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PRACTICAL PROCEDURE TO ASSESS THE EXPECTED CONSEQUENCES OF EARTHQUAKES ON BUILDINGS

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Abstract

The paper presents the last development of a ready-to-use procedure for the risk assessment of the consequences of seismic attacks on a r/c building. The procedure involves a process of knowledge acquisition and definition.

The seismic hazard at the site is defined within the context of the national zoning or through specific studies at the site. The vulnerability of the structure is evaluated according to a multi-scenario view. The characterization of the damage scenarios is based on the extension of damage. Different damage states are defined for the structural elements, the non structural elements and the contents. A section of the procedure is devoted to evaluate the consequences on the occupants.

The provided scenarios for which to evaluate the consequences are defined: "Light Damage", "Limited Damage", "Extensive Damage", "Extreme Damage". No damage scenario with consequences more severe than those associated with the maximum considered earthquake at the site is analyzed.

The quantification of risk is based on the evaluation of the expected economic consequences that takes into account the collapse extension of structural and non-structural elements. A risk index expressed in terms of probability of expected losses in the building lifetime is determined. Also the risk for the occupants can be computed: seriously injured and casualties are considered as expected losses.

Keywords: Seismic risk, Risk assessment, Existing buildings, R/C structures

1. Introduction

The development of design methodologies, construction detailing, and code prescriptions allows nowadays to build seismic-resistant buildings characterizing by good performance under a seismic attack, specially if advanced protection systems are applied. In these last cases their effectiveness has to be stressed. This demand was felt since the very beginning of the introduction of new technologies, so procedures for the evaluation of the consequences of a seismic attack on constructions were already developed in '80s and 90s [1, 2]. Despite this, the performances are not directly the target of the structural design that continues to be based on the control of the structural response rather than on the actual parameters defining the performance.

The actual parameters to be accounted for are the "consequences" of the seismic attack on the construction and material contents as well as on the occupants. Since the consequences depend on the seismic hazard, on the building vulnerability, on the exposition of elements and occupants, the way to account for them is to perform a risk analysis.

An analytical evaluation of the seismic risk has to address four main issues. First of all a model of the seismic hazard is required in terms of intensity of the expected earthquakes, a correlation between the elastic response spectrum shape, most of all the PGA, and the return period can be used [3]. Then a correlation between the vulnerability of the structure and the input seismic demand should be defined as a function of the required safety level [4]. Subsequently a correlation between the damage and the EDP's characterizing the seismic response has to be defined [5]. Finally, functions relating damage indicators and the expected consequences (losses or decision parameters) has to be adopted [6].

All the listed issues are characterized by randomness, so a rigorous methodology of risk assessment should be fully probabilistic leading to a probabilistic definition of the expected consequences. Such an approach was initially proposed in the first guidelines oriented to the performance base design [7] and was then continued in successive versions [8], but a fully probabilistic procedure is very complex and time consuming and not convenient to be used in an ordinary project of a single building.

With the aim to have a compact generalized tool to account for the randomness, the use of fragility curves - generally including the uncertainness in seismic response, damage and losses - is spreading. The fragility curves give the probability of losses of a type of constructions when varying the seismic demand. Curves can be found in literature for typological classes of building, so this tool can be usefully adopted for large scale evaluation of the seismic risk, that is at region, city, district dimension. It can be very hard and demanding to develop them for a single building.

For the practical use of a performance base design methodology based on the evaluation of the consequences there is a need of a quick semi-probabilistic procedure that can be used as a complement of an ordinary tool for seismic design and vulnerability assessment, such as a commercial design software.

This paper illustrates a revised version of a procedure, named f-RACE, developed and applied since some years [9, 10] that satisfies the requirements of an easy-to-use tool. The currently developed new formulation of the procedure is based on the experience gained from the vulnerability assessments, the damage analyses, the retrofitting design in the reconstruction of buildings struck by the Italian earthquakes of the last decades. The new formulation also provides for a strong data interchange with a seismic design software.

2 Framework of the procedure

The procedure provides for the evaluation of both the economic consequences and the consequences on the occupants of seismic attacks on a building. For the sake of brevity only the parts devoted to estimate the economic consequences are presented in detail. The procedure provides for the following tasks.

1. Definition of the seismic hazard through the correlation between return period and the parameters defining the site elastic response spectrum shape, particularly the PGA. The correlations given by the Italian code [11] or derived by special seismicity studies at the site are used.
2. Modelling of the structure within an ordinary software able to perform non linear seismic analysis of a framed structural system.
3. Definition of damage states for structural elements, non structural elements, contents.
4. Evaluation of global performance levels through nonlinear static analyses, performed on the numerical model, with lateral loads increased until predefined damage scenarios are reached.
5. Evaluation of the consequences of damage on structural and non structural elements, and on contents, through the costs derived by a data-base of retrofitting works and costs; also the consequences on the occupants can be estimated.
6. Evaluation of the global cost, given by direct and indirect costs, expressing the consequences.
7. Estimate of the expected consequences (or losses or decision parameter) in the building lifetime or in a predefined time interval.

Only the tasks from 3 to 7, really characterizing the procedure, are described in the following.

3 Damage states of building components

3.1 Damage levels of structural elements

With the aim of evaluating the structure vulnerability first of all the damage states applicable to the structural elements are defined.

Four damage levels are provided for beams, columns, walls: $D1^{(ST)}$ or "light damage"; $D2^{(ST)}$ or "medium damage"; $D3^{(ST)}$ or "serious damage"; $D4^{(ST)}$ or "collapse" (conventional).

The four damage states are identified with reference to the evolution of the moment-curvature correlation (Fig. 1) characterizing the plastic hinges arising at the ends of the elements [12]. Each damage state is identified by a status of the component materials: D1$^{(ST)}$ corresponds to the cracking of concrete; D2$^{(ST)}$ corresponds to the spalling of concrete cover; D3$^{(ST)}$ corresponds to the yealding of reinforcing bars; D4$^{(ST)}$ corresponds to the crashing of the confined concrete. Table I reports the values of the material strains determining the attainment of the damage states. When a shear failure occurs the damage state D4$^{(ST)}$ is considered immediately attained.

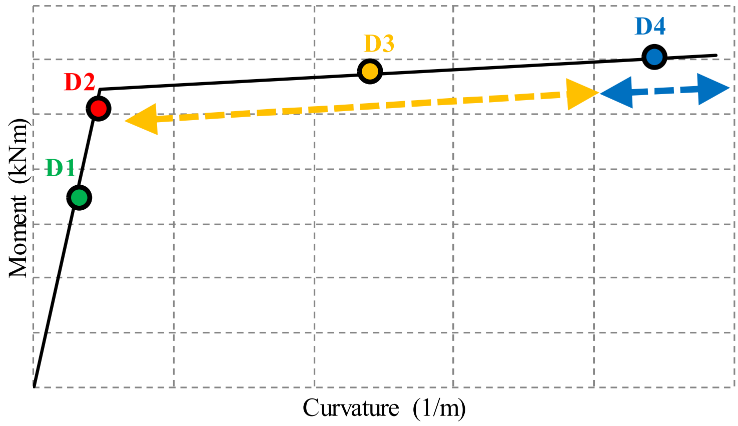


Fig. 1 – Typical moment-curvature diagram with critical status corresponding to damage states

Table 1 - Material strains at structural damage states

Mechanic characteristic	D1$^{(NS)}$	D2$^{(NS)}$	D3$^{(NS)}$	D4$^{(NS)}$
unconfined concrete strain	$\varepsilon_c = \varepsilon_{ct}$	$\varepsilon_{c,cov} = \varepsilon_{cuu}$	----	----
confined concrete strain	$\varepsilon_{c,con} < \varepsilon_{cuc}$	$\varepsilon_{c,con} < \varepsilon_{cuc}$	$\varepsilon_{c,con} < \varepsilon_{cuc}$	$\varepsilon_{c,con} = \varepsilon_{cuc}$
reinforcing bars strain	$\varepsilon_s < \varepsilon_y$	$\varepsilon_s < \varepsilon_y$	$\varepsilon_s = \varepsilon_y$	$\varepsilon_s > \varepsilon_y$

Legend: ε_{ct} concrete strain at tensile strength (core) (i.e. $\varepsilon_{ct} = 0.0016$)
ε_{cuu} ultimate strain of the unconfined concrete (cover) (i.e. $\varepsilon_{cuu} = 0.0035$
ε_{cuc} ultimate strain of the confined concrete (core) (i.e. $\varepsilon_{cuc} = 0.0105$)
ε_y steel strain at yielding (i.e. $\varepsilon_y = 0.0019$)

3.1 Damage levels of non structural elements

With the aim of evaluating the structure vulnerability also the damage states applicable to the non structural elements are defined. Three damage levels are provided for claddings and partitions: D1$^{(NS)}$, light damage; D2$^{(NS)}$, medium damage; D3$^{(NS)}$, serious damage.

The damage states are defined correspondently to the actual damage levels experimentally evidenced in masonry panels [13]. So the state D1$^{(NS)}$ corresponds to the presence of fine cracking, the state D2$^{(NS)}$ corresponds to the presence of local wide cracks, the state D3$^{(NS)}$ corresponds to the extensive presence of wide cracks with local crashing. The level of the non structural damage of claddings and partitions depends on the interstory drift ratio *Dr*. The three defined damage states D1$^{(NS)}$, D2$^{(NS)}$, D3$^{(NS)}$ correspond to the limit values of the interstory drift ratio $\Delta_{lim,D1} = 0.003$, $\Delta_{lim,D2} = 0.010$, $\Delta_{lim,D3} = 0.025$, respectively.

3.1 Damage levels of contents

At present, only one damage state is considered for the contents: D1$^{(CO)}$. Indeed in general it is very hard, or not possible, to define a scale of damage for these elements. So they can be simply considered undamaged or damaged: it is assumed that if damaged they should be substituted.

Contents are subdivided in three classes. For each class a control parameter among the EDP's characterizing the seismic response of the construction and the value of this parameter for which contents damage is activated, are defined. Table 6 reports the classes, the control parameters, their activation values.

Table 2 - Contents: classes, damage control parameter, activation limit, cost incidence

Class of contents	**Damage control parameter**	**Activatio n value**
Closets/cabinets	Floor acceleration	0.25 g
Electronic equipments	Floor acceleration	0.20 g
Ceilings	Interstory drift ratio	0.005

4 Global performance levels: Vulnerability

The structure capacity and the consequences are evaluated for different damage scenarios, corresponding to different performance levels, defined on the basis of the interstory drift ratio, and on the basis of the number of conventionally collapsed structural elements (structural elements attaining the damage state $D4^{(ST)}$). Also the floor accelerations are computed on the basis of the story shears. The considered damage scenarios are described in the following. The basic scenarios provided within the procedure can be redefined by the user.

L0 - "Light Damage" scenario. The scenario corresponds to the situation in which the non structural elements attain damage states $D1^{(NS)}$ or $D2^{(NS)}$ while the structural elements reach damage state not greater that $D1^{(ST)}$. In terms of EDP characterizing the building response, the scenario is identified by the achievement of a story drift ratio $\Delta \geq 0.003$ at least at one story or by the achievement of the damage state $D2^{(ST)}$ for one structural elements (with a number of structural elements at a damage state $D1^{(ST)}$).

L1 - "Limited Damage" scenario. The scenario corresponds to the first collapse (attaining of $D4^{(ST)}$ damage state) of a structural elements. According to the current Italian standard [11], this performance condition identify the life safety limit state and then the conventional vulnerability of r/c structures. The scenario corresponds to a very localized damage with limited impact in terms of repairing cost and consequences on the occupants.

L2 - "Extended Damage" scenario. This scenario provides for performance conditions beyond the first structural collapse. It corresponds to the collapse of 10% of the vertical structural elements of the whole building or to the 20% of the elements at a single story. The definition criterion for this scenario was recruited by analogy to the percentage of the collapsed portion of r/c buildings in the complete damage state estimated in the provisions of Hazus procedure [14, 15]. This scenario allows the possibility of local collapse of the construction involving relevant consequences for the occupants.

L3 - "Extreme Damage" scenario. The scenario provides for the collapse (attaining of D4 damage state) of 50% of the structural elements of the structure or to the formation of a collapse mechanism (i.e. soft of weak story mechanism) within the structural scheme. It represents an ultimate performance condition of the construction to which the actual collapse of large portions corresponds with very serious consequences on the occupants.

The state of the structure correspondent to each scenario is automatically identified within the pushover analyses of the numerical model as a function of: (i) the evolution of the activated plastic hinges, (ii) the intersory drift ratio, (iii) the formation of a collapse mechanism.

Each scenario is characterized by a damage level of each structural and non structural element (each element attained a damage state) as well as by the damage of equipments and contents.

5 Consequences (economic losses) for the building components

The evaluation of the consequences (losses) related to a scenario account for various components: the structural damage, the non structural damage, the equipment damage, the damage of the contents.

5.1 Economic consequences of the structural damage

For each of the four damage states of the structural elements the restoration cost can be defined thanks to an embedded cost-data-base implemented within the procedure. The cost are differentiated for different types of structural elements: columns, walls, beams with deep section, beams with wide section (usually having the heigth of the floor). Costs have been stored as a function of the following variable parameters: A, cross section area; H, story height; L, beam span; ρ, reinforcement percentage; c, cover thickness; s, floor depth.

The data-base has been built through simulation of rehabilitation costs performed using Italian standard construction pricelists and, most of all, the pricelists for the reconstruction works after the 2016 Central Italy Earthquake. In particular, the costs of the basic structural works (listed in Table 3) as well as those related to the so called ancillary works have been defined for each damage state. Ancillary works include demolition and reconstruction of partitions, flooring, subfloor, ceiling and the reconditioning of equipment and fixtures. Their costs have been evaluated as a function of the damage state of the structural element, that is of the extension of the provided works.

The cost data-base allows to get the retrofitting costs of a structural element, $c_{DS,j}$, for any values of the listed parameters. It has been found that the most significant control parameter resulted to be the area of the element cross section.

Fig. 2a reports the diagrams of retrofitting costs of columns as a function of the damage state for different cross section area. Fig. 2b shows the diagrams of the retrofitting costs for columns at the different damage state as a function of the cross section areas, while assuming for the other parameters the default values shown in Table 4.

Table 3 - Retrofitting works provided for the different damage states

Damage state	**Retrofitting works**
$D1^{(ST)}$	cracking repair with resin or mortar injections
$D2^{(ST)}$	removal, surface cleaning, passivating treatment of reinforcing bars, section re-profiling
$D3^{(ST)}$	removal, surface cleaning, replacement and supplementation of bars, continuity holes, restoration with section re-profiling
$D4^{(ST)}$	r/c jacketing of the damaged portion

Table 4 - Default values of variable parameters

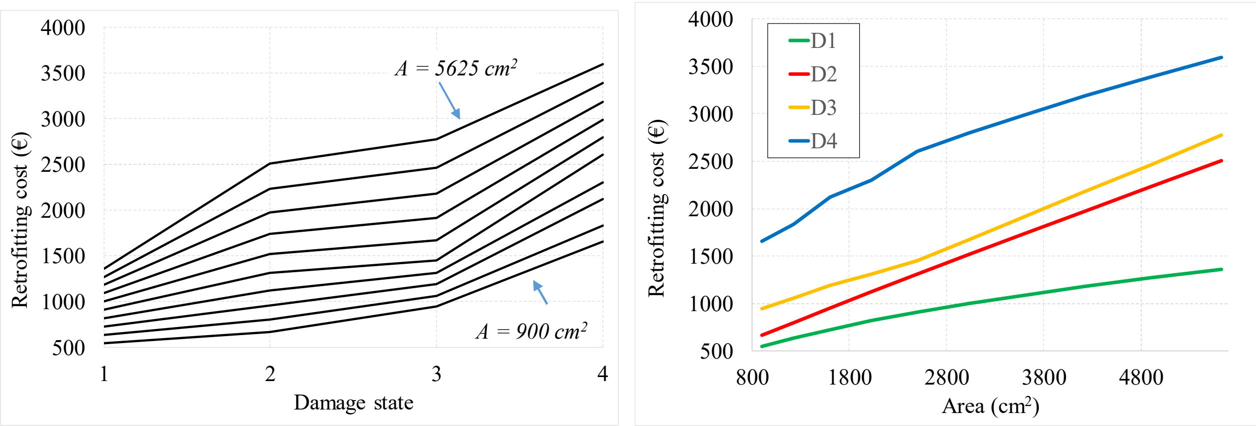
H	**L**	**ρ**	**c**	**s**
(m)	(m)	(%)	(mm)	(mm)
3,00	5,00	1,00	30	240

Once the retrofitting cost of each structural element has been defined as a function of its damage state and of its geometrical characteristics, the total cost of the structural damage results from the sum of the costs of the structural elements:

$$C_{DS} = \sum_{i=1}^{n} c_{DS,i} \tag{1}$$

where

n is the total number of structural elements.



(a) (b)

Fig. 2 (a) - Retrofitting costs of columns as a function of the damage state for different cross section areas; (b) retrofitting costs of columns as a function of the cross section areas for different damage state

5.2 Economic consequences of the non structural damage

The works required to retrofit the non structural elements are reported in Table 5, together with their unit cost c_{DNS}, for the different damage states. The indicated costs derive by a market analysis and include, for damage states D2$^{(NS)}$ and D3$^{(NS)}$, the cost of ancillary works concerning removal and resetting of fixtures and equipment.

Table 5 - Works and costs related to the damage states of non structural elements

Damage state	Type of works	partitions unit cost, c_{PART}	claddings unit cost, c_{CLAD}
D1$^{(NS)}$	filling, smoothing and painting	8,00 €/m^2	8,00 €/m^2
D2$^{(NS)}$	partial demolition and restoring of elements che constituting the cladding/partition panel	50,00 €/m^2	50,00 €/m^2
D3$^{(NS)}$	demolition and restoring of the whole panel	80,00 €/m^2	150,00 €/m^2

The unit parametric costs are multiplied by the areas of claddings and partitions present at the story along two reference ortogonal directions x and y so obtaining the total cost related to non structural elements C_{DN} at the story as reported in the following.

At m-th story it results as follows.

In direction x:

if $\Delta_{x,m} < \Delta_{lim,D1}$ then

$$C_{DN,x,m} = 0{,}00\ € \tag{2}$$

if $\Delta_{x,m} \geq \Delta_{lim,Dk}$ (k = 1 or 2 or 3), then

$$C_{DN,x,m} = A_{PART,x,m} \cdot c_{PART,K} + A_{CLAD,x,m} \cdot c_{CLAD,K} \tag{3}$$

In direction y:

if $\Delta_{y,m} < \Delta_{lim,D1}$ then

$$C_{DN,y,m} = 0{,}00\ € \tag{4}$$

if $\Delta_{y,m} \geq \Delta_{lim,Dk}$ (k = 1 or 2 or 3), then

$$C_{DN,y,m} = A_{PART,y,m} \cdot c_{PART,K} + A_{CLAD,y,m} \cdot c_{CLAD,K} \quad (5)$$

Finally

$$C_{DN} = \sum_{m=1}^{M} (C_{DN,x,m} + C_{DN,y,m}) \quad \text{(M = number of stories)} \quad (6)$$

In the previous espressions:
$\Delta_{x,m}$, $\Delta_{y,m}$ are the interstory drift ratio at story *i* in direction *x* and *y*, respectively;
$A_{PART,x,m}$, $A_{PART,y,m}$ are the surface of partitions, at story *i* in direction *x* and *y*, respectively
$A_{CLAD,x,m}$, $A_{CLAD,y,m}$ are the surface of claddings, at story *i* in direction *x* and *y*, respectively
$c_{PART,k}$ = unit cost of non structural elements with damage level Dk (k = 1, 2, 3)
$c_{CLAD,k}$ = unit cost of non structural elements with damage level Dk (k = 1, 2, 3)

5.3 Economic consequences of the contents damage

The maximum potential cost of contents is defined as a rate β_I of the total construction cost of the building [16]. Table 6 reports the considered maximum potential cost rate for different occupancy type of buildings.

Table 6 - Cost incidence β_I (rate of the construction cost) of the classes of contents

	Class of contents		
Building occupancy	**Closets / cabinets**	**Electronic equipments**	**Ceilings**
Dwelling building	0.067	0.067	0.067
Office building*	0.075	0.125	0.075
Hospital*	0.100	0. 500	0.075

The cost associated to the loss of contents can be evaluated as

$$C_{DC} = \sum_{j=1}^{N} [\beta_{1,j} \cdot \beta_{2,j} \cdot (C_{DS} + C_{DN})] \quad (7)$$

being
N the number of classes of contents;
$\beta_{1,j}$ the rate of the total construction cost (structural and non structural elements) for the *j*-th class of contents;
$\beta_{2,j} = \kappa_{1,j} \cdot \kappa_{2,j}$
with
$\kappa_{1,j}$ varying from 0 to 1, according to the actual presence of the *j*-th class of contents with respect to the potential maximum presence;
$\kappa_{1,j}$ = 1 or 0, according to the circumstance that the activation level of the control parameter of the *j*-th class of contents was reached or not, respectively, in the scenario under consideration.

6 Global consequences for a damage scenario

The total economic consequences for one scenario are evaluated as the sum of the direct and indirect cost related to the damage framework at the considered scenario:

$$C_{EG} = C_{DIR} + C_{IND} \quad (8)$$

where
C_{DIR} is the sum of the direct costs
C_{IND} is the sum of the in\direct costs

The evaluation modalities of both direct and indirect costs are shown in the following.

6.1 Direct costs and Global Loss Index

The total economic consequences in terms of direct costs for a generic damage scenario can be evaluated as

$$C_{DIR} = (C_{DS} + C_{DN} + C_{DC}) \cdot \eta \tag{9}$$

In Eq. (9) η is a correction factor taking into account the incidence of works and fees required for the retrofitting of the construction. First of all it accounts for the costs related to the following aspects: provisional securing, clearance and disposal of resulting materials, excavations, clean-up, urbanization fees, charges for construction works, technical expenses, investigations on soil and materials, increment in seismic capacity. The correction factor η also accounts for the discount on the retrofitting costs that can be expressed as a function of the damage (and works) extension. Whit this aim a parameter F_d that estimates the ratio of damage (or works) extension has been defined:

$$F_d = C_{U,EST} / C_{U,REC} \tag{10}$$

where
$C_{U,EST} = (C_{DS} + C_{DN} + C_{DC})$ is the uncorrected computed retrofitting cost for the building;
$C_{U,REC}$ is the standard uncorrected reconstruction cost for the building (i.e. derived from the standard government contribution provided for post-earthquake rebuilding).

Fig. 3a shows the curve of the percent discount to be applied to the costs as a function of damage extension. Fig. 3b shows the diagram of the nominal values of the parameter F_d (dashed line): it can be observed that the factor η varies from a minimum of 1,1 for $F_d = 0$ to a maximum of 2,0 for $F_d = 1$. In the same figure also the diagram (continuous line) of the reduced values of η resulting if the introduced discount is accounted for, are reported. The curves have been derived analyzing the actual prices of the retrofitting projects concerning the reconstruction after the 2009 L'Aquila Earthquake [17].

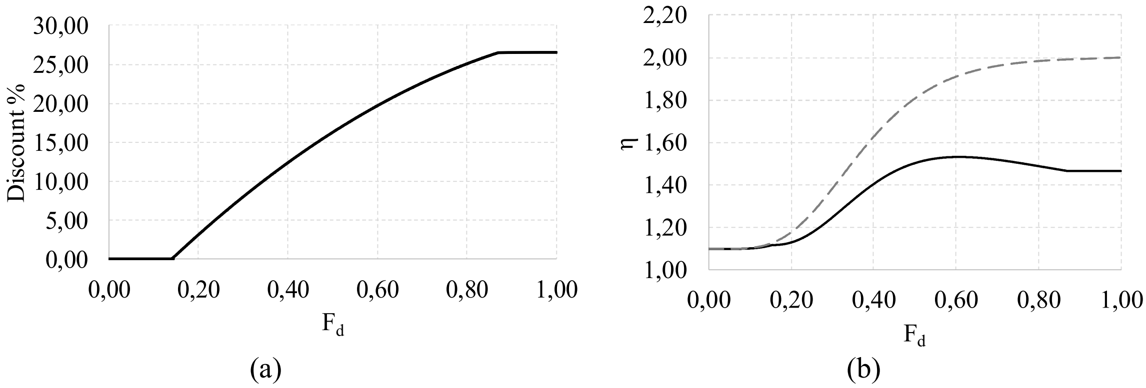


Fig. 3 - (a) Percent discount on retrofitting works vs. rate of damage extension. (b) Correction factor of direct costs vs. rate of damage extension: nominal values (dashed line), discounted values (continuous line).

Once the direct costs have been evaluated a Global Loss Index ID can be defined

$$ID = C_{U,DIR} / C_{U,conv} \tag{11}$$

where

$C_{U,DIR} = C_{DIR} / A_{exp}$;
A_{exp} is the usable floor area;
$C_{U,conv}$ is the conventional unit cost for demolition and reconstruction of buildings, in the present application it has been derived by the reconstruction costs provided by the Italian government for the buildings damaged in the 2016 Central Italy Earthquake. This cost - estimated for dwelling, or office or school buildings - is equal to 1400 €/mq.

6.2 Indirect costs

If the consequence evaluation concerns the performance assessment of the building from the point of view of the management of the building itself it is enough to consider the previously evaluated direct costs. With the aim of having a more general vision of the problem that includes the social, administrative, political, ethical, macro-economic aspects, besides the direct costs previously evaluated, also the indirect costs should be taken into account.

Indirect costs include costs related to: (a) temporary relocation of residents; (b) downtime for commercial activities; (c) first emergency aids; (d) structures devoted to the reconstruction management. The illustrated procedure can account only for the components (a) and (b).

First of all the effective downtime (in days) is defined as

$$T_{D,eff} = \eta_D \cdot T_{D,base} \tag{12}$$

where
$T_{D,base}$ is the downtime required by a full repairing of the whole building that depends on the typology of structural and non structural elements, types of repairing works, social and economic post-earthquake conditions; it can be easily estimated on the base of an expert evalution of the medium construction time of current buildings;
η_D is a correction coefficient accounting for the entity of works, so it can be expressed as a function of the global loss index ID according to the correlation shown in Fig. 4.

The indirect costs are finally evaluated with the following expression

$$C_{IND} = T_{D,eff} \cdot A_{BLDG} \cdot c_{UD} \tag{13}$$

where
A_{BLDG} is the commercial area of the whole building;
c_{UD} represents the rent daily cost per unit of area of an a similar building: on the basis of an Italian market research it is included in the range 0.05 - 0.50 €/m^2 depending on the building type and market conditions.

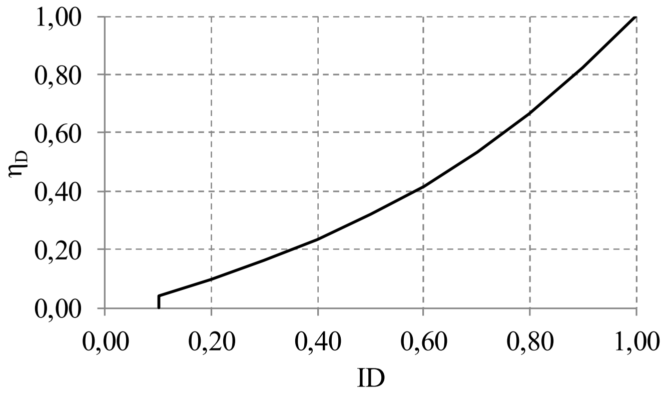


Fig. 4 - Downtime curve

6.3 Consequences on the occupants

The general flow of the evaluations leading to estimate the losses related to the occupants is similar to that illustrated for the economic losses, but there are significant differences in the evaluation modalities. In this context it is not possible, for space reasons, to detail the procedures, but just the computation principles can be given, while more details can found in previous papers [9, 10]. In few words the principle followed for accounting for the consequences to the occupants is based on the definition of quantities of floor surfaces associated to the damage of structural and non structural elements and of the contents. These surfaces, suitably extended both in building plan and elevation, lead to a global amount of floor area hit by the earthquake. Knowing the exposition in terms of usable floor area and occupants present per unit of area in different time intervals (of the day, week, month, season, year) the consequences on the occupants are evaluated.

7 Expected consequences in the building lifetime

The expected annual economic consequences (losses) are calculated by summing the cost C_{TOT} of each scenario multiplied by the annual probability of that consequence, approximately assumed to be equal to the probability to attain or overcome the event causing the scenario.

Actually, the most interesting parameter consists of the expected consequences (costs or losses) $C_{EXP}^{(N)}$ in an interval of time N that is significant in the decision making process. It can be computed with the following expression

$$C_{EXP}^{(N)} = F_A^{(N)} \cdot \left[\sum_{l=1}^{L-1} C_{EG,l} \cdot \left(P_l^{(N)} - P_{l+1}^{(N)}\right) + C_{EG,L} \cdot P_L^{(N)}\right] \quad (14)$$

where

$$P_l^{(N)} = 1 - e^{N/T_{R,l}} \cong 1 - \left(1 - \frac{1}{T_{R,l}}\right)^N \quad (15)$$

is the probability to reach of to overcome the l-th scenario in N years
being
L the number of scenarios;
$T_{R,l}$ the return period of the seismic intensity corresponding to the l-th scenario;
$F_A^{(N)}$ is the actualization factor related to the compound interest in next N years.

Ordinarily the interval of time for which computing the expected cost (or likely cost) is the conventional reference lifetime of the construction, but it can be a different one according to the objectives of the decision making process. Generally, from the numerical calculations it results that the investment in increasing the seismic capacity of a building becomes more and more cost-effective when the considered interval on which computing the consequences becomes larger and larger.

8. Case of study

The procedure f-RACE has been applied to various buildings, the results of one of these application are briefly reported in the following. The case-study building has five stories and a total height of 19.0 m. In plant it has an area of 450 m^2. The structural system consists of r/c frames with concrete-masonry floors. Fig. 5 shows a floorplan and a section of the building.

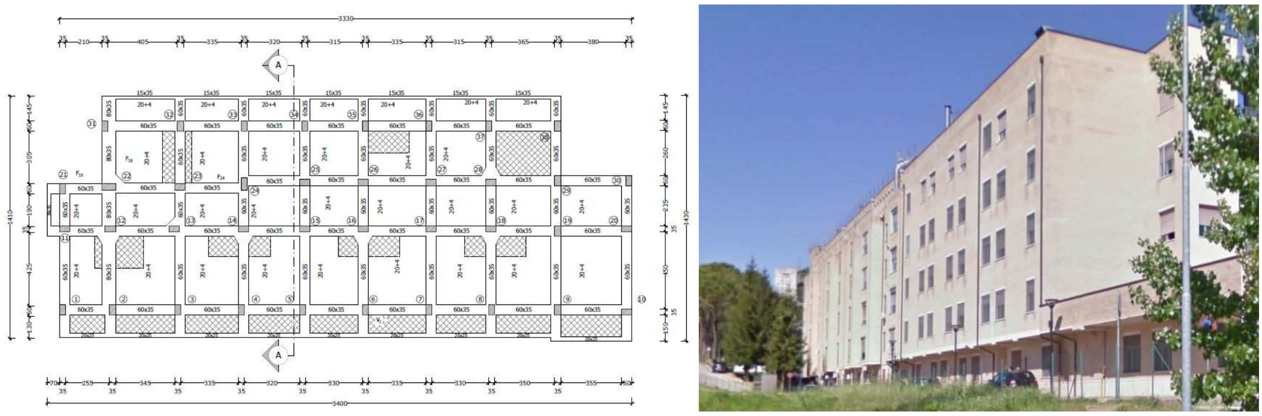


Fig. 5 - Floorplan and external view of the case-study building

Pushover analyses have been performed to produce the damage scenarios L0, L1, L2, L3. The return periods of the seismic intensity associated respectively to the four scenarios are: 24, 475, 582, 781 years.

For each scenario, Fig. 6a shows the percent of structural elements that achieved the different damage levels (D1, D2, D3, D4), while Fig. 6b shows the maximum interstory drifts of the five floors. Table 7 reports the cost components provided by the procedure and previously defined in the paper. The relevant parameters for a decision making process, that is the likely, or expected consequences (costs or losses) for different intervals of time, are finally reported in Table 8.

The results obtained by the procedure show low values of the expected costs with respect to the actual cost required by the actual retrofitting of the building, leading to the immediate consequence that it could be considered not convenient to implement a seismic retrofitting. It has to be said that a parallel evaluation carried out considering the human losses could lead to different comments, given the intangibility of the human life, but, apart of ethical consideration, in general the economic or human losses for different scenarios are proportional.

In any case the main objective of the procedure is a different one. It can be suitably used to support a choice among different hypotheses of retrofitting works for an existing building or among different seismic-resistant structural system for a new building. The effectiveness of the different choices can be objectively compared and the most suitable choice can be identified. Another significant application concerns the comparison of the consequences expected for different building of the same stock to identify a priority in a retrofitting program of seismic enhancement compatible with limited economic means.

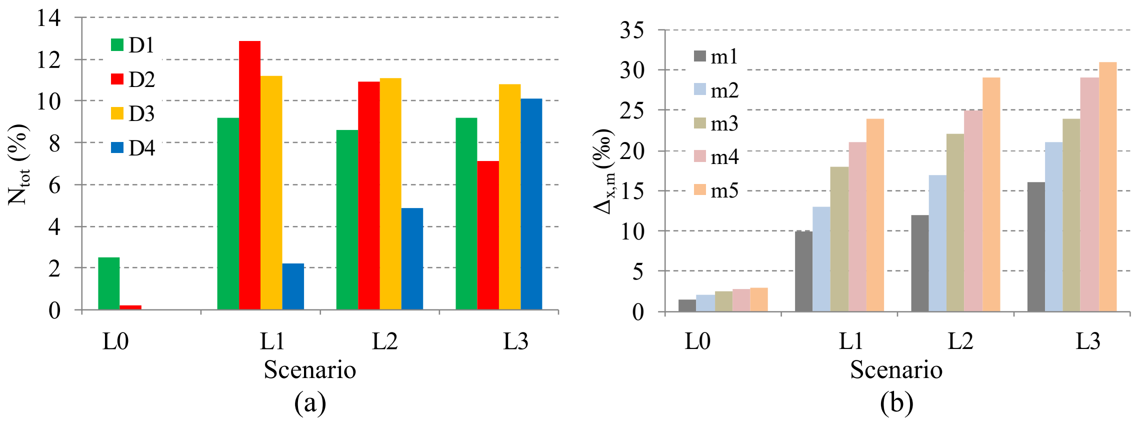


Fig. 6 - Damage and response at different scenarios: (a) percent of structural elements achieving the different damage levels; (b) maximum interstory drifts of the five floors

Table 7 – Return period and cost components of the considered damage scenarios

Scenario	C_{DS} (€)	C_{DN} (€)	C_{DC} (€)	η	C_{DIR} (€)	$C_{U,DIR}$ (€/m^2)	ID	C_{IND} (€)	C_{EG} (€)
L0	11,500	11,200	1,210	1.10	26,301	11.12	0.01	0,00	26,301
L1	493,500	346,500	88,350	1.27	1,179,004	589.50	0.42	105,000	1,284,004
L2	508,300	481,800	145,070	1.35	1,532,479	766.24	0.55	123,500	1,655,979
L3	565,200	553,159	162,650	1.39	1,780,602	890.30	0.64	178,450	1,959,052

Table 8 – Likely consequences (costs)

Years	5	30	100
C_{EXP} (€)	23,861	129,092	368,565

9. Conclusions

The product of recent studies having the objective of creating a tool for a cost-effective practical application of performance base design to prevent earthquake damage is presented. A ready-to-use procedure, called f-RACE, that is being implemented within an ordinary software for seismic analysis of buildings is illustrated. It allows to carry out, in a quick and guided way, a seismic design based on the consequences form earthquake attacks and can be applied to current projects of ordinary buildings. The results of a case study chosen among the performed applications are shown for demonstrating the effectiveness of the procedure.

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