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

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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, several Ordinances of the Prime Minister were issued to regulate the procedures and the public grant for the reconstruction of private buildings outside the historical centre of L'Aquila and surrounding municipalities. 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 1,500 private Reinforced Concrete (RC) buildings in terms of usability rating, construction age, number of storeys, empirical damage, as well as of Actual Repair Costs (ARCs) are herein discussed and presented. Building Damage Grades (DG) defined according to the European Macroseismic Scale EMS-98 have been computed based on the damage data collected with the AeDES forms.

Then, the relation between DG and ARCs, computed according to practitioners funding requests, is evaluated and discussed. A reasonable relationship between DG and ARCs is found if damage on non-structural components is taken into account. However, the study points out that the DG, defined as a function of the maximum damage detected on a structural or non-structural components, are not fully suitable to define a reliable correlation with ARCs. To this end, a more refined damage factor accounting for the damage extent on each structural and non-structural component and for the weight of the damage on a single component on the total repair costs of the building is needed.

Keywords: empirical damage, repair costs, loss estimation

1. Introduction

The frequent occurrence of strong earthquakes and their devastating effects have drawn the attention to the damage prediction and economic loss estimation.

Several methods are available in the literature to correlate damage to economic loss [1; 2; 3] or to assess the building reparability via the estimation of expected performance losses and associated costs of repair [4, 5, 6,7]. A reliable direct correlation between building damages and Actual Repair Costs, ARCs is still lacking. To fill this gap, a preliminary 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 damage detected on buildings has been derived by means of data collected using the first level survey form for post-earthquake damage and usability assessment, the AeDES form [8]. This form has been filled during in situ inspections of buildings, carried out to detect the level and extent of structural and non-structural damage and to assess whether the building could be safely used in case of aftershocks. Depending on the severity of structural damage detected, a team of experts evaluates the usability conditions of the building, providing six possible outcomes: i) A – usable; ii) B - temporarily unusable (partially or totally) but usable after short term countermeasures; iii) C - partially unusable; iv) D - temporarily unusable, requiring a more detailed investigation; v) E – unusable; vi) F - unusable due to external risk.

The *ARCs* have been derived from the applications for funding granted by the Italian government in the reconstruction process.

The study presented in this paper refers to a database of 1,500 Reinforced Concrete (RC) residential buildings damaged by the L'Aquila earthquake and located outside the historical centres (Di Ludovico et al. 2016a, b). The management of L'Aquila post-earthquake reconstruction process is briefly presented herein along with the data collected on 1,500 RC residential buildings in terms of usability rating, buildings characteristics and damage levels of building components (e.g. vertical structures, floor, stairs, roof, infills/partitions).. Then Damage Grades (DG), representative of the building damage, have been defined according to EMS-98 (Grünthal, 1998) damage grades; the empirical damage collected with the AeDES forms have been used to define DG. Two approaches have been assumed to determine the correspondence between the damage levels reported in the AeDES form and the DG: *i)* the empirical damage related to vertical structures, floors and roofs has been taken into account (as in [9]); *ii)* the empirical damage related to vertical structures and infills-partitions has been taken into account (as in [10]). The correlation between damage grade DG and usability rating of buildings is presented and discussed for both approaches. Finally the relationship between DG and ARCs are also presented.

2. Reconstruction policy for residential building

The reconstruction process of residential buildings outside the historical centres damaged by the L'Aquila earthquake was calibrated on the basis of usability assessment of each private building. The first phase of the reconstruction process involved buildings with B or C usability rating, the so-called "light damage reconstruction", while in a second stage the recovery involved E rating buildings, the so-called "heavy damage reconstruction". This to to differentiate the phases of the reconstruction process as a function of the observed damages on the vertical structures as issued in the specific post-earthquake laws, OPCM no. 3779 and relevant Annex, OPCM no. 3790 and relevant Annex, and OPCM no. 3881. The distinction in two phases enabled rapid re-occupancy of slightly damaged buildings, thus significantly reducing public costs incurred in housing the homeless. Details about the data related to both "light damage" and "heavy damage" reconstruction are reported in [16;17].

According to the ordinances specifically issued for the reconstruction of damaged buildings, the repair costs to restore original condition of damaged structural or non-structural 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 vulnerabilty of repaired buildings. The maximum grant for strengthening works was established as a function of the usability rating of buildings.

A suitable documentation, carried out by practitioners engaged by owners, was required to illustrate the damage, the design of repair and strengthening interventions, and to quantify the government financial support required (i.e. application for funding). The public grant was released once an administrative, technical and economical check was made by a proper commission, called "*Filiera*" (i.e. an Italian word to indicate a supply chain mechanism). Based on the building usability rating and strengthening intervention type (in several cases demolition and reconstruction was also allowed) four types of funding class were defined for application for funding: *i)* B-C funding class, for buildings with usability rating B or C, temporarily unusable (partially or totally) but usable after short term countermeasures; *ii)* E-B funding class, for buildings with E usability rating but with high non-structural risk and slight structural damage; *ii)* E funding class for buildings with E usability rating and significant structural damages; *iii)* E_{dem} funding class for buildings with E usability rating for which demolition and reconstruction resulted the most suitable strategy [17].

The *Filiera* activity allowed to collect a database containing technical and economic information on 5,775 buildings outside the historical centres of Abruzzi Region municipalities; in the next sections, the data related to 1,500 RC buildings derived both by the AeDES forms and the applications for funding, checked and approved by the Filiera are presented and discussed.

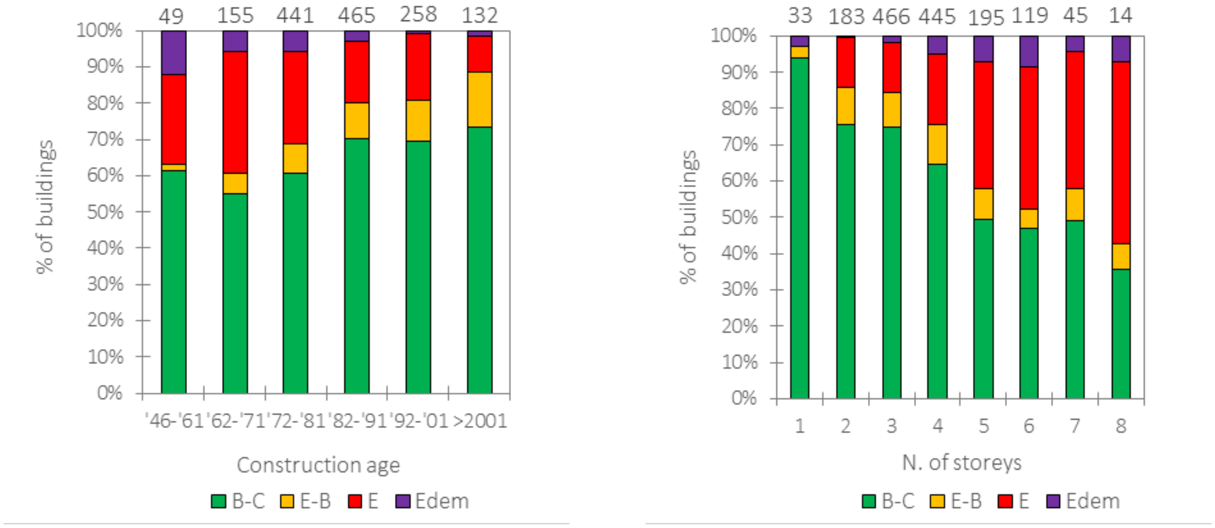
3. Building dataset

The usability assessment of buildings and the technical approval process of application for funding of damaged buildings allowed to collect in a unique database both technical, economic and damage data related to 1,500 RC residential buildings outside the historical centres of Abruzzi Region municipalities. The data related to these buildings are presented and discussed in this section in terms of: usability rating; construction age and number of storeys, level and extent of damage detected by in situ inspections on building components, and repair costs.

Out of 1,500 RC buildings, 985 buildings were assessed with B or C usability rating and 515 with E usability rating. The building stock with usability rating E consists of 140 buildings with light or no structural damage (E-B funding class in the approval process), 316 buildings with significant structural damage (E funding class in the approval process) and 59 buildings for which demolition and reconstruction resulted the most suitable strategy (E_{dem} funding class in the approval process).

The percentage ratio of buildings belonging to B-C, E-B, E and E_{dem} funding 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 eigth 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 classes before 1946 are not reported in Figure 1a because no 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 1946-1961 period which is poorly populated (about 3% of the dataset), Figure 1a shows that the percentage of buildings belonging to E and Edem funding classes has a clearly decreasing trend for more recent construction age periods, while an opposite trend can be observed for B-C and E-B funding classes. The percentage ratio of B-C buildings is always higher than that of E buildings (E-B, E and E_{dem} funding classes).

In terms of number of storeys, the buildings are distributed between one and eight storeys, with a peak for three or four storeys classes, which account about 60% (911 buildings, 466 buildings with 3 storeys and 445 buildings with 4 storeys), of the whole dataset. By contrast, the number of buildings with 1 story or 8 storeys is almost negligible (they represent about 5% of the dataset). Figure 1b shows that the higher the number of storyes, the higher is the percentage ratio of E and Edem funding class buildings. By contrast, the percentage ratio of E-B funding class buildings is almost costant by varying the number of storyes, The percentage ratio of E buildings is always greater than that of B-C buildings (i.e. exceeds 50%) starting from five-storey buildings class.



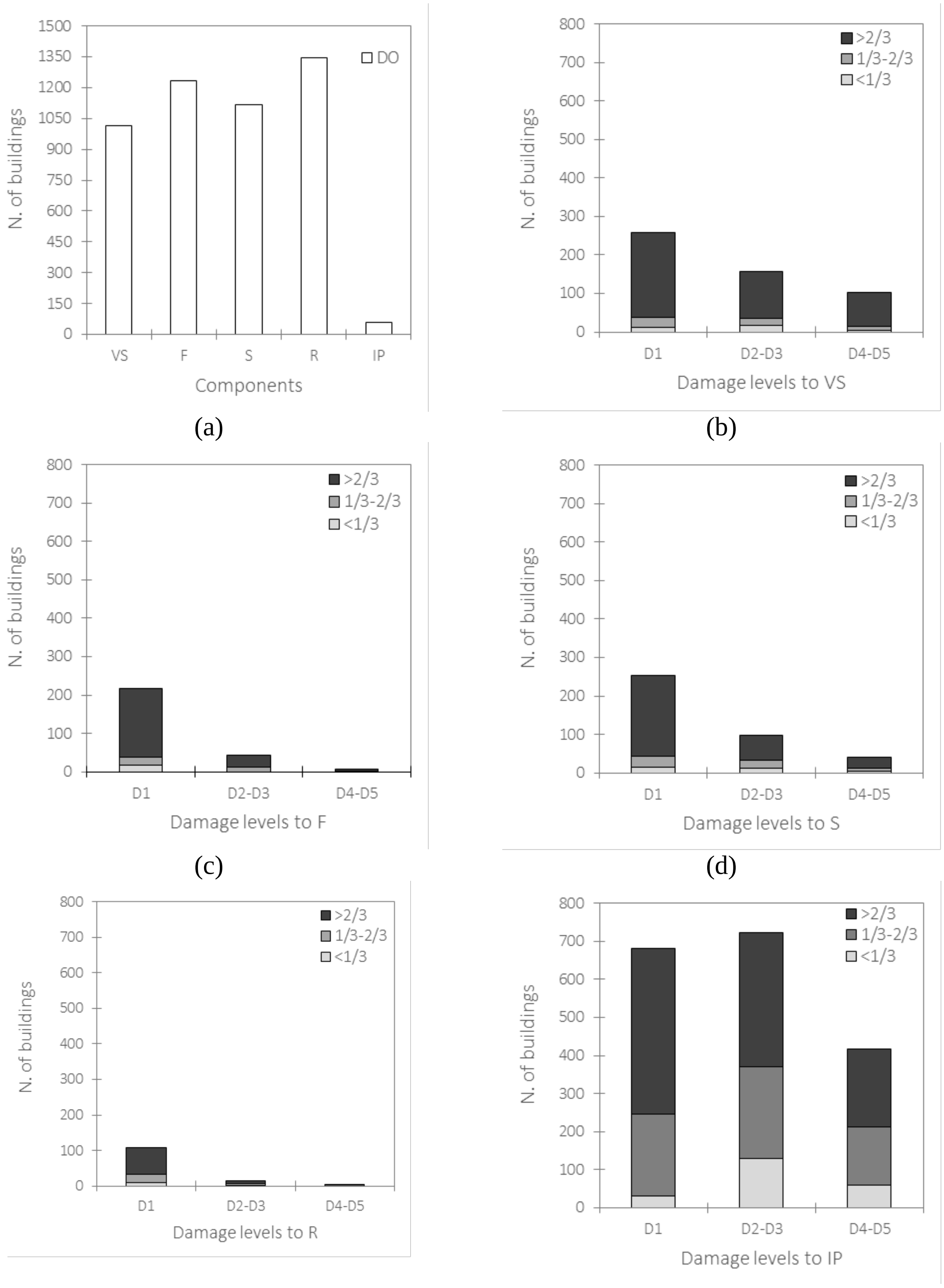
(a) (b)

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

The buildings damaged by the earthquake have been also classified based on the empirical damage detected in the "*Section 4 - Damage to the structural components*"of the AeDES form. This section identifies four damage levels (D0-no damage, D1, slight damage; D2-D3 medium-severe damage; D4-D5 very heavy damage or collapse). For each damage level, a relevant extent is also reported for structural components: Vertical Structures (*VS*), Floors (*F*), Stairs (*S*), Roofs (*R*) and Infills-Partitions (*IP*). The damage extent for each component can be lower than 1/3, between 1/3 and 2/3, and greater than 2/3 of the storey components. Note that Infills–Partitions are included by AeDES form in structural components, thus recognizing the significant role that they play in global structural response (Baggio et al. 2007).

In Figure 2 the distribution of the damage detected on the 1,500 RC buildings of the dataset is reported. In particular, Figure 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 damages level D1 and/or D2-D3 and/or D4-D5 and the relevant extents (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 59 buildings, corresponding to about 4% of the dataset of RC buildings, had null damage on *IP* while on the other components the null damage was found in any case for more than 1,000 buildings, that is more than 66% of the dataset. In particular, the less damaged component resulted the roof, *R*, D0 on 1,346 buildings while the most damaged one, except for *IP*, was the vertical structure, *VS*, D0 on 1,013 buildings. Furthermore, Figures 2b,c,d,e show that on *VS*, *F*, *S*, and *R* the most frequent damage was D1, with an extent greater than 2/3 of the storey components, while on *IP* the most frequent damage was D2-D3. The very heavy damage level, D4-D5, was detected in 103 buildings on *VS*, 8 buildings on *F*, 40 buildings on *S*, 4 buildings on *R*, 418 buildings on *IP*.



(a) (b)

(c) (d)

(e) (f)

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).

4. Definition of building damage

In the previous Section, the damage distribution has been shown for each structural components (VS, F, R, S and IP). In this Section, the damage data are elaborated in order to derive, for each building, a Damage Grade (DG) according to the European Macroseismic Scale EMS-98 [18]; in such a scale the following five damage grades are reported:

i) Grade 1 – *Negligible to slight damage* with fine cracks in plaster over frame members or in wall at the base and fine cracks in partitions and infills;

ii) Grade 2 – *Moderate damage* with cracks in columns and beams of frames and in structural walls, crack in partition and infill walls and falling mortar from the joints of wall panels;

iii) Grade 3 – *Substantial to heavy damage* whit cracks in columns and beam column joints of frames at the base and at joints of coupled walls, spalling of concrete cover, buckling of reinforced rods, large cracks in partition and infill walls and failure of individual infill panels

iv) Grade 4 – *Very heavy damage* with large cracks in structural elements with compression failure of concrete and fracture of rebars, bond failure of beam reinforced bars, tilting of columns, collapse of few columns or a single upper floor

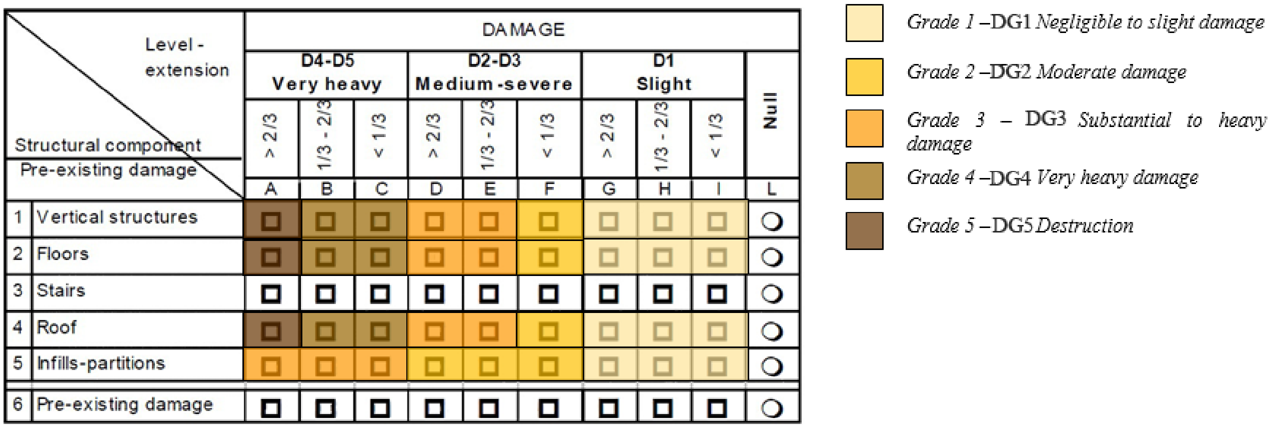
v) Grade 5 – *Destruction* with collapse of ground floor or parts (i.e. wings) of buildings.

A correlation between the damage levels according to the AeDES form and the EMS-98 damage grades (DG) maybe carried out to derive DG for each building. In particular two approaches have been adopted in order to define such a correlation: the empirical damage related to VS, F and R has been taken into account (as in [9]); *ii)* the empirical damage related to VS and IP has been taken into account (as in [10]).

According to [9] the maximum damage detected on components VS, F, and R is accounted for the correlation between empirical damage and EMS-98 DG; in particular, the correlation is defined as follows: the AeDES *Slight* damage (D1) is associated to the EMS-98 *Negligible to slight damage* (DG1); ii) the AeDES *Medium-Severe* damage (D2-D3), is associated to the EMS-98 *Moderate damage*, DG2 in the case of damage extent lower than 1/3 of the storey components or to *Substantial to heavy damage*,DG3 in the case of damage extent between 1/3 - 2/3, or greater than 2/3; iii) the AeDES *Very Heavy* damage (D4-D5) is associated to the EMS-98 *Very heavy damage,* DG4 in the case of damage extent lower than 1/3 or between 1/3 - 2/3of the storey components, or to *Destruction,* DG5 in the case of damage extent greater than 2/3.

In [10], the damage on IP is taken into account as a key parameter to define the building damage grade attained due to the earthquake; the maximum damage detected on VS or IP is accounted for the correlation between empirical damage and the building DG. The correlation between damage on VS and EMS-98 damage grades is equal to that defined in [9]. With reference to IP, the extent of damage is not accounted for and the correlation is defined as follows: the AeDES *Slight* damage (D1) is associated to the EMS-98 *Negligible to slight damage* (DG1*)*; the AeDES *Medium-Severe* damage (D2-D3) is associated to the EMS-98 *Moderate damage* (DG2); the AeDES *Very Heavy* damage (D4-D5) is associated to the EMS-98 “*Substantial to heavy damage*” (DG3).

The correspondence between the damage grades of EMS-98 (DG) and the damage levels (Di) of the AeDES form adopted is synthetically reported in Figure 5.



Structural component / Pre-existing damage \ Level - extension	DAMAGE									
	D4-D5 Very heavy			D2-D3 Medium-severe			D1 Slight			Null
	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
	A	B	C	D	E	F	G	H	I	L
1 Vertical structures	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
2 Floors	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
3 Stairs	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
4 Roof	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
5 Infills-partitions	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
6 Pre-existing damage	☐	☐	☐	☐	☐	☐	☐	☐	☐	○

Grade 1 – DG1 *Negligible to slight damage*

Grade 2 – DG2 *Moderate damage*

Grade 3 – DG3 *Substantial to heavy damage*

Grade 4 – DG4 *Very heavy damage*

Grade 5 – DG5 *Destruction*

Figure 5: Correlation between AeDES form damage levels and DG according to EMS-98

In each case, the DG0 has been associated to the building if a null damage, D0, has been reported in the AeDES form.

In the following, the damage grades derived according to these two approaches (approach I – [9] and approach II – [10]) are named $DG_{I\text{-approach}}$ and $DG_{II\text{-approach}}$, respectively.

The $DG_{I\text{-approach}}$ distribution as a function of usability ratings and funding classes of buildings is reported in Figure 6. A table is also reported to summarize the number of buildings of each funding class belonging to different DG. Figure 6 shows that out of 1,500 residential RC buildings, 61% (909 buildings) had no damage both to VS, F and R, 21% (324 buildings) attained DG1, and only 18% (267 buildings) attained damage grades equal or greater than DG2.

Figure 6 also shows that the higher the DG, the lower is the percentage ratio of B-C building. The number of B-C buildings is negligible for DG equal or greater than DG2, (27 buildings in DG2, 5 buildings in DG3, 1 building in DG4 and no building in DG5). By contrast, an opposite trend can be observed for building belonging to E and E_{dem} funding classes. It is noted that, according to approach I, a significant percentage of E buildings (E-B, E, and E_{dem} funding classes) belongs to DG0 or DG1; this because stairs and infill partitions (S and IP) are neglected in the analysis. Especially IP seem to be crucial to define DG since the damage to such components usually appears before structural damage occurs and it may strongly affect the seismic performance of RC buildings.[16;17; 19-22]

Funding Class	**Damage Grades**					
	DG0	**DG1**	**DG2**	**DG3**	**DG4**	**DG5**
B-C	730	216	33	5	1	0
E-B	73	33	18	3	13	0
E	100	65	66	22	62	1
Edem	6	10	8	5	27	3
Total	**909**	**324**	**125**	**35**	**103**	**4**

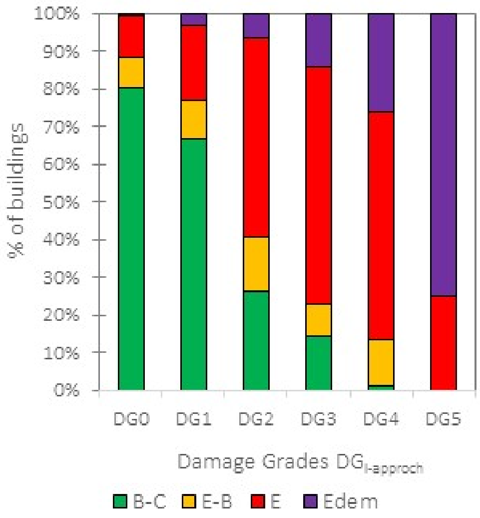


Figure 6: $DG_{I\text{-approach}}$ distribution as a function of building usability rating and funding classes.

If IP are taken into account in the definition of DG (approach II) the distribution of DG changes significantly as reported in Figure 7 and relevant table. In particular, a more rationale trend with respect to usability funding classes is found. Indeed, for DG lower than DG2, the percentage of E buildings (E-B, E, and E_{dem} funding classes) is null for DG0, 0.7% for DG1, and 25% for DG2 as expected for buildings with severe damage.

Funding			**Damage Grades**			
Class	**DG0**	**DG1**	**DG2**	**DG3**	**DG4**	**DG5**
B-C	53	429	408	94	1	-
E-B	-	3	54	70	13	-
E	-	-	79	178	58	1
Edem	-	-	1	28	27	3
Total	**53**	**432**	**542**	**370**	**99**	**4**

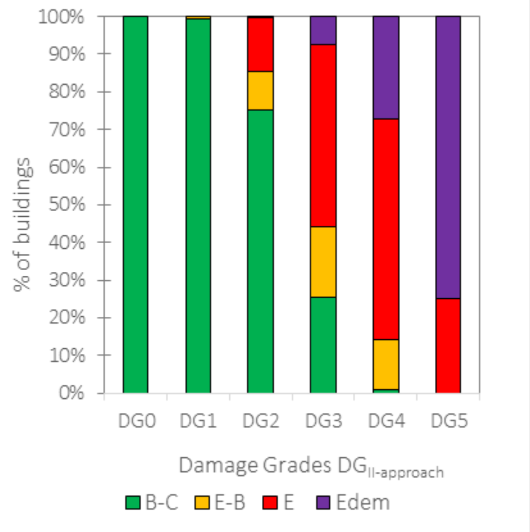


Figure 7: $DG_{II\text{-}approach}$ distribution as a function of building and funding classes

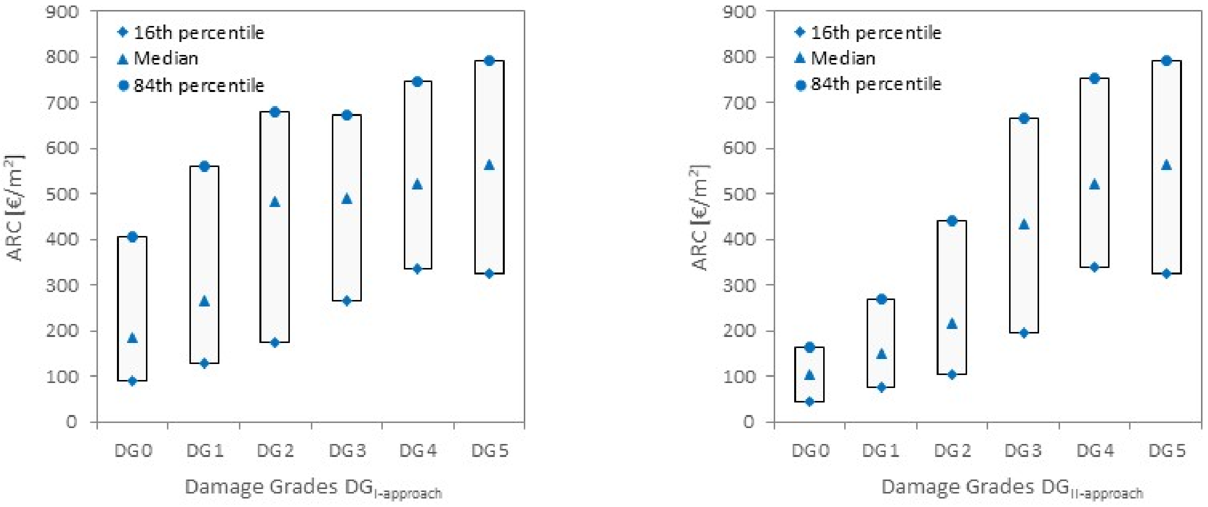
5. Damage grades vs. Actual Repair Costs

The relationship between Damage Grades (DG) and Actual Repair Costs (ARCs) granted after the Filiera checks and approval is investigated in this section. The costs related to strengthening works are not taken into account because they are not strictly related to the detected damage. The ARCs 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.). Furthermore, they includes the costs of i) building safety measures; ii) demolition and removal including transportation costs and landfill disposal; iii) repair and finishing works relevant to strengthening interventions; v) testing of facilities; vi) technical works for health and hygiene improvement; vii) technical works to improve facilities; viii) construction and safety costs; ix) charges for the design and technical assistance of practitioners; furniture moving. The ARCs are not inclusive of VAT (equal to 10% of costs for repair and local strengthening interventions and 20% for other costs). The ARCs are computed with reference to the overall building gross surface area, that is the area of the building footprint

The median, 16th and 84th percentile of *ARC* as a function of $DG_{I\text{-}approach}$ and $DG_{II\text{-}approach}$ are reported in Figure 8a and Figure 8b, respectively. They show that, for both approaches adopted to assess DG, the median ARC have an increasing trend passing from DG0 to DG5. However, a strong difference in terms of median ARC values is found in the DG classes lower than DG3. In particular, Figure 8a (approach I) shows that the median ARCs for DG0 buildings was 185.55 €/m^2, roughly one-third that for DG5 building class, 563.14 €/ m^2. Figure 8b (approach II) shows that the median ARC for DG0 buildings was about a fifth that for DG5 building class (102.83 €/ m^2 vs. 563.14 €/ m^2).

Figure 8 shows a wide range of ARC between the 16th and 84th percentile especially for DG0, DG1 and DG2 buildings in the case of approach I. This strongly confirms that the damage to IP had strongly affected the repair costs of buildings and is a key factor in the loss estimation analyses. Nevertheless, the scattering of ARC intervals shows that other parameters as the damage extent 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 may also strongly affect the funds required for repairs.

The median, 16th and 84th percentile of *ARC* as a function of $DG_{I\text{-}approach}$ and $DG_{II\text{-}approach}$, are summarized in Table of Figure 8a,b.



Damage Grade	16th percentile	Median	84th percentile
DG0	91.03	185.55	407.26
DG1	127.83	265.11	558.89
DG2	172.93	481.80	679.03
DG3	264.56	489.39	672.93
DG4	335.74	523.48	745.83
DG5	324.78	563.15	792.19

(a)

Damage Grade	16th percentile	Median	84th percentile
DG0	45.55	102.83	163.32
DG1	76.39	151.61	270.91
DG2	104.81	216.91	441.15
DG3	194.06	434.56	665.52
DG4	337.94	523.48	754.01
DG5	324.78	563.15	792.19

(b)

Figure 8: Actual repair costs as a function of damage grades $DG_{I\text{-approach}}$ (a) and $DG_{II\text{-approach}}$ (b)

5. Conclusion

The assessment of damage on buildings started in the immediate aftermath of L'Aquila earthquake under the coordination of the Italian Civil Protection Department. The damage and seismic usability assessment of each private building was carried out with in situ inspections. The reconstruction process of the damaged private buildings outside the historical centres of L'Aquila and the surrounding municipalities was regulated by specific Civil Protection Ordinances. They established the procedures and the amount of the public financial contribution for the reconstruction of private buildings. The damage levels and the actual repair costs, ARC, derived from usability assessment and application for funding on 1,500 RC buildings outside the historical center of L'Aquila have been analyzed. The data presented in this study shows that

i) altough the dataset refers only to a fraction of the damaged buildings damaged by L'Aquila earthquake and it involves buildings located in a vast area affected by different earthquake intensity, a direct link exists between the usability rating and construction age and between the usability rating and the number of storeys;

ii) the most damaged components resulted to be the Infill Partitions and the Vertical Structures;

iii) a correlation between the damage levels according to the AeDES form and the EMS-98 damage grades (DG) has been proposed according to two different approches, taking into account the damage on structural components or on both structural and non-structural components, respectively; the analysis has shown that the damage to infills-partitions play a key role in the building performance level and needs to be taken into account to establish a reliable correlation between damage and ARCs;

iv) for a given DG the ARCs are strongly scattered, especially if non structural components are not taken into account in the definition of the DG; to reduce this scattering the definition of a suitable damage factor, specifically calibrated for loss estimation analyses may be necessary. This parameter should take into account not only the maximum damage level attained on each structural and non-structural component but also the damage extent and the weight of the damage on a single component on the total repair costs of the building.

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