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Procedia Structural Integrity 44 (2023) 918–925

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XIX ANIDIS Conference, Seismic Engineering in Italy

Seismic risk assessment of a new RC-framed skin technology for integrated retrofitting interventions on existing buildings

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Abstract

A RC-framed-skin technology for the integrated seismic and thermal retrofitting interventions on existing buildings, recently proposed by some of the authors, is thoroughly investigated. By means of numerical analyses, its effectiveness and suitability within the framework of seismic risk class assessment is proved. The system is composed of a RC-framed structure with an external reinforced plaster layer that does not offer a structural contribution to the capacity of the system in ultimate conditions, but which can be effective by increasing the lateral stiffness in serviceability conditions. The system is realized from the outside of the existing building so guaranteeing limited invasiveness of the intervention and preventing the interruption of the building use by their occupants. An existing RC building, representative of a typical example of the Italian building stock, is analyzed as a case study, and its seismic risk class upgrade, obtained by the proposed strengthening intervention, is assessed by non-linear static analysis. The numerical models are developed within the OpenSees framework. The Expected Annual Loss (EAL) parameter, together with the Life Safety Index (LS-I), are chosen as synthetic measures that include both aspects related to Ultimate Limit state (ULS) and Serviceability Limit State (SLS) conditions. The risk class accounting for or disregarding the contribution of the external reinforced plaster are finally compared.

Keywords: RC-framed skin; seismic risk assessment; non-linear static analysis; existing RC buildings; retrofitting intervention.

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10.1016/j.prostr.2023.01.119

1. Introduction

In Italy, as in many other European countries, constructions present significant energy and structural inadequacies. Actually, most of the Italian existing building stock was built before the entry into force of Law 10/1991 which governs the reduction of energy consumption in buildings, and before the entry into force of the modern seismic codes, e.g., OPCM (2003), MI (2008), MIT (2018).

To increase the safety and well-being of citizens, the renovation of the existing building stock becomes a decisive issue and, to do this, two main options can be considered nowadays: demolition and reconstruction or retrofit interventions. In the second category, integrated interventions executed from the outside of the existing building are very promising, being more sustainable and easier to apply, requiring shorter relocation time and minimizing the occupant disturbance. Moreover, a lower environmental impact in terms of both consumption of raw materials and production of hazardous waste with respect to demolition and reconstruction option, is assured, see for instance Power (2010), Alba-Rodriguez et al. (2017). Recent studies demonstrated the effectiveness and the environmental sustainability of retrofitting solutions which combine seismic and energy improvement, reducing costs, invasiveness, construction time and materials waste, Marini et al. (2017), Manfredi and Masi (2018). Alternative integrated solutions have been developed in the last years (e.g., Pertile et al. 2018, Margani et al. 2020, Bournas 2018) employing different materials (e.g. reinforced concrete, engineered wood products, steel) and using different retrofitting approaches (e.g. additional external shear walls, external exoskeleton).

Among these solutions, the RC-framed skin for retrofitting of existing buildings, recently developed by some of the authors and thoroughly described in Pozza et al. (2021), Talledo et al. (2021), represents a particularly sustainable and effective system for the integrated thermal and seismic retrofit of existing buildings, being characterized by a limited impact and invasiveness towards the occupants. To assess the seismic performance of this technology, the approach proposed in the "Guidelines for the seismic risk classification of the constructions" (Guidelines in the following), approved in February 2017 by the High Council of Public Works (MIT, 2017), and updated in March 2020 (MI, 2020), is used in the present study, with reference to a typical existing RC building of the Italian building stock.

Non-linear static analysis is used to define the capacity curve and to calculate the return period of the earthquake leading to the attainment of the different limit states. Then the risk class of the existing building and the class upgrade of the retrofitted building, both accounting for or disregarding the contribution of the reinforced plaster, are evaluated

2. RC-framed skin technology

The proposed technology provides for an integrated renovation of existing RC or masonry buildings and is based on the idea of cladding the building with an external RC-framed skin. This technology, schematically depicted in Fig. 1 and extensively described in Pozza et al. (2021) and Talledo et al. (2021), consists in casting in-place a RC-framed structure, connected to the existing building at the foundation and at each floor level by means of mechanical anchors.

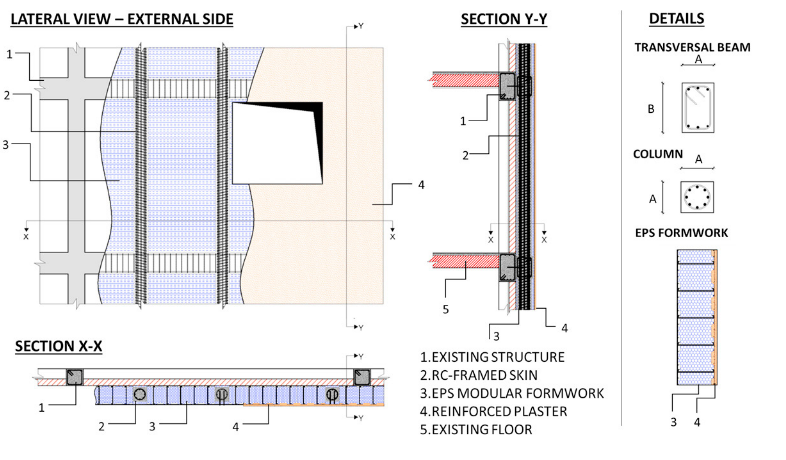


Fig. 1. The RC-framed skin technology.

The installation and casting phases are facilitated by the presence of prefabricated EPS modules that define the structural mesh and provide for the thermal insulating of the existing building. The structural mesh of the RC-framed is realized by means of square columns and rectangular transversal beams. The interspace of the columns spans from 1200 mm to 1750 mm even if it can be strongly conditioned by the façade opening geometry. The columns have a variable size in the range 150-300 mm. The transversal beams are positioned at the floor level and have a variable height in the range of 300–500 mm, while the base matches the columns sides.

Columns are characterized by a special reinforcement pattern realized by means of longitudinal bars confined using continuous spiral stirrups, while transversal beams are reinforced using standard longitudinal bars and stirrups. The prefabricated EPS modules are specifically shaped to allow the realization, on the external surface, of a thick (in the range 25 – 50 mm, with an average value of 35 mm) and impact-resistant finishing plaster. The external plaster is reinforced with a steel mesh pre-assembled on the EPS modules and connected to the reinforcement RC frame by means of anchor rods. Plaster reinforcement is realized using galvanized Fe50 steel with a mesh composed by ϕ 5 mm, 50 mm spaced vertical wire and ϕ 3 mm, 100 mm spaced horizontal wire.

From the structural point of view, the RC-framed skin is conceived as a multi-performance system: the RC-frame is very ductile, ensuring a seismic strengthening and an improvement of the displacement capacity for the ultimate conditions (i.e., high drift levels), while the external reinforced plaster, which is not considered as a resistant structural element in ULS design, provides for a stiffening of the systems in the serviceability conditions (i.e., small drift levels).

3. Seismic risk assessment

The Guidelines (MI, 2017; MI, 2020) define the general principles and the technical rules to evaluate the seismic risk class of existing buildings and the class upgrade due to seismic strengthening interventions on private buildings, Cosenza et. al. (2018). In particular, two different methods - respectively the conventional and the simplified approach - are proposed. The conventional method requires a detailed seismic assessment of the structure at each limit state and allows for evaluating the upgrade of two or more seismic risk classes by means of strengthening interventions.

According to the conventional method, the seismic risk class of a building is defined as the minimum class between those associated with the economical parameter Expected Annual Loss (EAL) and the structural parameter Life Safety Index (LS-I). The EAL parameter can be interpreted as the repair cost of the damage produced by seismic events that will eventually occur during the life of the building, broken down annually, and expressed as a percentage of the reconstruction cost. The EAL is analytically evaluated as the area under the curve representing the direct economic losses, i.e., the repair costs, as a function of the mean annual frequency of exceedance of the seismic action λ (defined as the reciprocal of the earthquake return period) of the events that cause the achievement of a series of limit states for the structure. According to Cosenza et. al. (2018), the repair costs are expressed as %RCost, that is a fraction of the Reconstruction Cost (indicated as RCost).

The procedure to obtain the λ–%RCost curve is detailed in the Guidelines (MI, 2017; MI, 2020) and requires the evaluation of the building capacity associated with each limit state specified by the Italian building code (MI 2018), i.e. Operational (OLS) and Damage Limitation (DLLS) at Serviceability Limit State (SLS); Life Safety (LSLS) and Collapse (CLS) at Ultimate Limit States (ULS). The capacity of the structure can be defined in terms of the seismic action which corresponds to the achieving of the specific limit state (LS), identified by the earthquake return period $T_{R,C}^{LS}$ or by the corresponding Peak Ground Acceleration PGA_C^{LS} related to the capacity at the various LS (i.e. OLS, DLLS, LSLS, and CLS). It is worth noting that, according to the Guidelines, the PGA_C^{LS} on the rigid soil leading to the fulfillment of the various Limit States can be computed by means of any of the methods allowed by the building codes, i.e., linear/non-linear and static/dynamic.

In the present paper, the non-linear static approach is adopted and the value of the capacity of the structure at Life Safety and Damage Limitation Limit States are evaluated. In particular, for the LSLS both ductile and brittle (i.e., shear) mechanisms are checked for all elements according to (MIT, 2018; Circolare n.7, 2019), and the displacement capacity of the structure is evaluated. Then, the curves are bi-linearized according to the procedure proposed in (Circolare n.7, 2019) and the seismic action corresponding to the spectrum for which the target point is equal to the structural capacity is computed, both in terms of PGA_C^{LS} and $T_{R,C}^{LS}$. Concerning the building performance at the DLLS, it can be conventionally assessed by evaluating the maximum interstorey drift (MI 2018, Cosenza et al. 2018). For the case of stiff brittle infills in RC structures, the upper bound limit to the interstorey drift for DLLS is 0.5% (MI, 2018).

An additional check could be carried out by limiting the chord rotation at DLLS with the yielding chord capacity of each element of the existing building.

Once PGA_C^{LSLS}, PGA_C^{DLLS} and the corresponding values of the mean annual frequency of exceedance of the earthquake $\lambda_C^{LSLS} = 1/T_{R,C}^{LSLS}$ and $\lambda_C^{DLLS} = 1/T_{R,C}^{DLLS}$ have been calculated, finally the λ for the other limit states (i.e., OLS and CLS) can be computed according to the simplified relations given by the Guidelines (MIT, 2017): $\lambda_C^{CLS} = 0.49\ \lambda_C^{LSLS}$ and $\lambda_C^{OLS} = 1.67\ \lambda_C^{DLLS}$.

A reliable evaluation of loss assessment of existing buildings under seismic events should require complex probabilistic analysis and specific cost data related to the building and the adopted reinforcement technology. In order to simplify the evaluation of loss assessment in the conventional approach, a number of research studies, based on macro-seismic analyses as well as post-earthquake observational data, have been carried out and are summarized in Cosenza et al. (2018) where an estimation of the repair costs has been proposed. In particular the %RCost associated with DLLS and LSLS is set equal to %RCost = 15$\%$ and %RCost = 50$\%$ of the reconstruction cost, respectively. For the other limit states, the conventional values of repair costs, provided by the Guidelines (MI, 2017) are summarized in Table 1. It is worth noting that these values were calibrated to include all the repair actions associated with a specific damage level. In this Table, two additional conventional Limit State are considered, i.e. the Initial Damage Limit State (IDLS) and the total loss or "Reconstruction" Limit State (RLS), conventionally related to a fixed $\lambda_C^{IDLS} = 10\%$ and $\lambda_C^{RLS} = \lambda_C^{CLS}$, for which the %RCost are assumed respectively equal to the 0 and 100%. For a detailed description of the calibration of %RCost, see Cosenza et al. (2018).

Table 1. Building repair cost (%RCost) associated with each LS

Limit State	%RCost
RLS	100 %
CLS	80 %
LSLS	50 %
DLLS	15 %
OLS	7 %
IDLS	0 %

Finally, the Life Safety Index (LS-I) is defined as the ratio between the Peak Ground Acceleration for which the Life Safety Limit State is reached, also called "capacity PGA" or PGA_C^{LSLS}, and the PGA expected for the site where the construction is located, for the same Limit State, i.e. the "demand PGA" or PGA_D^{LSLS}.

4. The case study: safety assessment of a unreinforced and retrofitted building

The safety assessment procedure using EAL parameter and LS-I index is applied to the RC existing frame building extensively analyzed in Talledo et al. (2021), representative of a typical example of the Italian building stock, in the original state as well as retrofitted with the proposed technology with reference to a high-level seismic zone, i.e., Aielli (AQ), with a soil type C and a reference period of 50 years, characterized by the following PGA values for ultimate and serviceability limit state respectively: $PGA_D^{LSLS} = 0.346g$ (i.e., return period of the seismic action equal to 475 years) and $PGA_D^{DLLS} = 0.156g$ (i.e., return period of the seismic action equal to 50 years), respectively. The selected building, designed without adequate seismic details and level of seismic action, is characterized by a rectangular plan with 14.30 m x 18.30 m dimensions and 3.30 m to 3.50 m inter-story height. The frames bearing the vertical loads are set in the X-direction, whereas in the Y-directions only two lateral frames are present.

The first phase of the safety assessment procedure consists of carrying out the pushover analyses with the aim of evaluating the seismic performances pre- and post-intervention. The pushover analyses are carried out with the distribution of forces proportional to the masses and to the first mode of vibration, in the two main directions X- and Y- of the building. Fig. 2 shows the three models of the existing building, in the original and the two retrofitted configurations, considering or disregarding the external plaster, respectively. The models are developed in OpenSees framework, McKenna et al. (2010), and using the pre- and post-processor STKO, Petracca et al. (2017). In this phase of the research, the effect of the external plaster is simulated by means of an equivalent truss with a simple constitutive law, assuming a linear elastic behavior with stiffness equal to the shear deformability up to the shear strength of the panel, followed by a linear softening branch. For each capacity curve obtained by the pushover analyses, the N2 procedure (Fajfar 1996) is carried out and the Peak Ground Acceleration, as well as the return period of the earthquake, corresponding to the spectrum for which the target point is equal to the structural capacity, is evaluated with respect to both Life Safety (LSLS) and Damage Limitation (DLLS) Limit States ($PGA_C^{LSLS}, T_{R,C}^{LSLS}$ and $PGA_C^{DLLS}, T_{R,C}^{DLLS}$).

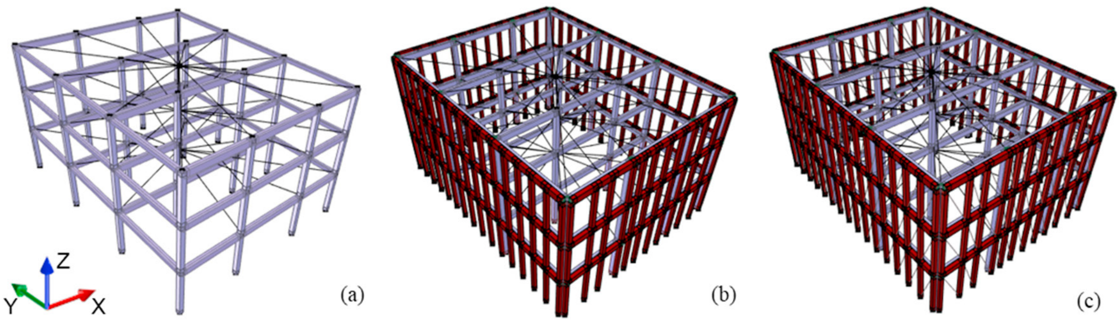


Fig. 2. FE models: (a) existing RC building; (b) retrofitted building with bare RC-framed skin; (c) retrofitted building with RC-framed skin.

4.1. Nonlinear static analysis for the existing RC frame building and for the retrofitted building

Fig. 3 shows the capacity curves in X- and Y- directions obtained by the pushover analysis for the existing building, adopting a modal and a proportional to the masses (uniform) distribution of horizontal forces. The attainment of the ultimate chord rotation is highlighted with a yellow circle, and the brittle shear failure with a green triangle. In both cases, a label indicates if the failure element is a beam, 'B', or a column 'C'. Finally, the attainment of drift equal to 5‰ is indicated with an orange circle. The bi-linearized curves are also reported with a thicker line.

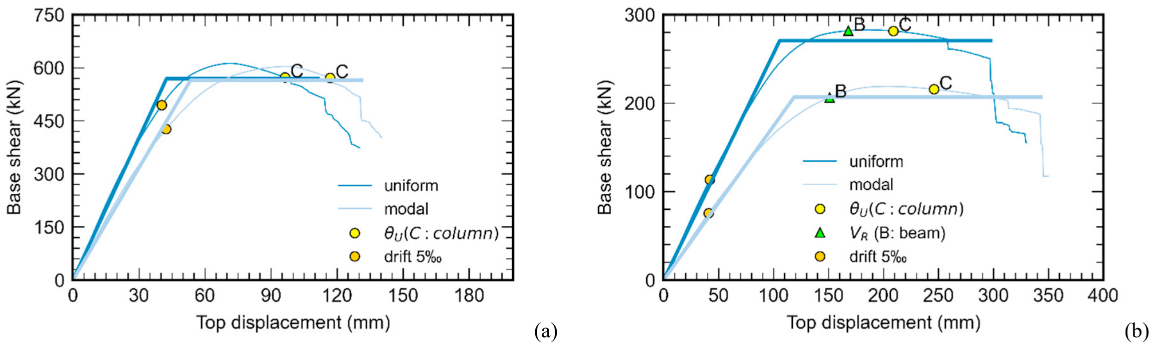


Fig. 3. Capacity curves and bi-linearization procedure for existing RC building: (a) X-direction; and (b) Y-direction.

As expected, the pushover curve of the existing building in the Y-direction is characterized by strong deformability associated with a lower strength (about one half) compared to the response in the X-direction (i.e., the strong direction). However, despite the apparent ductility of the capacity curve, in Y-direction the structure is subjected to a brittle shear failure occurring on the flat beams, while in X-direction the failure is due to the attainment of the limit chord rotation in two central columns of the ground floor. Therefore, the existing building exhibits a remarkably different behavior in the two main directions.

Fig. 4 and Fig. 5 show the capacity curves for the existing building retrofitted with the RC-framed skin with columns sections of 250 mm x 250 mm, by considering or not the external reinforced plaster. The adoption of the proposed retrofitting technology, both with and without the external reinforced plaster, regularizes the response of the building in the two directions and in all cases, the failure is achieved for the attainment of the limit chord rotation in a column of the existing building, with a peak strength around 2500 kN (see Fig. 4), about 4 times greater than that of the unreinforced structure in X-direction. The use of the RC-framed skin with external plaster (Fig. 5) produces a significant increase in the initial stiffness of the system (i.e. more than double) with respect to the bare RC-framed skin case; on the other hand, the strength and the post-strength behavior of the system are not affected significantly by the presence of the external plaster, because its contribution for large displacements vanishes due to the softening behaviour. With reference to the LSLS and to the DLLS, Table 2 summarizes the earthquake return periods of the seismic action $T_{R,C}$ and the corresponding PGA_C for the unreinforced and retrofitted buildings.

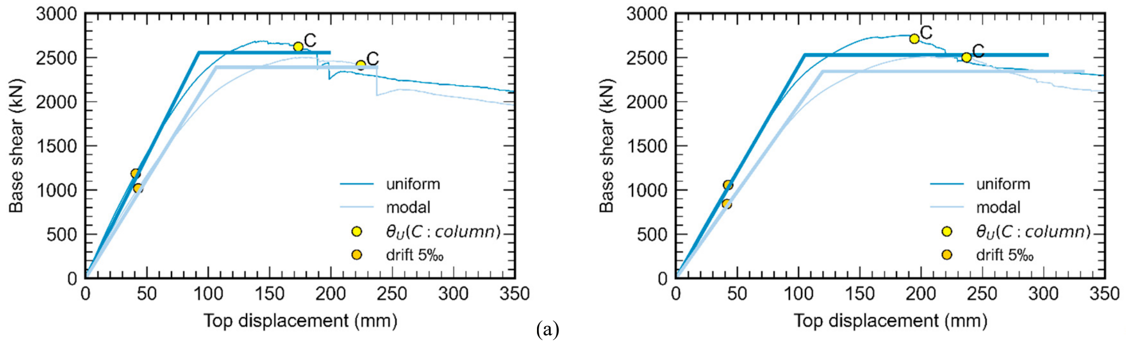


Fig. 4. Capacity curves and bi-linearization procedure for retrofitted building with bare RC-framed skin: (a) X-direction; (b) Y-direction.

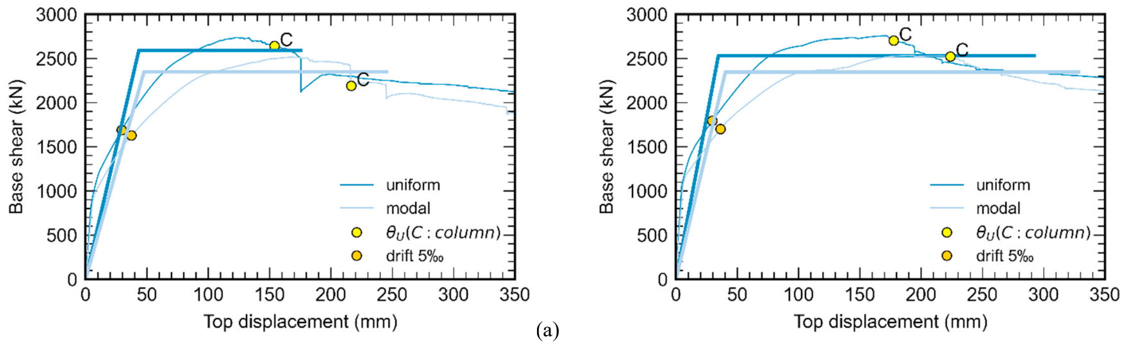


Fig. 5. Capacity curves and bi-linearization procedure for retrofitted building with RC-framed skin with external plaster: (a) X-direction; (b) Y-direction.

Table 2. Return periods of the earthquake $T_{R,C}$ and the corresponding peak ground acceleration PGA_C capacity values for the two different distributions of forces proportional to the masses and to the first mode of vibration in each direction.

		X-direction uniform		**X-direction modal**		**Y-direction uniform**		**Y-direction modal**	
Examined configuration		$T_{R,C}$ **(yrs)**	PGA_C **(g)**	$T_{R,C}$ **(yrs)**	PGA_C **(g)**	$T_{R,C}$ **(yrs)**	PGA_C **(g)**	$T_{R,C}$ **(yrs)**	PGA_C **(g)**
Existing RC building	**LSLS**	135	0.237	160	0.252	103	0.213	86	0.197
	DLLS	22	0.104	19	0.097	8	0.062	7	0.061
Existing RC building retrofitted by using bare RC-framed skin	**LSLS**	≥2475	≥0.467	≥2475	≥0.467	≥2475	≥0.467	≥2475	≥0.467
	DLLS	47	0.150	42	0.141	45	0.146	35	0.127
Existing RC building retrofitted by using RC-framed skin with external plaster	**LSLS**	≥2475	≥0.467	≥2475	≥0.467	≥2475	≥0.467	≥2475	≥0.467
	DLLS	52	0.157	69	0.179	66	0.176	80	0.191

It can be noted that the existing building demonstrates poor structural performances exhibiting the minimum value of the return period of the seismic action $T_{R,C}^{LSLS}$= 86 years, in Y-direction with modal distribution, well below the required demand $T_{R,D}^{LSLS}$ = 475 years. The existing building is far from the required performance level also for DLLS, with a minimum $T_{R,C}^{DLLS}$ = 7 years (again in Y-direction with modal force distribution), well below the required $T_{R,D}^{DLLS}$ = 50 years. The retrofitted configurations have a good behavior with regard to LSLS; however, it is worth observing that the retrofitting with bare RC-framed skin does not meet the DLLS requirements with a minimum $T_{R,C}^{DLLS}$ = 35 years, while the case of retrofitting with RC-framed skin and external plaster shows a satisfactory behavior also for DLLS.

4.2. Risk class evaluation

The values of $T_{R,C}^{LS}$ and PGA_C^{LS} reported in Table 2 are used to compute EAL and LS-I parameters, as described in Section 3, Table 3 summarizes the obtained EAL parameter and the Life Safety Index LS-I evaluated in both X- and Y- directions for the two different force distributions, proportional to the masses and to the first mode of vibration. The risk class of the building is therefore obtained as the minimum class between the EAL and the LS-I classes. Therefore, the actual risk class of the existing building is class E (in Y-direction), while the retrofitting intervention allows the improvement of the safety of the construction, moving from class E to class B with the bare RC-framed skin, and to class A when considering the external reinforced plaster.

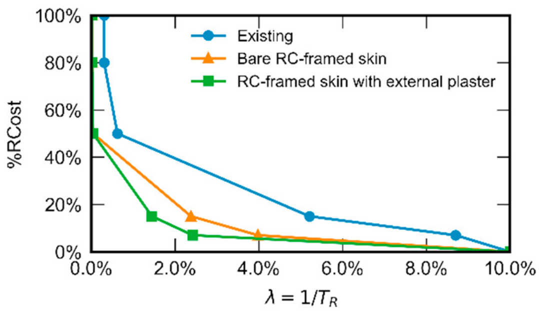
Table 3. LS-I and EAL values of existing and retrofitted building, for the two different distributions of forces proportional to the masses and to the first mode of vibration, in both directions. The seismic risk class is indicated in the parenthesis.

Examined configuration		**X-direction uniform**	**X-direction modal**	**Y-direction uniform**	**Y-direction modal**
Existing RC building	**EAL**	2.26% (C)	2.43% (C)	3.73% (E)	3.83% (E)
	LS-I	0.685 (B)	0.728 (B)	0.616 (B)	0.570 (C)
Existing RC building retrofitted by using bare RC-framed skin	**EAL**	<1.09% (B)	<1.18% (B)	<1.13% (B)	<1.34% (B)
	LS-I	>1.350 (A+)	>1.350 (A+)	>1.350 (A+)	>1.350 (A+)
Existing RC building retrofitted by using RC-framed skin with external plaster	**EAL**	<1.02% (B)	<0.86% (A)	<0.89% (A)	<0.80% (A)
	LS-I	>1.350 (A+)	>1.350 (A+)	>1.350 (A+)	>1.350 (A+)

As expected by the results of the pushover analyses, the existing building has a lower safety class in the Y- (weak) direction (class E), rather than in the X- (strong) direction (class C), confirmed by a higher EAL value for seismic action in the Y- direction.

Moreover, in all cases the proposed technology leads to an improvement of the risk class (both according to EAL and to LS-I). For retrofitting with bare RC-framed skin, the unsatisfactory performance at DLLS leads to higher EAL values (and consequently lower classes) with respect to the case of retrofitting with RC-framed skin and external plaster. This can be clearly seen from λ–%RCcost curves depicted in Fig. 6 for forces in X-direction and Y-direction (for the sake of simplicity the only case of modal force distribution is considered).

Both retrofitting configurations improve the behavior of the building for ultimate limit states (i.e. LSLS, CLS, RLS), while the configuration with external reinforced plaster (green line) has a significant effect on serviceability limit states (i.e. DLLS and OLS), so reducing the area under the curve and then leading to an higher risk class.



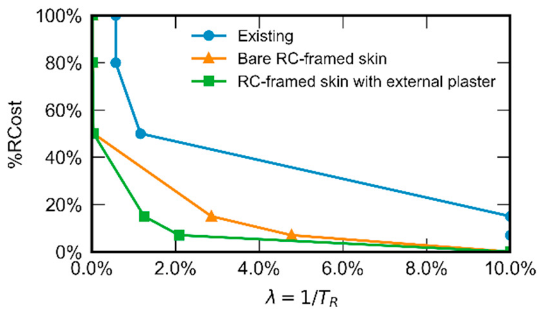


Fig. 6. λ–%RCost curves, from pushover analysis with modal force distribution (a) X-direction, (b) Y-direction.

5. Conclusions

In the present paper, the efficiency in reducing the seismic risk of existing buildings adopting the RC-framed skin technology proposed by some of the authors is evaluated according to the principles exposed in the Guidelines (MIT, 2017), with reference to a typical existing RC building designed without adequate seismic details and level of seismic action. In particular, both life safety index (LS-I) and expected annual loss (EAL) are evaluated for three different configurations: the existing building, the retrofitted building with the bare RC-framed skin, and the retrofitted building with RC-framed skin accounting for the contribution of the external reinforced plaster. The analyses prove that the proposed retrofitting technology effectively improves the seismic performance of the existing building (the risk class moves from E up to B and A, respectively, without and with the contribution of the external plaster) also regularizing its seismic behavior, eliminating the marked difference in the seismic response in X- and Y-direction (i.e., strong and weak directions, respectively). Furthermore, the contribution of the external plaster proves to be decisive with its stiffness for limitation of damage for low-magnitude recurrent earthquakes, as demonstrated by the significant decrease of EAL parameter due to better performance for DLLS.

Further analyses will be carried out as a next step of this research with a new set of parametric analyses (e.g. changing the dimension of the RC-framed skin elements) and also considering different prototype RC buildings.

Acknowledgements

The Authors would like to thank the partner company NTC&R for the support in the experimental campaign and Dr. Claudio Azzolini for the kind cooperation. This research was funded by Regione Emilia Romagna POR-FESR 2014/2020 - Asse 1.2.2 – project TIMESAFE - CUP J44I18000070007 - PG/2018/631222_16/10/2018.

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