Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 2765-2776

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

EMPIRICAL DAMAGE AND ACTUAL REPAIR COSTS ON MASONRY PRIVATE BUILDINGS AFTER L'AQUILA EARTHQUAKE

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Keywords: empirical damage, repair costs, loss estimation

Abstract. *In the first phase of the emergency management after the April 6, 2009, L'Aquila earthquake, field inspections were carried out through the AeDES form, a first level survey form for post-earthquake damage and usability assessment, to evaluate the usability conditions of buildings. Once the damage and usability assessment was completed, the reconstruction process of residential buildings outside the historical centre of L'Aquila and surrounding municipalities was regulated by several Ordinances of the Prime Minister. The public grant was released according to funding requests made by practitioners and checked by a proper commission entrusted by the Government. The data collected on a set of about 1,000 residential masonry buildings in terms of vulnerability class, construction age, number of storyes, empirical damage, as well as of Actual Repair Costs (ARCs) are herein discussed and presented. Building Damage Factor, DF has been computed based on the damage data of structural and non-structural component collected with the AeDES forms. A calibration of different parameters, as the damage extent and severity on each structural and non-structural component and the weight of the damage on a single component on the total repair costs of the building, was carried out. The calibration allow us to determine the best correlation between the empirical damage and ARC. The proposed relationship between empirical damage and ARC may drive decision makers, in the immediate post-earthquake, to make preliminary estimates of the repair costs, only based on quick surveys on residential buildings. The relationship may also be used as a tool to figure out repair costs based on damage scenarios.*

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5605.17552

1 INTRODUCTION

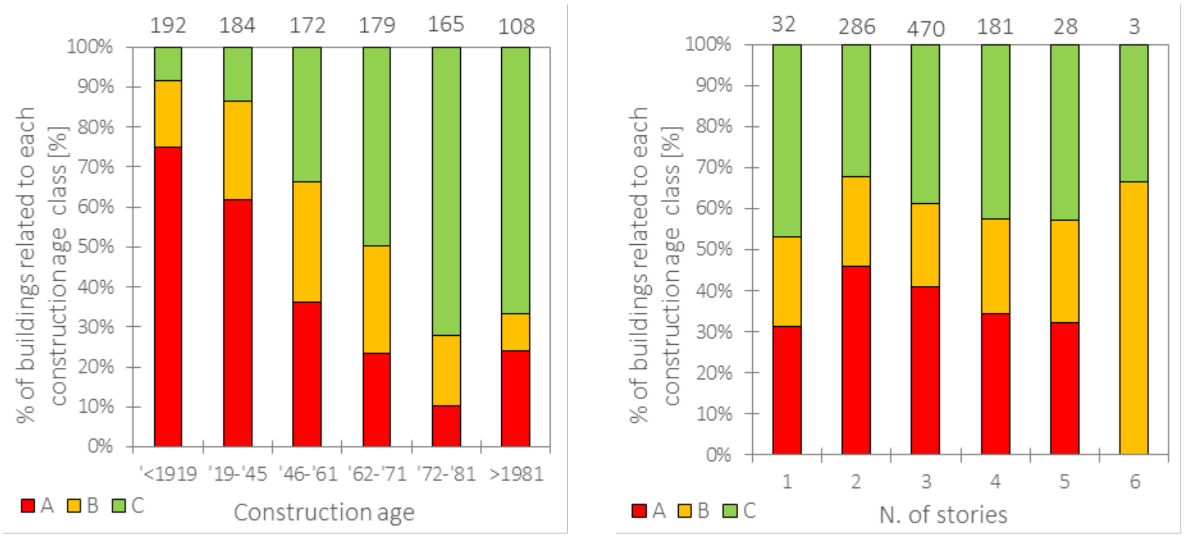
The frequent occurrence of strong earthquakes and their devastating effects have drawn the attention to the importance rule played by the usability and damage assessment in the emergency phase. The concept of usability assessment, although with different procedures, is common to all earthquake prone countries and it is a worldwide task in the emergency phase [1,2,3,4,5]. Instead, the damage assessment, aimed at quantifying the direct economic losses caused by the earthquake, is carried out only in few earthquake prone countries. After 2009 L'Aquila earthquake the damage assessment was carried out together with the usability assessment by means of the AeDES form [5], the first level survey form adopted by government to assess the safety conditions of the buildings. This form has been filled during in situ inspections effectuated by team of experts. The damage data collected are related to the four damage level and relevant extent both for structural components (i.e. Vertical Structure, VS, Floor, F, Roof, R, Stairs, S) and not structural components (i.e. Infill-Partition, IP). The genesis of definition of damage to different structural components has been defined according to the European Macroseismic Scale EMS- 98 [6]; however, EMS-98 reports six damage states and they are related to the buildings and not to the single components. In literature, several methodologies have been applied to convert the damage to structural and non-structural components in a global damage of the building. In [7] a procedure is outlined to determine the global damage of a building as the sum of the damages detected on structural and non-structural members weighted by coefficients calibrated based on average repair costs. The damage for each member is computed as the sum of damage levels, Di, multiplied by their extension, ei. Then six levels, from 0 to 5, can be determined to represent the global damage index. In [8,9] starting from the procedure reported in [7] only the damages detected on the vertical structures to find a global damage index has been taken into account. In [10] the same approach has been assumed, but the damage extension on the structural components has not been taken into account. By contrast, the damage grades D2-D3 and D4-D5 were split into the corresponding EMS-98 damage state depending only on the mean damage detected on VS for the building class in the selected location: the higher the mean damage, the higher the probability of being in the heaviest DS. A correlation between empirical damage derived by AeDES form and the six damage grades as defined by EMS-98 was provided also by [11] and [12]. According to [11] the maximum damage detected on structural components VS, F, and R is accounted for the correlation between empirical damage and the building DS. In [12], the damage on IP is taken into account as a key parameter to define the building damage state attained due to the earthquake; the maximum damage detected on VS or IP is accounted for the correlation between empirical damage and the building DS. In spite of the numerous studies revised carried out to analyze the empirical damage, a study to correlate the empirical damage to the cost computed by practitioners to repair the damage suffered by each structural and non-structural component, namely Actual Repair Costs, ARC, is still lacking. To fill this gap, a study to evaluate the relationship between damage detected by in-situ inspections and repair costs determined according to repair interventions designed and computed by practitioners engaged by owners in the L'Aquila post-earthquake reconstruction process is herein presented. The management of L'Aquila post-earthquake reconstruction process is briefly presented herein along with the data collected on 1,000 masonry residential buildings in terms of vulnerability classes, buildings characteristics and damage levels. Finally, a further suitable index, named Damage Factor (DF), specifically calibrated to take into account the weight and extent of damage to each structural component on repair costs, is presented. Furthermore, a correlation between DF and ARC is presented. The proposed relationship may allow making a preliminary estimate of the repair costs, based on a quick inspection on the damaged residential building. The same relationship has been carried out also for 1,500 RC residential buildings damaged by L'Aquila earthquake and reported in [13].

2 RECONSTRUCTION POLICY FOR RESIDENTIAL BUILDINGS

The reconstruction process of residential buildings outside the historical centers damaged by the L'Aquila earthquake was calibrated based on usability assessment of each private building. Depending on the severity of structural damage detected, the team of experts provided six possible outcomes of usability conditions of the building, named with a letter from A to F. The reconstruction process was supported by the Italian Government using public resources and the technical and financial review provided by a commission, called "Filiera" (i.e. an Italian word to indicate a supply chain mechanism) properly set up to oversee the projects and relevant funding applications related to residential buildings with B or C and E usability rating. Details about the reconstruction process are reported in [14;15] According to the ordinances specifically issued for the reconstruction of damaged buildings [16,17,18,19,20], the repair costs to restore original condition of damaged structural or nonstructural components were fully covered by the public grant. In addition, according to the "building back better" principle, strengthening costs were also covered by the government in order to reduce the vulnerability of repaired buildings. The maximum grant for strengthening works was established as a function of the usability rating of buildings. Technical and economic information on 5,775 buildings outside the historical centers of Abruzzi Region municipalities has been collected in a database thanks to the Filiera activity; in the next sections, the data related to 1,000 masonry buildings derived both by the AeDES forms and the applications for funding, checked and approved by the Filiera are presented and discussed.

3 BUILDING DATASET

The usability assessment of buildings and the technical approval process of application for funding of damaged buildings allowed to collect in a database both technical, economic and damage data related to 1,000 masonry residential buildings outside the historical centers of Abruzzi Region municipalities. The data related to these buildings are presented and discussed in this section in terms of: vulnerability classes; construction age and number of storeys, severity and extent of damage detected by in situ inspections on building structural and nonstructural components, and repair costs. The building features contained in the AeDES survey forms, as type of vertical and horizontal structures, allow us to divided the dataset in three vulnerability classes, A, B and C, as a function of the building seismic behavior according to criteria adopted in [7,10]. The most vulnerable class, A, consists of 405 (about 40%) buildings while the other vulnerable classes, B and C, consist of 216 and 379 buildings (about 22% and 38%), respectively. The percentage ratio of buildings belonging to A, B and C vulnerability classes as a function of buildings' construction age or number of storeys is reported in Figure 1a,b, respectively. The construction age is grouped in eight different periods in the AeDES form according to the census data collections made by National Statistics Institute, ISTAT (i.e. before 1919, 1919- 1945, 1946-1961, 1962-1971, 1972-1981, 1982-1991, 1992-2001, >2001). The buildings built after 1981 were grouped in classes after 1981 in Figure 1a because few buildings are found in these classes in the dataset. Figure 1a also reports the number of buildings belonging to each construction age period. Except for after 1981 period, Figure 1a shows that the percentage of buildings belonging to A and B vulnerability classes has a clearly decreasing trend for more recent construction age periods, while an opposite trend can be observed for C vulnerability class. In terms of number of storeys, the buildings are distributed between one and six storeys, with a peak for two or three storeys classes, which account about 75% (756 buildings, 286 with 2 storeys and 470 buildings with 3 storeys) of the whole dataset. By contrast, the number of buildings with 1 story or 6 storeys is almost negligible (they represent about 3% of the dataset). Figure 1b shows that the higher the number of storeys better is the quality of masonry and more rigid are the horizontal structures. By contrast, the percentage ratio of B vulnerability class buildings is almost constant by varying the number of storeys.



(a) (b)

Figure 1 – Funding classes of RC buildings measured against construction age (a) or number of storeys (b)

In Figure 2 the distribution of the empirical damage detected on Vertical Structures (VS), Floors (F), Stairs (S), Roofs (R) and Infills-Partitions (IP) of 1,000 masonry buildings is reported. In particular, Figures 2a depicts the number of buildings with null damage, D0, to each component; in the other graphs of Figure 2 the number of buildings with damage level defined according to Section 4 - Damage to the structural components"of the AeDES (D1, slight damage; D2-D3 medium-severe damage; D4-D5 very heavy damage or collapse) and relevant extent (i.e. lower than 1/3, between 1/3 and 2/3, and greater than 2/3 of the storey components) are reported for each structural component. Figures 2a shows that only 142 buildings, corresponding to about 14% of the dataset of masonry buildings, had null damage on VS while on S and R components the null damage was found in for more than 700 buildings, that is more than 70% of the dataset. In particular, the less damaged component resulted the stairs, S, D0 on 792 buildings while the most damaged one, except for VS, was the infill-partitions, IP, D0 on 273 buildings. Furthermore, Figures 2b,c,d,e show that for F, S, R and IP the most frequent damage was D1, with an extent lower than 1/3 of the story components, while on VS the most frequent damage was D2-D3 with an extent between 1/3 and 2/3. The very heavy damage level, D4-D5, was detected in 162 buildings on VS, 30 buildings on F, 27 buildings on S, 31 buildings on R, 80 buildings on IP.

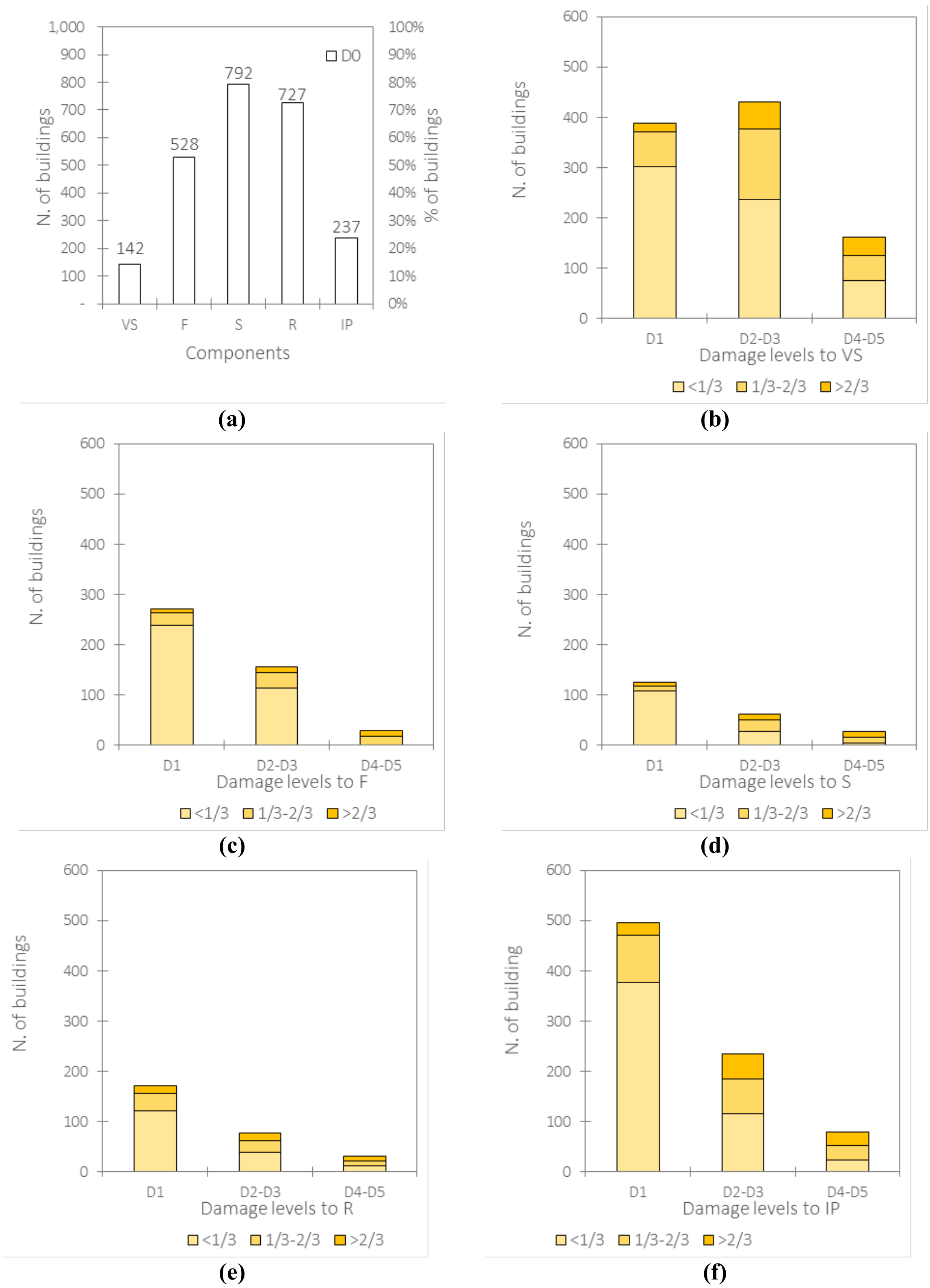


Figure 2. Distribution of null damage D0 for each component (a), distribution of damage levels D1, D2-D3, D4-D5, and relevant extent related to VS (b), F (c), S (d), R (e), and IP (f).

The building damage has been defined according to [7]. To this end, the following expression has been assumed:

$$DF = \sum_j D_j \cdot \gamma_j \tag{1}$$

where

- D_j is the damage level and extent related to the j^{th} structural component (i.e. j=*VS*, *F*, *S*, *R* and *IP*)
- γ_j is a coefficient, ranging between 0 and 1, which takes into account the weight of the damage on the j^{th} structural component on the building repair costs.

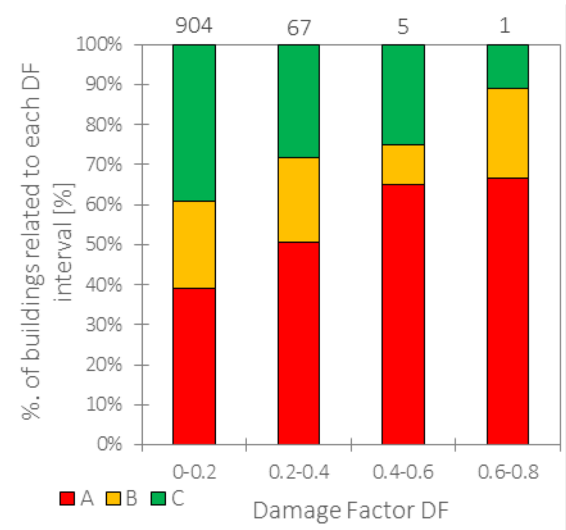
The damage level and extent related to the j^{th} structural component, D_j, can be computed according to the following expression:

$$D_j = \frac{\sum_{D=D0}^{D5} D \cdot e_{k,D}}{5} \tag{2}$$

where:

- D is the damage level (D0 = 0; D1 = 1; D2-D3 = 2.5; D4-D5 = 4.5),
- $e_{k,D}$ is a coefficient, ranging between 0 and 1,which takes into account the damage level extent k less than 1/3, between 1/3 and 2/3, and greater than 2/3 ($e_{k,D1} = e_{k,D2\text{-}D3} = e_{k,D4\text{-}D5}$ = 0.17 for k<1/3, $e_{k,D1} = e_{k,D2\text{-}D3} = e_{k,D4\text{-}D5}$ = 0.5 for 1/3<k<2/3, and $e_{k,D1} = e_{k,D2\text{-}D3} = e_{k,D4\text{-}D5}$ = 0.83 for k>2/3).

The DF assessed according to (1) and (2) varies between 0 and 0.75 and it is on average equal to 0.08. Over the 90% of building dataset has a damage factor in the range 0-0.2. The DF has been also computed with reference to the building vulnerability classes. The DF resulted on average equal to 0.1, 0.08 and 0.06, respectively for A, B and C vulnerability classes. Figure 3 confirms the relationship between DF and vulnerability classes. Indeed the percentage of A buildings increases from the 0-0.2 DF class to 0.6-0.8 DF class (i.e. 38% of the sub-dataset of building pertaining to the initial DF interval up to 67% of the sub-dataset of buildings pertaining to last one).



Vulnerability class	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	Total
A	352	34	13	6	405
B	198	14	2	2	216
C	354	19	5	1	379
Total	904	67	20	9	1000

Figure 3. Vulnerability classes of masonry buildings measured against damage factor, DF

4 DF - ARC REGRESSION FUNCTIONS

The relationship between the empirical damage and ARC is investigated in this section.

In order to determine the best correlation between the empirical damage and Actual Repair Costs, ARC granted after the Filiera checks, a proper Damage Factor has been assessed by varying the value of the damage extent, $e_{k,D}$ on each structural and non-structural component and the weight of the damage on a single component on the total repair costs of the building, γ_j in the equations (1, 2).

The ARC are related to repair interventions of damaged non-structural parts and relevant finishing works; local repair of damaged structural components; demolition and reconstruction of fully damaged or unsafe non-structural or secondary structural elements (i.e. interior or exterior infills, outdoor curtains, heavy plasters, fireplaces and chimney-pots, porches, eaves, repair of damaged facilities, etc.). The ARCs are not inclusive of VAT (equal to 10% of costs for repair and local strengthening interventions and 20% for other costs). The ARC are computed with reference to the overall building gross surface area, that is the area of the building footprint.

In order to define a proper DF, first of all it was necessary to define the constraints for the value of γ_j and $e_{k,D}$. In particular, it was assumed:

- $\sum \gamma_j = 1$.
- for a given damage extent k, $e_{k,D1} \leq e_{k,D2-D3} \leq e_{k,D4-D5}$;
- for a given damage level D, $e_{k<1/3,D} < e_{1/3<k<2/3,D} < e_{k>2/3,D}$;
- $\sum_{D=D0}^{D5} D \cdot e_{k,D} \leq 5$

Defined the constrains, the calibration of γ_j and $e_{k,D}$. values started in order to obtain the best correlation (i.e. maximum value of coefficient of determination, R^2) between DF and ARC. The calibration is based on iterative procedure as shown in Figure 4. It consists of the following steps: i) assume γ_j and $e_{k,D}$. values of first tentative; ii) compute DF according to expression (1) and (2) for each building of the dataset and the relevant actual repair cost, ARC, is associated to each building; iii) find the regression function which provides the correlation between DF and ARC; iv) steps i) to iii) are repeated by varying γ_j and $e_{k,D}$ values according to constraints until the coefficient of determination R^2 of regression function attains its maximum value.

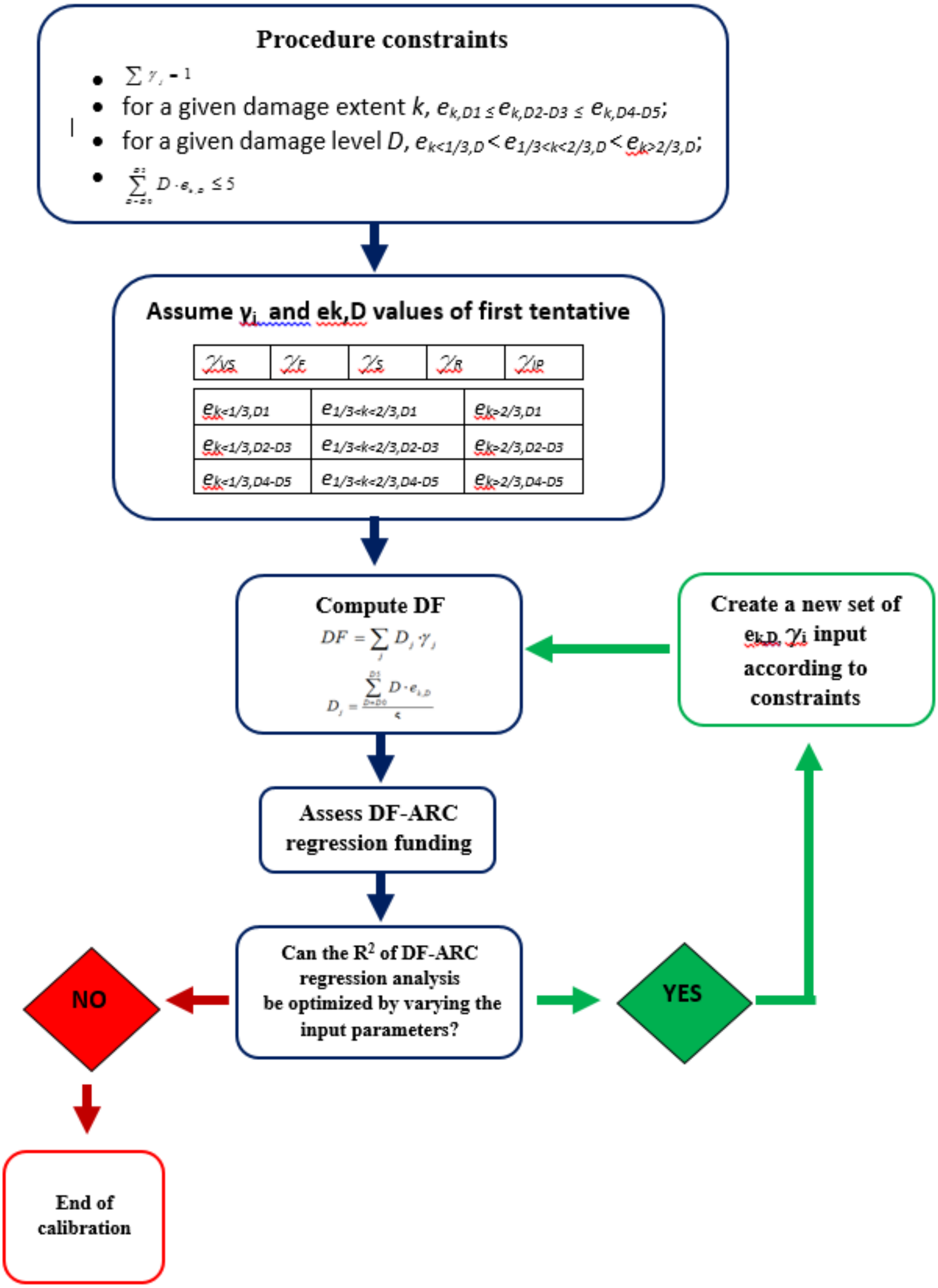


Figure 4. Flowchart related to the iterative procedure

The γ_j, $e_{k,D}$, and $D{\cdot}e_{k,D}$ values calibrated according to such procedure are summarized in Table 1, Table 2, Table 3.

Table 1. Coefficient γ_j

γ_{VS}	0.40
γ_F	0.12
γ_S	0.00
γ_R	0.30
γ_{IP}	0.18

Table 2. Coefficient $e_{k,D}$

	k<1/3	1/3<k<2/3	k>2/3
$e_{k,D1}$	0.40	0.60	0.80
$e_{k,D2-D3}$	0.40	0.70	0.89
$e_{k,D4-D5}$	0.50	0.80	0.89

Table 3. $D \cdot e_{k,D}$.

	k<1/3	1/3<k<2/3	k>2/3
$D1 \cdot e_{k,D1}$	0.40	0.60	0.80
$D2\text{-}D3 \cdot e_{k,D2-D3}$	1.00	1.75	2.23
$D4\text{-}D5 \cdot e_{k,D4-D5}$	2.25	3.60	4.00

The (DFb, ARCb) points related to each building and the regression functions are reported in Figures 4. Each point represents one building and the vulnerability class is also reported. In Figure 5, it is possible to note that the most vulnerable building classes are mainly represented by points located in the upper-right zone of the graph which is representative of significant level of damage and amount of ARC. By contrast, the C vulnerability class is represented mainly by points located in the lower-right zone of the graph. Furthermore, the relationship between DF and ARC is also reported in terms of an a-dimensional cost ratio obtained as a ratio between the actual repair costs related to the building and the average building demolition and reconstruction cost, Building Repair Cost Ratio (Cr). The unit costs for demolition and reconstruction of private residential buildings damaged by L'Aquila earthquake resulted 1,192.00 €/m^2, [12,13]. Based on the regression analyses the following function has been determined:

$$C_r = 0.12+0.71 \cdot DF-0.23DF^2 \qquad [ARC = 143+849DF-277DF^2] \tag{3}$$

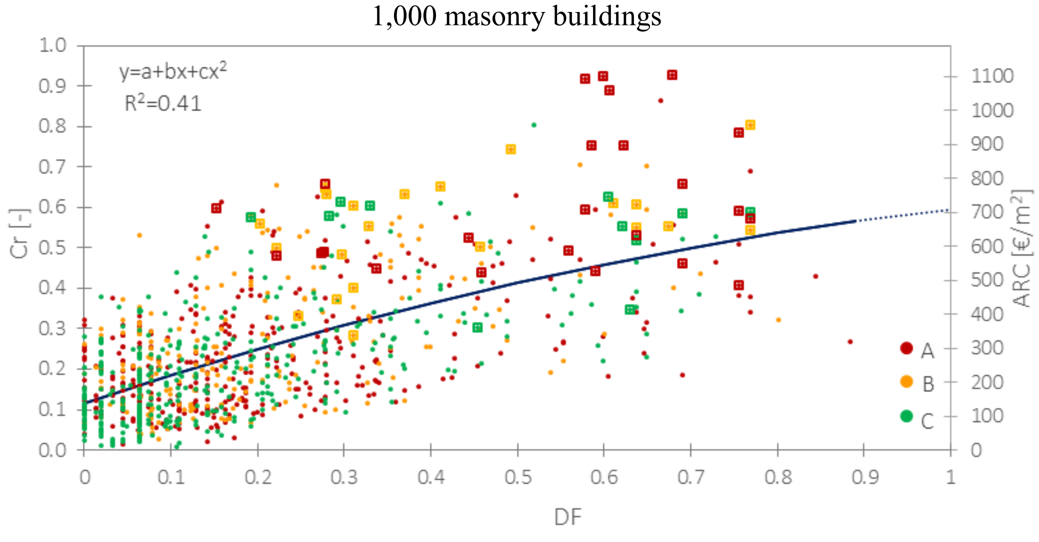


Figure 5. DF – ARC regression function

Figure 5 shows that the regression functions gives Cr = 0.12 in case of DF = 0. This is because even on buildings with DF = 0 damage to non-structural components (i.e. false ceiling, chimneys, parapets, services, etc.) was detected.
The point marked in Figures 4 with a square are related to 56 masonry buildings out of 1,000 of the dataset, for which the demolition and reconstruction resulted economically more viable than repair and strengthening works. This means that the ARC (or Cr) computed for these buildings and depicted in Figures 4 are related to the design of repair interventions although they actually were not realized. On these buildings, the DF and ARC expressed in terms of Cr vary as follows: Cr = 0.28-0.93 with a median of 0.57. It is pointed out that the class of demolished buildings is represented in Figures 10 by points mainly located in the upper-right zone of the graph.
Finally, the regression functions in the range of *DF* greater than those attained for the buildings of the database (i.e. *DF*>0.89) is represented with a dashed line in Figure 5.

5 CONCLUSIONS

The data collected by field inspections in the aftermath of a damaging earthquake aim to establish the building usability in view of aftershocks. To this goal, the main characteristics of the buildings and the level and extent of damage on components are commonly detected and reported in suitable damage and vulnerability assessment forms. The data collected with ref-erence to 1,000 masonry buildings outside the historical centres after the 2009 L'Aquila earthquake have been presented and discussed in the paper along with the actual repair costs derived from funding requests on private residential buildings damaged by the 2009 L'Aquila earthquake. The data presented in this study have shown that:

- the most damaged component have come out to be the vertical structures
- three classes for masonry buildings based on the type of vertical and horizontal structures have been defined according to building in situ inspection. A good correlation was found between the proposed vulnerability classes and the empirical damage detected on each building component.
- a proper damage factor *DF* is necessary to determine a correlation between empirical damage and actual repair costs, *ARC*; the damage factor should take into account not only the damage level on each building component but also the damage extent and the weight of the damage on a single component on the total repair costs of the building.

A calibration of extent of damage and of the coefficient, ranging between 0 and 1, which takes into account the weight of the damage on the j^{th} structural component on the building repair costs have been carried out in order to determine an optimised the relationship between *DF* and *ARC*. The proposed relationships may represent a useful tool to predict costs of repair for residential buildings outside historical centres when subjected to earthquakes.

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