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IDENTIFICATION OF MOST RELEVANT FACTORS FOR DEMOLITION: A STUDY ON DAMAGED BUILDINGS AFTER L'AQUILA EARTHQUAKE

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Abstract

The evaluation of building reparability after damaging earthquakes is a complex issue, involving factors such as the damage state, residual capacity and post-earthquake safety, initial performance level with respect to design earthquake and repair and retrofit costs [1]. In the post-earthquake reconstruction process after the 2009 L'Aquila earthquake, the funding request had to be accompanied by a detailed assessment of repair costs, the pre-earthquake safety level respect to new building standard (%NBS) and, if needed, by a detailed design of retrofit intervention and costs. Here we examine the database of severely damaged buildings after L'Aquila, collecting information of repair and retrofit costs as well as the final decision on reparability, to determine most important factors influencing demolition decisions for Reinforced Concrete (RC) buildings; 122 out of 472 severely damaged RC buildings were demolished. A logistic regression is performed to estimate the probability of demolition p_{dem} for building typologies. Considering pre-earthquake information, the construction age is the most influential parameter, with older buildings having a higher p_{dem}. Other significant parameter is %NBS. Considering post-earthquake information, the repair cost is expectedly the most important parameter. It results that p_{dem} can be expressed as a function of construction age, %NBS and repair costs.

Keywords: reparability, demolition, reconstruction, decision, post-earthquake

1. Introduction

Existing structures often exhibit poor seismic performance as demonstrated by the numerous collapses, either partial or total, surveyed in the aftermaths of moderate-to-high magnitude strong motions worldwide; damage provided by earthquakes is a concern for a society as a whole in terms of loss of life and direct and indirect costs.

Recently the 2009 L'Aquila earthquake in Italy resulted in over 300 deaths and more than 50,000 buildings damaged to structural or non-structural infilled walls [2]. The damage and seismic usability assessment of public and private buildings started immediately after the earthquake; it aimed at evaluating the safety conditions of the buildings in order to enable people to return to their houses and social and economical activities to start again [2]. The usability and damage assessment of buildinigs has been carried out by teams of surveyors made up of two or three experts. The AeDES survey form [3] was adopted as a tool for the seismic damage and usability assessment. The form can be filled based on the visual in situ inspection of the building, which represents the minimum structural unit with a significant impact on the people safety. According to the AeDES survey form, the buildings can be classified into the following categories: A. Usable buildings (slightly damaged, can keep on housing the functions to which it was dedicated); B. Building usable only after short term countermeasures (buildings with limited or no structural damage but with severe non-structural damage); C. Partially usable building (buildings with limited or no structural damage but with severe non-structural damage located in a part of the building); D. Building to be re-inspected (due to atypical damage scenario a specific, but still visual, investigation is required); E. Unusable building (high structural or non-structural risk, high external or geotechnical risk); F. Unusable building for external risk only. According to usability and damage assessment of buildinigs records, about 26% out of about 72,000 private and public buildings surveyed resulted unusable (E usability rating).

It is not surprising that older buildings, designed with obsolete seismic provisions and construction practices, are seismically deficient and prone to significant damages in case of seismic events. For these kind of sub-standard buildings the key question in the aftermath of damaging earthquakes is not only if a damaged building should be simply repaired or also retrofitted, but often if it is more convenient to repair and retrofit or to demolish and rebuild it [4]-[5]-[6]-[7]. To this end, the paper focuses on the analysis of the most important factors that have driven the demolition decisions for a subset of data related to private Reinforced Concrete (RC) buildings severely damaged by the 2009 L'Aquila earthquake.

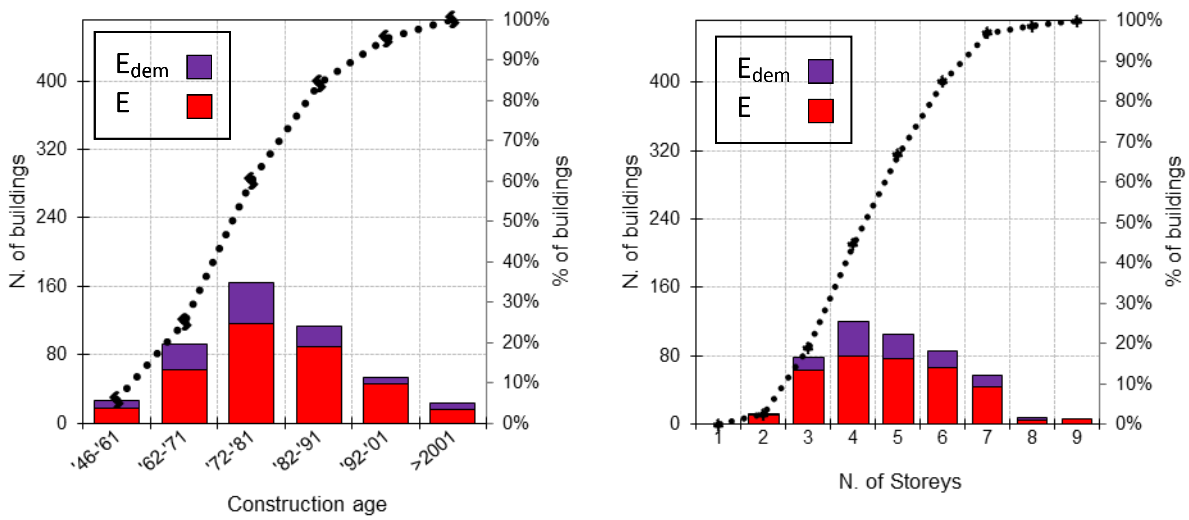
2. The database of severely damaged buildings after L'Aquila earthquake

The reconstruction process of residential buildings outside the historical centers damaged by the L'Aquila earthquake was regulated by several Ordinances of the President of the Council of Ministers: [8]-[10] and [12] and relevant Annexes [9] and [11].

The ordinances established that the financial support of the Italian government to the reconstruction was given and managed by private owners; a government financial support was established including measures not only for damage repair but also for seismic vulnerability reduction. Repair and energy efficiency upgrading works were totally covered by public grants, along with strengthening interventions to increase the seismic safety level of buildings. If economically more convenient or technically required (i.e. partially or totally collapsed buildings, poor concrete quality or elevated columns residual drift in RC structures), the public contribution covered the demolition and reconstruction of the buildings severely damaged by the earthquake (buildings with E usability rating according to post-earthquake surveys). In particular, OPCM no. 3881 [12] allowed demolition and reconstruction for buildings with usability rating E. The property owners may select demolition and reconstruction instead of repair and strengthening interventions, if economically viable. In these cases, the practitioner should compare the costs for repair and strengthening works (to meet at least 60% of New Building Standards, %NBS) as well as health-hygiene and energy and acoustic efficiency upgrading with those for demolition and reconstruction computed according to specific provisions issued by the Resolution Regional Council [15]. The minimum between these two costs was granted by the public contribution. Thus in order to compare such costs, it was necessary to provide a proper documentation including a global analysis to determine the pre and post interventions building safety level (%NBS_{ante} and %NBS_{post}) as well as repair and strengthening costs. The safety index is expressed as %NBS = PGA_c/PGA_d, where PGA_d is the anchoring peak ground acceleration related to the design acceleration spectrum according to Italian current seismic code [16] and PGA_c is the minimum anchoring peak ground acceleration such as to determine building conventional collapse for brittle or ductile failure modes.

The data collected on the recovery works related to 5,775 damaged residential buildings outside the historical centres are reported in details in [13]-[14] while a subset of data related to severely damaged RC buildings is herein discussed. In particular, a subset of 472 RC buildings with usability rating E is presented in this section in order to investigate on the most relevant factors for demolition. The subset of data consists of severely damaged buildings that were repaired and strengthened (named E buildings class in the following) or demolished and rebuilt (E_{dem} class in the following).

The number (and percentage) of E and E_{dem} buildings of the dataset pertaining to different construction age periods and number of storeys as well as their cumulative percentages are presented in Fig. 1 (a)-(b); the E buildings are depicted in red colour while E_{dem} in violet colour.



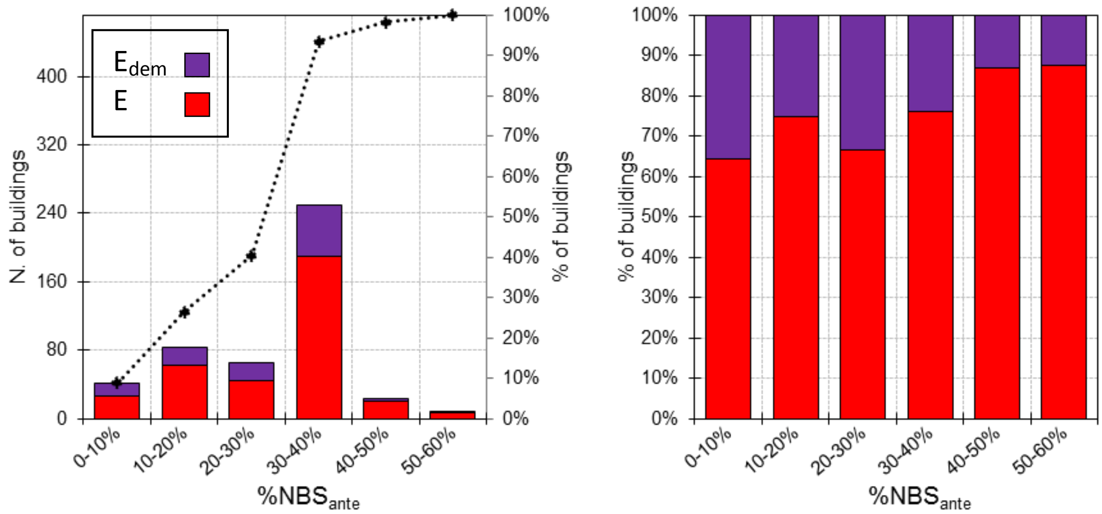
(a) (b)

Fig. 1 – Construction age and number of storeys of severely damaged buildings

Fig. 1 (a)-(b) show that almost 70% of buildings of the dataset were built between 1972 and 2001 and number of storeys between 3 and 7 are the most frequent. A decreasing trend of demolished buildings can be clearly observed for buildings built after 1972 and with number of storeys greater than 3.

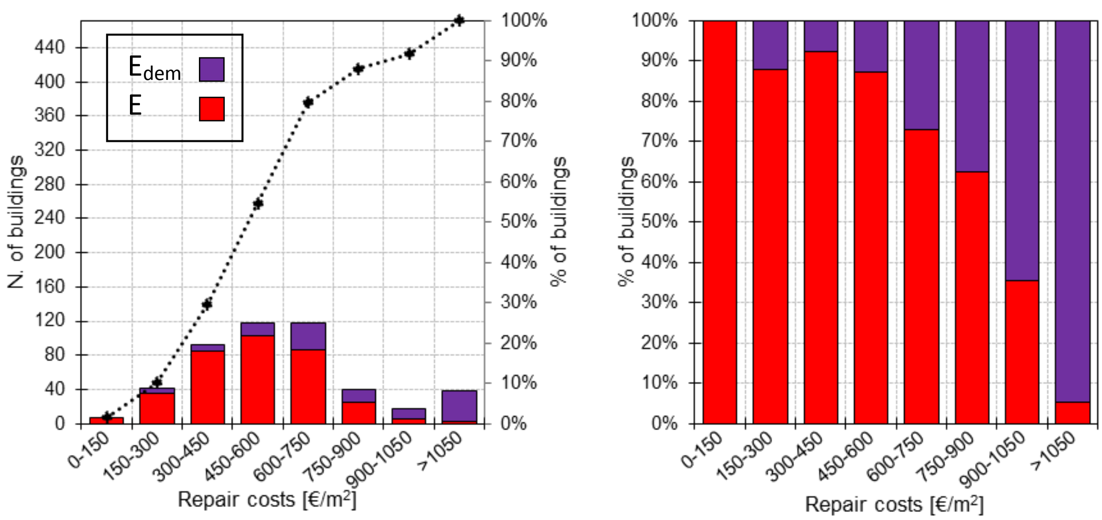
The number (and percentage) of E and E_{dem} buildings of the dataset pertaining to different intervals of %NBS_{ante} as well as their cumulative percentages are presented in Fig. 2 (a); Fig. 2 (b) shows the ratio of E_{dem} buildings pertaining to each %NBS_{ante} interval. The most populated class of buildings is related to that with %NBS_{ante} = 30-40%; a decreasing trend of demolished buildings can be observed by increasing the original seismic safety level, see Fig. 2 (b).

The number (and percentage) of E and E_{dem} buildings of the dataset pertaining to different unit repair costs intervals (i.e. the repair costs per square meter of the overall building gross surface area) as well as their cumulative percentages are presented in Fig. 3 (a); Fig. 3 (b) shows the ratio of E_{dem} buildings pertaining to each repair cost interval. The repair costs are inclusive of: building safety measures; demolition and removal, including transportation costs and landfill disposal; repair interventions; repair and finishing works relevant to strengthening interventions; testing of facilities; technical works for health and hygiene improvement; technical works to improve facilities; construction and safety costs; charges for the design and technical assistance of practitioners; furniture moving. The costs are inclusive of charges for the design and technical assistance of practitioners, but does not include VAT (10% of costs for repair and local or global strengthening costs and 20% for other costs). A clear increasing trend of demolished buildings can be observed by increasing the unit repair costs, see Fig. 3 (b).



(a) (b)

Fig. 2 – Number of buildings belonging to several intervals of $\%NBS_{ante}$ (a); percentage of buildings repaired and strengthened, E (red bars), or demolished, E_{dem} (purple bars), for several intervals of $\%NBS_{ante}$ (b)



(a) (b)

Fig. 3 – Number of buildings belonging to several intervals of unit repair costs (a); percentage of buildings repaired and strengthened, E (red bars), or demolished, E_{dem} (purple bars), varying repair costs intervals (b).

3. Influence of single variables on demolition

In order to evaluate the influence of the different parameters described in the previous section on the demolition probability, the effect of each single variable is firstly investigated. All the variables can be considered as categorical. To have a preliminary evaluation of the effect of each single parameter on demolition it is useful to refer to codified variables $x_j \in [-1,1]$, defined as:

$$x_j = \frac{X_j - (X_{j,max} + X_{j,min})/2}{(X_{j,max} - X_{j,min})/2} \tag{1}$$

with $X_{j,max}$ and $X_{j,min}$ the higher and lower values, respectively, of the j^{th} variable. Before standardization, the minimum value of %NBS was set to 30% to adjust unrealistic low values obtained using commercial software; the latter usually do not allow automatic scaling of code spectrum (evaluated according to [16]) below certain thresholds of PGA.

Representing the single codified variables along with the demolition decision (indicated as =1 if the building was demolished and =0 if not) the charts in Fig. 4 are obtained. In figure, also the simple linear interpolation line and the relative coefficients are shown; the latter are representative of the relative weight of model parameter X_j (codified as x_j) on response Y [17], i.e. on demolition decision.

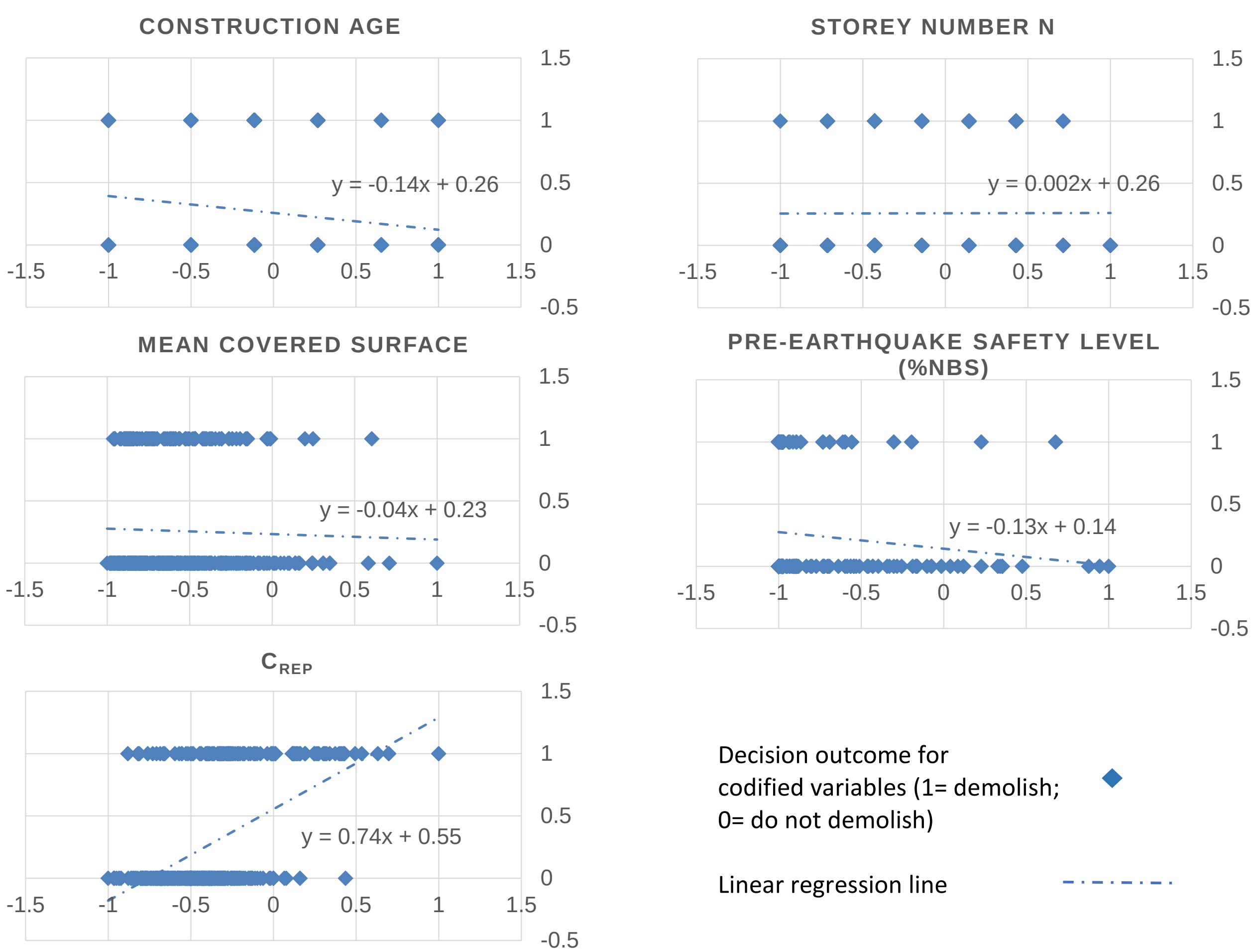


Fig. 4 – Influence of single variables on demolition decision (0= no demolition, 1=demolition)

As it could be expected, the most influential parameters is the repair cost (C_{rep}). Among the parameters that are available also in "peace time", before an earthquake occurred, it seems that the construction age has the higher weight towards demolition, while it appears that some parameters, such as the storey number, do not significantly affect the decision.

4. Evaluation of demolition probability for severely damaged buildings

Adopting the same approach as proposed in [18], a logistic regression is performed in order to find a suitable function to describe the probability of demolition p_{dem}. Indeed, the binary events (demolition) and (no demolition) can be considered as realizations of a random variable Y which has a binomial distribution; hence for the i^{th} observation

$$Y_i \sim B(n_i, \pi_i) \tag{2}$$

with n_i the i group size (for grouped data, e.g. k groups within a dataset of global size n) and π_i the frequency of failed tests (in our case the number of demolished buildings) within group i; the case of individual data can be seen as a special case of grouped data with n groups of size one, so k = n and n_i = 1 for all i.

In order to build a robust linear model for probability, i.e. a model that is linear while being contemporarily bounded between 0 and 1, the logit function of the probability of demolition is firstly introduced as in Eq. (3)

$$\mathrm{logit}(p) = \log\frac{p}{1-p} \tag{3}$$

Then, logit(p) can be estimated with a linear regression such that

$$\mathrm{logit}(p(x_1,...x_n)) = \beta_0 + \sum_{i=1}^{n}\beta_i \cdot x_i \tag{4}$$

with x_i the generic variable influencing the decision outcome (here codified variables as in previous paragraph) and β_i the associated regression coefficient (and β_0 the intercept, if considered). Finally, the demolition probability can be calculated with Eq. (5):

$$p(x_1,...x_n) = \frac{1}{1+e^{-(\beta_0+\sum_{i=1}^{n}\beta_i \cdot x_i)}} \tag{5}$$

The model defined in Eq. (2) and (4) is a generalized linear model with binomial response and link logit. The regression coefficients (β_1,… , β_n) can be interpreted as in linear models but remembering that left-hand side term in Eq. (4) is a logit rather than a mean; hence β_j represent the change in the logit of the probability associated with a unit change in the j^{th} predictor holding all other predictors constant [19].

In our case a maximum number of 5 predictors is considered, i.e. x_1= *age* (construction age); x_2= *N* (storey number); x_3= S_c (mean covered surface); x_4= $\%NBS_{ante}$ (pre-earthquake safety level expressed as % of new building standard, indicated in the following simply as *%NBS*); x_5= C_{rep} (repair cost). Some of the predictors are available already in "peace time", before an earthquake occurred, namely *age*, *N*, S_c and *%NBS*; the first three are relatively easily determined at a large scale while the latter needs specific evaluation on a building by building case. C_{rep} is available only after the effective costs needed in the reconstruction phase are determined, not before some few months after the earthquake. Each of the predictors has a (major or minor) effect on demolition probability, but in general it is not to be expected that their combined effect helps better to explain the demolition probability; therefore it can happen that the best model does not depend on all the predictor variables available. Because it can be useful to infer demolition probability (in case of damaging earthquake) even if cost information are not available, we considered separately the case of (a) predictors available in "peace time" (x_1 to x_4 altogether or sub-sets of them) and (b) the whole set (x_1 to x_5 altogether or sub-sets of them including always C_{rep}). In order to choose the best model to predict the demolition probability we followed a three step strategy, applied separately to the (a) and (b) cases: 1) for each combination of predictors and the corresponding model (e.g. for case (a) $x_1+x_2+x_3+x_4$ or $x_1+x_2+x_3$ or x_1+x_3 etc.) the Hosmer–Lemeshow (H–L) test is performed and the model is rejected if goodness-of-fit yields $p<0.05$, meaning that the null hypothesis of a good model fit to data is not tenable; 2) if the (H–L) test is acceptable the p-values of the regression coefficients are checked and the model is admitted if all $p<0.05$ or relaxing the confidence level from

95% to 90% or 85% if some p are greater than 0.05 but close to 0.1 or slightly above it; 3) having selected "tenable" models for both (a) and (b) cases the AIC value (Akaike Information Criterion [21]) is calculated and compared to the AIC of alternative models in each sub-group (a) or (b); generally it is to prefer the model (within each subgroup) with lower AIC in the group. Concerning the last point, if the difference between lower AIC is small (e.g. ≤2) there is no strong evidence that a model is better with respect to another; in this case an additional criterion built from the H-L test is adopted, as discussed hereafter. The H–L statistic is a Pearson chi-square statistic, calculated from a 2 × g table (the contingency table) of observed and estimated expected frequencies, where g is the number of groups formed from the estimated probabilities [20]. As example, Table 1 shows the Contingency Table (CT) resulting from H-L test of the models with I) *age* and C_{rep} (AIC= 409.3) and II) *age*, *%NBS* and C_{rep} (AIC= 409.1). In the Table, for each model, "observed" are the number of demolitions observed within each group, while "expected" are the predicted ones adopting the respective model.

Table 1 – Contingency Table (CT) for Hosmer-Lemeshow goodness-of-fit test

CT – model I: *age* and C_{rep} as predictors				CT – model II: *age* , *%NBS* and C_{rep} as predictors			
Group	Observations	Expected	Observed	Group	Observations	Expected	Observed
1	47	1.45	3	1	47	1.37	3
2	47	2.65	3	2	47	2.58	4
3	47	3.87	8	3	47	3.66	5
4	47	5.76	4	4	47	5.52	5
5	47	7.86	6	5	47	7.91	7
6	47	9.99	9	6	47	10.1	9
7	47	12.54	9	7	47	12.77	9
8	47	15.51	15	8	47	15.93	15
9	48	22.44	23	9	48	22.82	23
10	48	39.93	42	10	48	40.19	42

As additional criterion for model selection, in case AIC is not informative, the lower mean squared error calculated from "observed" and "expected" values in the contingency table is adopted. With the example in Table 1 and the adopted additional criterion the model II is chosen as the best one (within group (b)) because it has a mean squared error of 2.7, lower than the one of model I, that is 4.5.

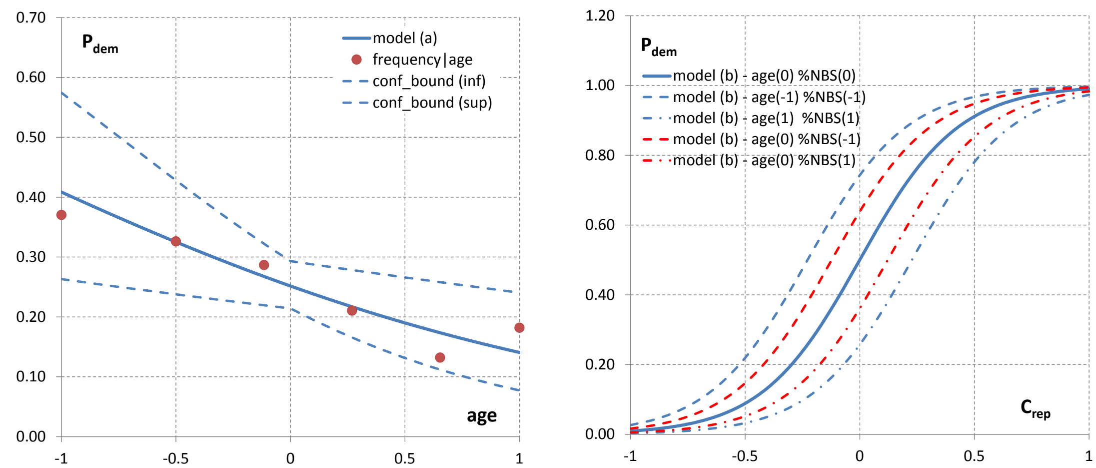
As a final result the models described in Table 2 are selected, namely Model (a) (including only predictors available in "peace time", before an earthquake) depending only on *age* and Model (b) depending on *age, %NBS* and C_{rep}; the latter model does not include the constant term.

Table 2 – Coefficients for models (a) and (b)

	model (a): *age* as predictor			model (b): *age* , *%NBS* and C_{rep} as predictors; no constant term		
Predictor	β_{mean}	$\beta_{inf}(95\%)$	$\beta_{sup}(95\%)$	β_{mean}	$\beta_{inf}(90\%)$	$\beta_{sup}(90\%)$
Constant	-1.09	-1.30	-0.88	-	-	-
age	-0.72	-1.18	-0.27	-0.49	-0.95	-0.03
%NBS	-	-	-	-0.57	-0.92	-0.22
C_{rep}	-	-	-	4.66	3.83	5.48

Note that the confidence interval for model (b) is estimated with α=0.1.

Fig. 5 (a) show the probability of demolition evaluated with model (a) (continuous line) as well as probabilities obtained considering lower and upper bounds with coefficients in Table 2 (dashed lines); for comparison, also the frequency of demolition calculated from real data in the relevant age ranges are shown (red dots).



(a) (b)

Fig. 5 – (a) Probability of demolition p_{dem} evaluated with model (a), depending only on construction age. (b) p_{dem} evaluated with model (b), depending on C_{rep}, %NBS and construction age; in figure %NBS and construction age are kept constant, letting vary the sole C_{rep} to allow clear visualization f its influence.

Fig. 5 (b) show the probability of demolition evaluated with model (b) letting vary C_{rep} and with predictors *age* and *%NBS* fixed at 0 (continuous line). In order to show the influence of *age* and *%NBS* four other curves are shown: one relative to the "worst" case, obtained adopting both *age* and *%NBS* equal to -1 (blue dashed line), one to the "best" case, with *age* and *%NBS* equal to 1 (blue dash-dot line), one with *age* equal to 0 and *%NBS* equal to -1 (red dashed line) and one with *age* equal to 0 and *%NBS* equal to 1 (red dash-dot line). As it can be seen the probability of demolition is significantly influenced also by *age* and *%NBS.* Considering them both to their extreme values the probability of demolition shifts from (case C_{rep} =0) 26% (with *age* = *%NBS*=1) to 74% (with *age* = *%NBS*=-1); even if only the effect of *%NBS* is accounted for (case C_{rep} =*age*=0) the probability of demolition shifts from 36% (with *%NBS*=1) to 64% (with *%NBS*=-1).

5. Conclusions

This paper analyzed the most important factors that have driven the demolition decisions for private Reinforced Concrete (RC) buildings severely damaged by the 2009 L'Aquila earthquake.

A database of 472 RC buildings classified with E usability rating according to post-earthquake surveys (unusable buildings mainly because severely damaged by the earthquake) was investigated considering relevant available parameters, namely construction age, number of storeys, mean covered surface, safety index expressed as % of new building standard %NBS and repair costs.

The analysis of the effect of each single (standardized) parameter on demolition decision showed that, as it could be expected, the most influential parameter is the repair cost (C_{rep}). Among the parameters that are available also in "peace time", before an earthquake occurred, the construction age has the higher weight towards demolition, followed by %NBS, while it appears that some parameters, such as the storey number, do not significantly affect the decision.

A logistic regression was performed in order to find a suitable function to describe the probability of demolition p_{dem}. In particular both the cases of (a) predictors available in "peace time" (construction age, number of storeys, mean covered surface, %NBS - altogether or sub-sets of them-) and (b) the whole set of available parameters (including also C_{rep}) were considered to propose relevant regression formulas. For the first case, the model better describing p_{dem} depends only on construction age; the construction age is certainly the most influential parameter, with older buildings having generally a higher probability of demolition.

On the other hand, for case (b), p_{dem} can be expressed as a function of repair cost C_{rep}, construction age and %NBS. The repair cost is expectedly the most important parameter, with higher correlation with demolition probability. However, the inclusion of the two latter parameters allows a better description of p_{dem}, as they have a clear influence on the decision outcome.

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