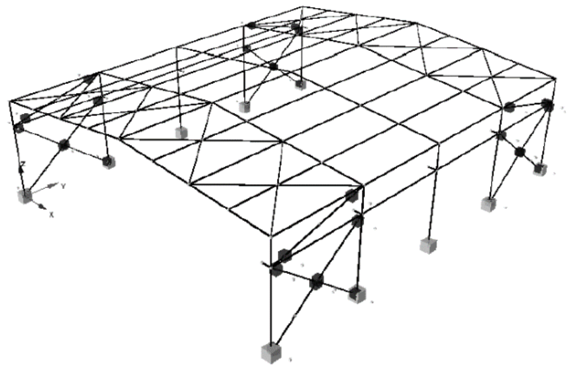

Fig. 1. Structural scheme of the industrial building case study.

The system has been subjected to nonlinear dynamic analysis, through the application of both seismic sequences and single mainshock. A series of relevant sequences of Italy and Japan has been selected. The events constituting the sequences have been obtained through the Engineering Strong Motion database (ESM- INGV) for the italian events, and Strong-Motion Seismograph Networks (K-NET, KiK-net) for the Japanese ones. The sequences have been composed letting 30 seconds of rest between subsequent events, in order to completely stop the structure. For example, the characterization of the sequence of Friuli-Forgaria Cornino is given in Table 1 and in Fig. 2. In total, 40 seismic sequences have been considered and compared with the 40 main events.

Table 1. Events that make up the considered natural seismic sequence of Friuli – Forgaria Cornino.

Sequence	Station code	Date	Time	Mw	Direction	PGA	Epicentral distance	Depth	Duration
		[yyyymmdd]	[hhmmss]			[cm/s^2]	[km]	[km]	[s]
Friuli – Forgaria Cornino	FRC	19760511	224400	5	HNE	-300.262	4.6	12.3	18.09
	FRC	19760611	171640		HNE	85.74014	2.8	9.9	13.02
	FRC	19760911	163110	5.2	HNE	109.7431	16.6	9.8	15.04
	FRC	19760911	163501	5.6	HNE	-229.363	18.6	4.3	18.56
	FRC	19760915	31518	5.9	HNE	210.1253	17.4	6.8	21.995
	FRC	19760915	92118	6	HNE	-326.848	16.2	11.3	24.595

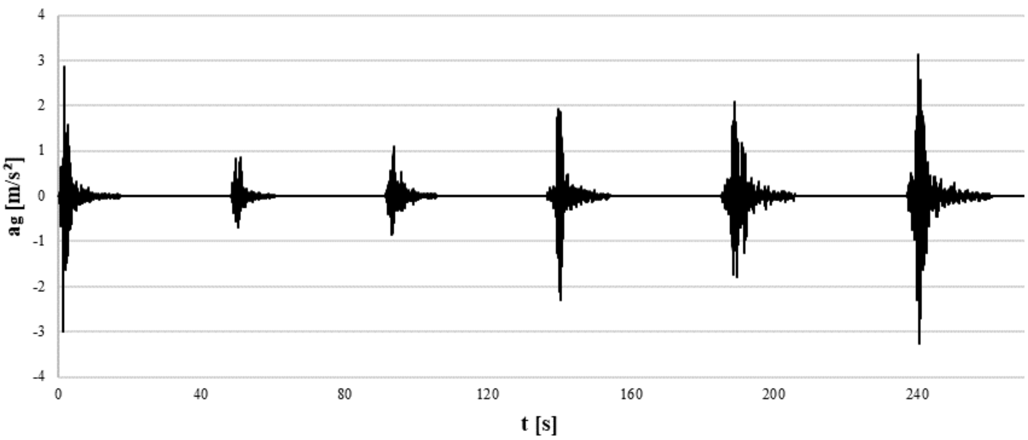

Fig. 2. Ground accelerations time-history for the natural seismic sequence of Friuli (1976) – Forgaria Cornino.

Then, fragility curves have been built, with the aim to evaluate the seismic vulnerability. A fragility curve defines the probability of exceeding a certain level of damage (a limit state) with a parameter that indicates the seismic intensity (IM-Intensity Measure). In this work the “Cloud Analysis” method (Han et al., 2015; Hosseinpour and Abdelnaby, 2017; Jalayer et al., 2015; Porter, 2021) has been used, by considering PGA as IM, and the storey drift as “Engineering Demand Parameter” (EDP). Drift limit values given in (Applied Technology Council et al., 1997) are considered, according to damage (DL), severe damage (SD) and near collapse (NC) limit states.

Totally, 160 nonlinear dynamic analyses have been performed, by also considering the two different combinations of seismic action directions. Fragility curves have been built by distinguishing the response of the moment resisting portal frames from the X-CBFs one. The final results, given in Fig. 3, have shown that fragility curves due to seismic sequences are generally on the left compared to those of the single main events, therefore indicating a damage accumulation due to the succession of events. However, the increase of the probability of exceedance is quite limited and around a maximum value of 6% for the near-collapse limit state, and lower for the other limit states. In particular, it is observed how the effect of the sequences is more relevant for the X-CBFs than the portal frames, for whom the effects are even lower.

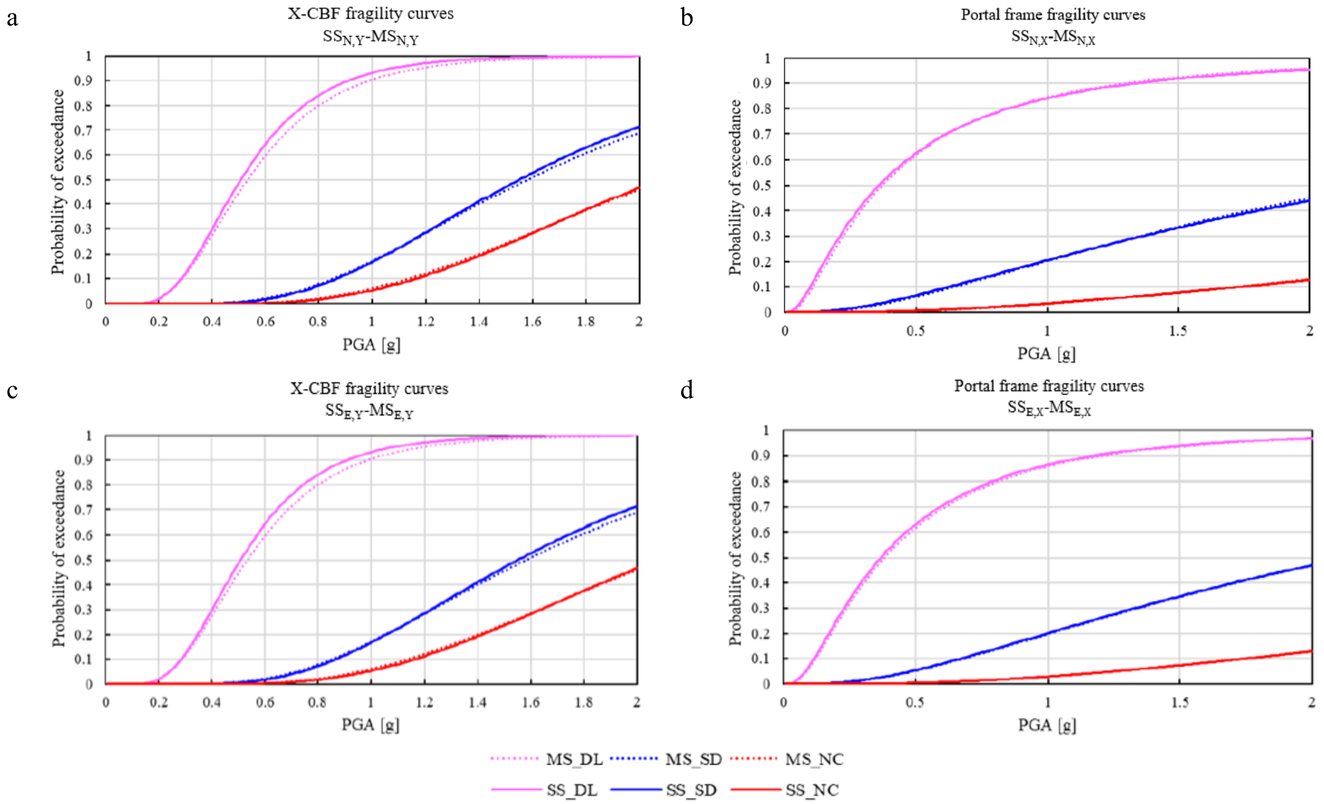

Fig. 3: Fragility curves for X-CBFs and portal frames of the industrial building with PGA as IM, for both main-shocks (MS) and seismic sequences (SS) and for the three limit states (DL: limitate damage; SD: severe damage; NC: near collapse): (a) case with North-South seismic component (N) applied in longitudinal direction (Y) for X-CBF; (b) case with North-South seismic component (N) applied in transversal direction (X) for portal frame; (c) case with East-West seismic component (E) applied in longitudinal direction (Y) for X-CBF; (d) case with East-West seismic component (E) applied in transversal direction (X) for X-CBF.

3. Analysis on the X-CBF

This section is focused on the evaluation of the single X-CBFs. In particular, the “BC0” model experimentally tested by Wakabayashi (2010) has been considered (the geometrical characteristics of the connecting plates, not described by Wakabayashi, have been taken from Faggiano et al. (2018)). The numerical model has been implemented with Seismostruct (Seismosoft, 2020). Initial geometric imperfections equal to L/1000, applied in the middle of each diagonal semi-length and in-plane of the X-CBF, have been considered. The imperfection value is taken from the Dicleli and Calik relationship (2008). The calibration process follows what has been carried out by Amadio et al. (2022). Fig. 4a shows the great correspondence between experimental and numerical shear-displacements cycles. Thus, the model has been considered calibrated. Then, with the aim to evaluate a system with greater seismic weight, two masses of 70 tons have been applied on the top of the columns (Fig. 4b). These masses correspond to the ones applied to an X-CBFs belonging to the same structure assessed in Section 2, but with 13 moment resisting portal frames instead of 5.

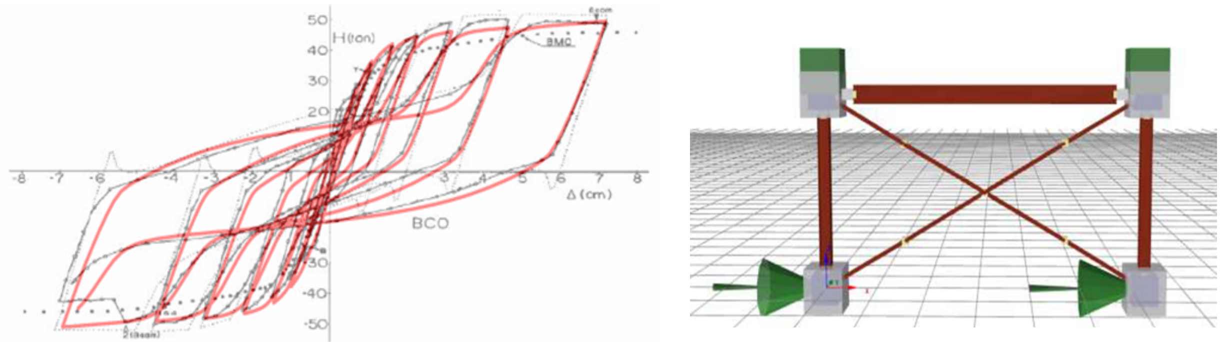

Fig. 4. (a) Comparison between the results of the numerical model implemented with Seismostruct and the experimental test (BC0 curve - black continuous line; image taken and adapted from Wakabayashi et al., 2010); (b) Model calibrated, with the application of the masses on the top.

In addition to the calibrated model (with H100x50x4x6 brace), two more solution have been investigated by varying the brace section. Finally, the following profiles have been considered:

- RHS 120x40x4 ($\bar{\lambda} = 1{,}47$)
- H100x50x4x6 ($\bar{\lambda} = 2{,}12$)
- R50x20 ($\bar{\lambda} = 4{,}21$)

The effects of seismic sequences have been evaluated, as done for the preliminary case study, by comparing the displacement requests obtained with the single main-shock and with the entire seismic sequences.

As example, some results obtained from the Friuli – Forgaria Cornino sequence (characterized through Table 1 and Fig. 2) are given. This is a typical case of a sequence with comparable events inside it, that can lead to an important effect on the structure. This sequence has been compared to the 6th event, that is the one with the maximum spectral acceleration at the main period of the three different structures. Shear-displacement cycles for the sequence and for the considered main shock, are given in Fig. 5, for each X-CBFs assessed. The increase of the ductility demand is evaluated by measuring, for both sequences and main-events, these quantities:

- $\delta_{max,+}$ = maximum displacement in the positive direction;
- $\delta_{min,-}$ = minimum displacement in the negative direction;
- δ_{max} = maximum displacement in absolute value;
- Δ = maximum displacement excursion (difference between maximum positive and minimum negative).

These displacements are given with the ratio value between sequences and main shock in Table 2. It can be observed that the ratios can greatly vary, depending on the considered quantity and on the brace profile. Moreover, it can be seen that this sequence has a great effect on X-CBF with the largest brace profile, with ratios higher than 1. The ratios are lower for the other slender braces, even with ratios lower than 1.

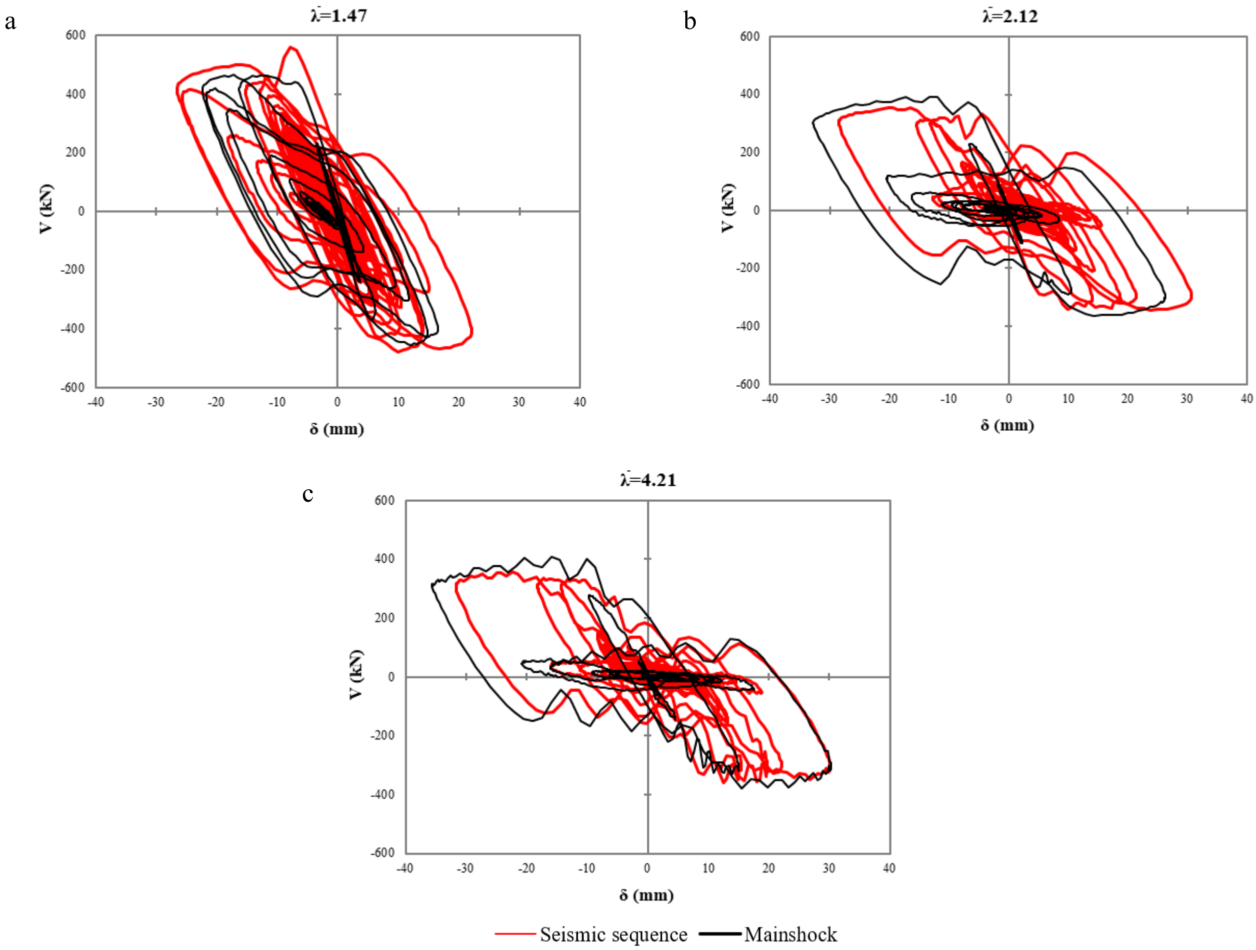

Fig. 5. Comparison between dynamic cycles from seismic sequence and mainshock for the case of Friuli – Forgaria Cornino for each normalised slenderness: 1.47 (a); 2.12 (b); 4.21 (c).

Table 2. Displacement demands for the analyses carried out through the natural seismic sequence of Friuli-Forgaria Cornino; SS = Seismic sequence; MS = Main Shock; SS/MS = ratio between them; measurements are in millimeters.

$\bar{\lambda}$		$\delta_{max,+}$	$\delta_{min,-}$	δ_{max}	Δ
	SS	22.2	-27.3	27.3	49.5
1.47	MS	16.6	-23.1	23.1	39.7
	SS/MS	**1.34**	**1.18**	**1.18**	**1.25**
	SS	30.7	-29.2	30.7	59.9
2.12	MS	26.2	-33.6	33.6	59.8
	SS/MS	**1.17**	**0.87**	**0.91**	**1.00**
	SS	30.2	-32.4	32.4	62.6
4.21	MS	30.2	-36.3	36.3	66.5
	SS/MS	**1.00**	**0.89**	**0.89**	**0.94**

Table 3: Values of the increase ductility demand for the different analysis group and final indicators.

Mean increases of ductility demand				
Analyses group	**M1**	**M1+σ_{M1}**	**M2**	**M2+σ_{M2}**
$\bar{\lambda}$=1.47	4.71%	18.11%	6.45%	19.86%
$\bar{\lambda}$=2.12	1.78%	11.34%	3.77%	16.68%
$\bar{\lambda}$=4.21	0.97%	5.20%	3.10%	14.70%
Averages	2.49%	11.55%	4.44%	17.08%

Generally, by evaluating all the obtained results, it can be observed that the sequences that lead to a significant increase of the ductility demand are those that have after-shocks with a comparable intensity to the main-shock ones. For the others, the effects are minimum.

Globally, 40 seismic sequences were analyzed for each analysis group, by calculating the mean increase of ductility for the different structures. The next two indicators are considered, for each j-th analysis group (the three structures, characterized by normalized slenderness equal to 1.47, 2.12 or 4.21):

$$M1_j = \frac{\sum_i^{n°seq_j} \delta_{seq,max,i}/\delta_{main,max,i}}{n°seq_j} \quad (1)$$

$$M2_j = \frac{\sum_i^{n°seq_j} \Delta_{seq,i}/\Delta_{main,i}}{n°seq_j} \quad (2)$$

in which the quantities have been previously defined and can be referred to seismic sequences ("seq") or to main shocks ("main"): M1 is calculated by considering the ratios of the maximum absolute value of displacements and M2 by evaluating the ratios of the maximum displacement excursions. The indicators M1 and M2 for each analyses group are also given with the respective standard deviations σ in Table 3. Besides, final average values are calculated by mediating the values obtained for each different normalized slenderness.

In Fig. 6, cumulative frequency curves of the two ratios are given for the cases with normalized slenderness equal to 1.47, highlighting the average values Mi and Mi+σi. It is clearly observable that the averages are higher than 1, thus indicating an increase of the ductility demand by passing from mainshocks to seismic sequences.

a b

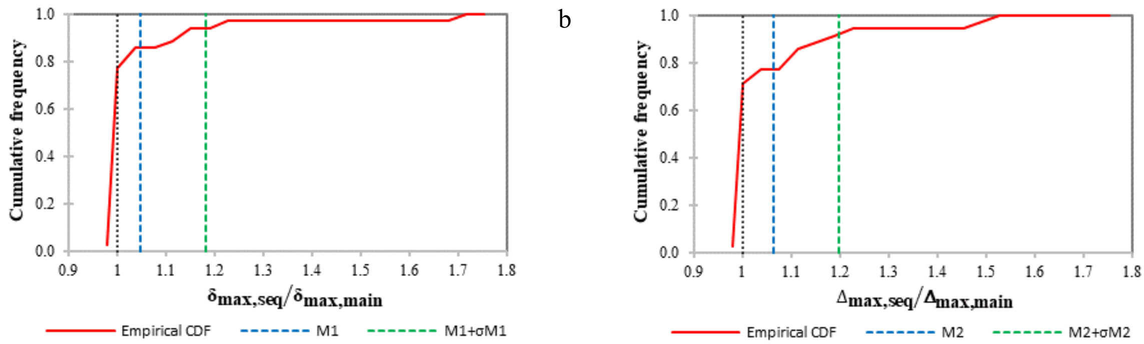

Fig. 6. Cumulative frequency curves, averages Mi and averages plus standard deviations Mi+σi for the different ratios $\delta_{max,seq}/\delta_{max,main}$ (a) and $\Delta_{max,seq}/\Delta_{max,main}$ (b) are given for the normalized slenderness equal to 1.47.

Generally, the effect of the seismic sequences can significantly vary on the basis of the sequence characterization, the adopted indicator and the structure considered. An increase in demand is also observed by passing from high to low normalized slenderness of the braces, maybe due to the higher vibration period for the structure with high normalized slenderness of the brace, that lead to lower spectral acceleration.

4. Conclusions

In this work the effects of the seismic sequences on the vulnerability of steel X-CBFs one floor industrial buildings were analysed. First, a whole industrial building has been evaluated as preliminary case study, to identify the major vulnerabilities of this kind of structures. Then, the study has been focused on a single XCBFs, calibrated on experimental cyclical test. Different profile braces have been evaluated. The proposed final indicators M1 and M2 give an estimate of the increase of ductility demand, by passing from single main events to repeated ground shakings. The results of the analyses show a great variability depending on the sequence typology, the profile of the brace and the indicator considered. Final average values added to one standard deviation are considered, in order to estimate the significant possible effects of seismic sequences. In average, increases of ductility demand are equal to 11.55 and 17.08 %, for M1 and M2 respectively (Table 3). Since a major ductility demand corresponds to an equivalent lower availability in terms of behaviour factor, an appropriate reduced q-factor q_{seq} can be proposed, according to equation (3).

$$q_{seq} = \eta_{seq}\, q \tag{3}$$

in which the reduction factor $\eta_{seq} \cong 0.8 \div 0.9$ can be prudently estimate as a result of these first analyses. This reduced behavior factor leads to as a conservative preliminary estimate of the effects of seismic sequences on steel X-CBFs dissipative systems for one floor industrial buildings. It is important to underline that this approach addresses only the increment of vulnerability due to the effect of seismic sequences. The influence of the hazard is not considered here. Future developments of this work will be focused on the evaluation of a larger set of seismic sequences and a larger number of analyzed structures.

Funding: The research was financed by DPC-ReLUIS project 2019-2021 (WP12), Italy.

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