Performance of the health facilities during the 2016-2017 central Italy earthquakes

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Abstract

This paper presents an overview on the response of the healthcare system in the area mostly affected by the 2016 Central Italy earthquake based on specific surveys and information from local health authorities. The authors collected in the field information on the seismic response capacity of the healthcare system. They surveyed five hospital complexes from medium to small dimension whose maximum capacity was up to 50 beds. This type of hospitals are representative of those ones present in the small towns located along the Apennines mountain range, usually including few buildings (i.e. 3 to 5) constructed in different periods and with different structural types. In all the surveyed hospitals there were partially or totally unusable buildings causing severe limitations to the functionality of the healthcare services, forcing to move many patients to other hospitals and to stop outpatient treatment. This was due mainly to severe damage to non-structural components and, in some cases, to moderate damage to structural components. In the present paper, two hospital case studies, namely “Tolentino” and “San Severino” hospitals, both located in Marche region, are analysed and discussed in detail in order to better understand their performance to the earthquakes, by also estimating their seismic risk via simplified methods, including the WHO Safety Index and the Cosenza and Manfredi, (1997) damage index.

1. **INTRODUCTION**

The healthcare system plays an essential role in the response to disasters. Hospitals and health facilities should be able to provide adequate care for the victims of any type of event and also to continue the services necessary to maintain the health of the community they serve (WHO 2006). There is a widely held expectation that hospitals, and other health facilities, are prepared to deal with any crisis, including earthquakes. Unfortunately, past experience has demonstrated that health facilities and health systems may be particularly vulnerable to earthquakes.

The 2003 Iran earthquake (M_w 6.6) reportedly destroyed almost all of the health facilities in the affected area, with the loss of almost 50% of the local health staff (UNICEF 2004). The 2005 Pakistan earthquake (M_w 7.6) caused the closure of 68% of the health facilities in the affected region (IASC 2005). After the 2007 earthquake in Peru, 60% of health facilities in the affected area reported some damage, but 80% continued to provide services after the event (Chapin et al., 2009). The 2005 Kashmir earthquake (Mw=7.6) caused the closure of 68% of the healthcare facilities in the affected region (IASC 2005). The 2010 Haiti earthquake (M_w 7.0) destroyed or severely damaged 22% of the hospitals in the entire country and essentially all in Port au Prince (PDNA 2010).

As a result, huge earthquake-induced losses were estimated along with the loss of functionality. Surveys carried out in the aftermath of recent numerous medium-to-high magnitude earthquakes world-wide, have widely demonstrated the poor seismic performance of existing hospital buildings, e.g. after: the 2009 L'Aquila (M_w 6.3, Price et al., 2012), Italy; the 2010-2011 Darfield-Christchurch, New Zealand, (M_w 7.1 Jacque et al., 2014); the 2011 Van, Turkey (M_w 7.1), and the 2012 Emilia-Romagna, Italy, (M_w 6.1, Masi et al., 2013; Di Sarno et al., 2013). For such structures the observed damage was primarily caused by the inadequate performance of non-structural components and building contents with particular regard to specific medical equipment.

In response to this situation, risk mitigation policies have been established all over the world to help ensure the continuous operations of healthcare facilities. Besides the numerical seismic analysis on hospital buildings (Masi et al. 2013), numerous guidelines on rapid seismic assessment for both developing and developed countries hospitals were proposed in the last years by the World Health Organization (WHO 2008) within the Safe Hospitals campaign promoted by the Hyogo Framework (UNISDR, 2005).

Unfortunately the recent earthquake sequence that occurred in the Central Italy in 2016 and 2017, starting with M_w 6.0 earthquake 24 August 2016 03:36 AM local time, has emphasized that a lot of work is needed

to ensure the functionality of hospitals and health facilities in the aftermath of severe earthquakes, even in an area recently affected by a medium earthquake like the 1997 Marche-Umbria Regions Earthquake (Biondi et al., 1998).
To take stock of the situation this paper summarizes the impact of the Central Italy earthquake sequence on all the healthcare buildings interested by the impacts of the earthquakes, at three different levels of details.
Firstly, the list of the eleven hospital complexes that reported some consequence due the seismic sequence, including partial or total evacuation of one or more buildings due to structural or non-structural damage, is provided along with general information on their buildings and the felt seismic intensities, estimated from shake maps.
Secondly, for four hospital complexes, out of the eleven aforementioned, where it was possible to fill out or collect the information to fill-out the AeDES form (Baggio et al., 2007), a detailed description of the damage occurred is provided clarifying, furthermore the impact on functionality, that was increasingly aggravated after each one of the main events of the seismic swarm.
Finally, for two case studies, out of the previously mentioned four hospitals, namely "Tolentino" and "San Severino", a detailed description of the damage to structural and non-structural elements has been provided along with the relevant seismological parameters characterizing the felt seismic events. This latter were also compared with code based seismic design loads obtaining useful indication on the hospitals' seismic performance. Moreover, a rough estimation of the damage level, according to the EMS 98 damage scale (Grunthal et al. 1998), has been carried out, based on the data collected with the AeDES form.
For the sample of buildings it has been possible to apply the procedure recommended by WHO (2008.), as far as the analysis of the structural performance is concerned. This is aimed to understand, whether or not and to what extent, the parameters accounted for by the WHO (2008) procedures were actually among the critical ones for the hospital investigated.

2. AFFECTED HEALTHCARE FACILITIES AND MAIN DAMAGE OCCURRED

Background information on the Central Italy earthquake sequence

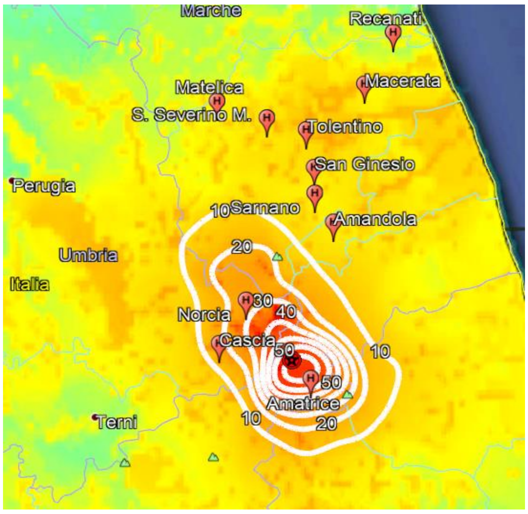
Between August and October 2016, three major earthquake events occurred in Central Italy. The first event, with magnitude M_w 6.1, took place on 24 August 2016 (Lanzano et al., 2016, ReLUIS-DPC, 2016), the second (M_w 5.9) on 26 October and the third (M_w 6.5) on 30 October 2016 (ReLUIS-INGV, 2016). This earthquake sequence occurred along the spine of the Apennine Mountain range on normal faults in a time-gap between two earlier damaging events, i.e. the 1997, M_w 6.1, Umbria-Marche earthquake to the north-west, and the 2009 M_w 6.1 L'Aquila earthquake to the south-east. This area had been previously recognized as a zone of high seismic risk (e.g. GdL INGV-DPC, 2016). Each one of the event of the sequence produced substantial damage to local towns and villages. The 24 August 2016 event caused massive damage to the villages of Accumoli, Amatrice (Lazio region, Masi et al. 2017), Arquata del Tronto and one of his districts, Pescara del Tronto (Marche region) causing in total, 299 fatalities (Lanzano et al., 2016) mainly due to the collapse of unreinforced masonry dwellings. The October events caused significant further damage in the villages of Visso, Ussita (Marche region) and Norcia (Umbria region) but, luckily, did not cause fatalities, since the area had been largely evacuated after the August 2016 event.
A further series of four major earthquakes struck Central Italy between Abruzzo, Lazio, Marche and Umbria regions on 18 January 2017. A magnitude M_w 5.1 earthquake struck 25 km northwest of L'Aquila on 18 January at 10:25 local time at a depth of 9 km. A M_w 5.5 hit the same epicentral area at 11:14 local time. A third earthquake of magnitude M_w 5.4 struck 11 minutes later and, finally, at 14:33 local time, the fourth one (M_w 5.0) was recorded. These earthquakes were followed by multiple aftershocks occurred in adverse weather conditions.
The area affected by the 2016-2017 Central Italy earthquakes belongs to four different regions, namely: Lazio, Marche, Umbria and Abruzzo (Fig. 2.1). Tab. 2.1 lists the healthcare facilities, which reported damage due the seismic sequence undergoing either some level of service interruptions or becoming completely unusable.

Tab. 2.1. Healthcare facilities damaged by the 2016-2017 central Italy sequence

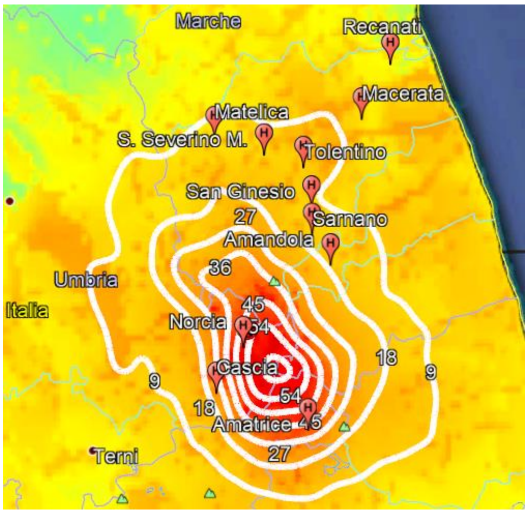
Id	Region	Town/Village	Name	N.of beds	Building Material
1	Lazio	Amatrice	Francesco Grifoni	10	Masonry/RC
2	Marche	Amandola	Vittorio Emanuele II	50-100	Masonry/RC
3	Marche	Tolentino	San Salvatore	50-100	RC
4	Marche	San Severino Marche	Bartolomeo Eustachio	50-100	RC
5	Marche	Macerata	Generale Provinciale	320	RC/Masonry
6	Marche	Matelica	S. Sollecito	50-100	RC
7	Marche	San Ginesio	-	<10	Masonry
8	Marche	Sarnano	-	<10	Mixed RC-Masonry
9	Marche	Recanati	Santa Lucia	50-100	RC/Masonry
10	Umbria	Norcia	-	<10	Masonry
11	Umbria	Cascia	-	N/A	RC

RC: only RC buildings
Masonry: only masonry buildings
RC/Masonry: presence of both masonry and RC buildings
Mixed RC-Masonry: buildings with masonry and RC members in the same structure

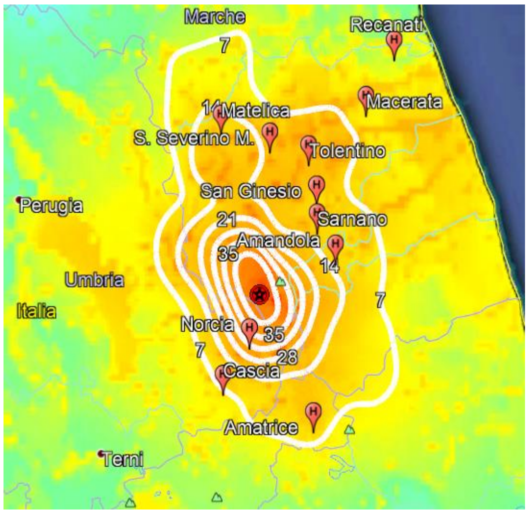
The affected healthcare facilities were located mostly in Marche region. Two hospitals were damaged in Umbria region, only one in Lazio (i.e. Amatrice hospital). No hospitals with significant damage were found in Abruzzo. The damage and lack of service for the affected hospitals have been managed by three different regional jurisdictions, as, in Italy, healthcare services are administrated at regional level.
The first six hospitals in Tab. 2.1 are small-medium facilities with 50-100 beds exception made for Amatrice (i.e. ID=1, 10 beds) and Macerata (i.e. ID=5, 320 beds). The latter suffered only light damage and just one building (out of 10) was declared partially and temporary unusable after the October 2016 events. Some of the hospitals provide a limited range of services since they are located in small provincial towns with a number of inhabitants ranging from 2.600 (as in the case of Amatrice) to about 20.000 as for the case of Tolentino. The healthcare structures, with ID labelling from 7 to 11 in Tab. 2.1, are small facilities with few beds providing mainly first aid and outpatient consultancy services. In some case, as for Cascia, they are just rehabilitation centres. However, if damage was low or absent, the kept functionality of small health facilities would have been critical to provide first aid to the people affected by the earthquakes by means of surgery and ER departments.
There were no casualties in healthcare facilities during the entire seismic sequence, despite the extensive damage observed. However, inpatients and hospital staff were exposed to a significant risk.
Fig 2.1 shows the location of each one of the health facilities in Tab. 2.1, overlaid to the seismic intensities felt in the area due to the three strongest seismic events, namely: a) August 24, 2016, 01.36 (UTC) M_w 6.0; b) October 26, 2016, 19.18 (UTC), M_w 5.9; c) October 30, 2016, 06.40 (UTC), M_w 6.5.



a) August 24, 2016 01.36 (UTC) M_w=6.0



c) October 30, 2016 06.40 (UTC) – M_w=6.5



b) October 26, 2016 19.18 (UTC) – M_w=5.9

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.06	0.2	0.8	2.0	4.8	12	29	70	>171
PEAK VEL.(cm/s)	*<0.02*	*0.08*	*0.3*	*0.9*	*2.4*	*6.4*	*17*	*45*	*>120*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 2.1. Area affected by the Central Italy earthquakes, locations of the affected healthcare facilities and felt intensities (http://shakemap.rm.ingv.it/shake/index.html) and PGA isolines (in % of g) for the earthquakes: a) August 24, 2016; b) October 26, 2016; c) October 30, 2016.

The authors could only survey the first four hospitals complexes in Tab. 2.1, (i.e. the ones with ID from 1 to 4) located in Amandola, Tolentino, San Severino Marche and Amatrice. For these hospital complexes, it was possible either to fill-out or to collect the information to fill-out the AeDES form, the form officially used by the Italian Civil Protection Department to assess post-earthquake damage and usability for residential and strategic buildings (Baggio et al., 2007). Therefore, a significant level of detail is available for these hospitals, including a detailed description of damage, as reported in Tab. 2.2, and some structural information.

Tab. 2.2 – Surveyed hospital complexes

					August 24, 2016 (1st event)		October 26, 2016 (2nd event)		October 30, 2016 (3rd event)	
Id	**Hospital**	**Main services**	**No. of Buildings**	**Total Beds**	**PGA (cm/s^2)**	**n. of unusable buildings**	**PGA (cm/s^2)**	**n. of unusable buildings**	**PGA (cm/s^2)**	**n. of unusable buildings**
1	Amatrice	ER, medicine, image diagnostic, outpatient services	2	10	916	2	104.9	2	607.0	2
2	Amandola	ER, Surgery, dialysis, rehabilitation, medicine, gynecology, image diagnostic	6	59	78.6	3	61.0	4 and 2 partially unusable	117.2	6
3	Tolentino	ER, image diagnostic, surgery, medicine, psychiatry, dialysis and chemotherapy	5	65	120.1	1	119.9	4	115.4	4
4	San Severino Marche	ER, surgery, medicine, Ophthalmology, obstetrics, paediatrics, long-term care	3	83	72.1	1 partially unusable	226.96	1 partially unusable	123.2	1 partially unusable

The Amandola hospital complex, made up of six buildings, felt almost the same intensity due to the August 24, 2016 and October 26, 2016 earthquakes, hereafter reported as 1st and 2nd event, respectively. Three out of the six buildings of the Amandola hospital complex were declared unusable after the 1st event and the remaining three after the second event. When the October 30, 2016 earthquake stroke, hereafter defined as the 3rd event, the hospital was already evacuated (if minimal administrative activities are disregarded).
For the Tolentino hospital complex the 2nd and 3rd events were felt stronger, causing the closure of three buildings in addition to the building already declared unusable after the 1st event.
The San Severino hospital complex, that felt almost the same intensity as for the Tolentino one during the 2nd event and slightly lower during the 3rd event, performed fairly well. Only few rooms were declared unusable due to minor relative displacements observed in simply supported RC beams. The Amatrice hospital, that felt high seismic intensities in all the three events, was heavily damaged after the 1st event and declared unusable.
This first analysis does not report on possible local amplification effects due to topographic or stratigraphic peculiar conditions at the hospitals' sites.
The particular overtime distribution of the seismic sequence, with strong events (even stronger than the 1st one) after two months, discouraged all the actions that the hospital managers were implementing to recover the hospital services after the 1st seismic event. This is particularly true for the Tolentino and Amandola hospitals subjected to partial unusability after the 1st event. In this latter complex a lot of repairing works were stopped and failed due to 2nd and 3rd events. For opposite reasons Amatrice and San Severino hospitals did not deal with this problem, since the Amatrice hospital was totally evacuated after the 1st event and San Severino suffered very minor damage as a result of all the three events.

2.1 Detail of damage for the Amatrice and Amandola hospitals

The Amatrice hospital was the most damaged of the entire area, forcing the authorities to demolish it in the first months of 2017. Two different buildings compose this little infrastructure. A part of the hospital was hosted in a historic three-storeys masonry building that nearly collapsed after the 1st event. Opened cracks showed a very uneven masonry typology, made of limestone blocks and clay bricks. The building also included an annexed church building (Fig. 2.2) without any structural or seismic joints.

Fig. 2.2 – Amatrice hospital: damage to the masonry building and annexed church.

Significant damage, mainly to non-structural components, occurred also in the RC building as can be seen in Fig. 2.3a. It was impossible to visit the hospital due to the risk of collapse of the masonry block, so that the survey was carried out only from outside. However, the steel HVAC equipment placed outside did not show apparent damage (Fig. 2.3b). This latter was mainly fixed to the ground and did not experienced amplification effect due to the structure dynamics.

a)

b)

Fig. 2.3 – Amatrice hospital: a) Damage to the RC building and b) undamaged steel HVAC component

The whole damage framework after the August seismic events forced to immediately close the hospital moving all the inpatients in the parking in front of the hospital and, then, to other hospitals. Remarkable contribution to damage was caused also by the 2nd and 3rd event, after which the masonry parts nearer to the collapse were demolished in order to guarantee safety conditions along the nearby road.
Another remarkably damaged hospital is the Amandola complex made-up of three RC and three masonry buildings. Despite the significant distance from the epicentre of the 1st event (about 35 km) the hospital suffered an extensive damage to architectural non-structural components, which caused the closure of two out of the three RC buildings. Some external brick coatings totally collapsed due to their as-built ineffective

connection to the RC structure. All the internal partition walls were heavily damaged (see Fig. 2.4a) and damage was observed also in correspondence of the ceilings (Fig. 2.4c). Moreover, some minor structural damage was found in both the RC and masonry buildings, also as a result of poor structural details (see Fig. 2.4b).

b)

a) c)

Fig. 2.4 – Amandola hospital, damage to a) partitions, b) stairs and c) suspended ceilings.

After the seismic events on October 2016, damage significantly increased in both the masonry and RC buildings forcing Authorities to close the entire hospital. Particularly, the weak connections to the structure of the external brick coating, as above discussed, determined a high collapse risk for them, as can be seen in Fig. 2.5.

Fig. 2.5 – Separation of the external brick coating and provisional supports.

From the point of view of medical equipment, the survey allowed checking that no significant damage occurred after the event on August 24. A technical check was carried out on the Computed Tomography machine, reporting no problem.

Other hospitals surveyed by the authors have been the Tolentino and San Severino Marche ones. They are described in the following sections reporting detailed analysis of their features and response to the earthquakes.

3. METHODS

Aiming to gather information on the behaviour of hospitals during the 2016-2017 Central Italy seismic sequence, the authors carried out several surveys at different level of accuracy depending on whether or not the hospitals were accessible and opened. All of these surveys were carried out strictly in cooperation with Regional Healthcare Departments. For some of the hospital complexes it was possible to undertake a complete survey accurately assessing the damage to both structural and non-structural components and to medical equipment, if any.
In some cases (building with Id=2, 3 and 4 in Tab 2.1) it was possible to fill-in the AeDES form, i.e. *Post-Earthquake Damage and Usability Assessment* form, in Italian "*Agibilità e Danno nell'Emergenza Sismica*". The main focus of the form is the usability evaluation at single building level, jointly accounting for earthquake-induced structural, non-structural and geotechnical risk. Moreover, the data collected via the AeDES form are useful for a gross assessment of the earthquake losses at a territorial scale. The AeDES form, structured in nine different sections, supports the collection of information in post-earthquake surveys, including:

1. Building identification
2. Building description
3. Building typology
4. Damage to structural elements and existing short-term countermeasures
5. Damage to non-structural elements and existing short-term countermeasures
6. External risk induced by other constructions and existing short-term countermeasures
7. Soil and Foundation
8. Usability assessment
9. Notes

As an example fig. 3.1 reports Section 4 where damage grades are grouped into three levels, namely D1 Slight, D2-D3 Medium-Severe, and D4-D5 Very Heavy.

Level - extension / Structural component / Pre-existing damage		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	☐	☐	☐	☐	☐	☐	☐	☐	☐	○

Fig 3.1. Damage grades in the AeDES form

To convert the three-level damage scale adopted by the AeDES into the 5 level damage scale adopted by the European Macroseismic Scale, EMS 98 (Grunthal et al. 1998), and to attribute an overall damage grade to the building accounting for the damage to its structural components, the procedures proposed by some of the authors in (Augenti et al., 2004; Masi et al., 2016) were applied. The AeDES procedure (see Tab. 3.1) accounts for both the damage levels and its extension. Reference is made to the maximum damage level among vertical structure, floors, stairs, roof and infill walls. For each one of the aforementioned structural components the more severe damage state is considered when more than one was reported in the form.
Clearly it is to note that AeDES is a general procedure for buildings subject to an earthquake sequence: no specific evaluation regarding hospital facilities is implemented in this in-situ sheet. Only a particular attention paid by the surveyors permits to well take into account the hospital's needs and characteristics.

The AeDES form is useful in the post-earthquake condition, when it is required to collect damage data as well to proceed rapidly, while, in "peace-time", when it could be useful evaluating the seismic risk of a hospital complex from a holistic point of view, the WHO (2008) safety index procedure can be used.
This latter is a level "0" method for the assessment of hospital's seismic safety. It can be operatively implemented via a spreadsheet including three main sections devoted to gather data, through a series of questions, on structural, non-structural and organization (or functional) aspects.

Tab. 3.1 - Correlation between AeDES damage data and EMS98 damage levels.

	Damage Extension (AeDES form)		
Damage Level (AeDES form)	**<1/3**	**1/3-2/3**	**>2/3**
None	D0	D0	D0
D1	D1	D1	D2
D2-D3	D2	D3	D3
D4-D5	D4	D4	D5

The section devoted to structural safety includes 13 questions targeting the main factors that can influence the seismic behaviour (a qualitative judgment is required). The part related to non-structural components includes 71 questions related to telecommunication, electrical, water supply, medical gases, diagnostic and laboratory facilities, architectural elements (e.g., partitions, ceilings). The last section, containing 61 questions, is related, among others, to the presence of emergency plans for the restoration of critical services.
A low, medium or high-risk level is assigned for each question, and cumulated to obtain three risk indexes: I_{STR}, I_{NSTR} and I_{ORG}. These three indices contribute to calculate the risk index of the facility, named "*Safety Index*".
In the following, this procedure is applied to some hospital buildings here studied to evaluate the risk prediction capability of the method. However, as mentioned earlier, the surveys carried out by the authors were devoted to collect information to fill the AeDES form, thus they did not provide data about the part of non-structural components (except the architectural elements) and organization aspects. In so doing, only the I_{STR} is computed in order to estimate the structural risk. The results in terms of I_{STR} are relevant to the safety of buildings. So, the higher is the index, the higher is the safety of the structure. When applying this procedure, the coefficient S = (1 - Safety Index) is computed (Masi et al., 2015) referring to the risk. Being $0.0 \leq S \leq 1.0$ it can be directly compared to the capacity demand ratio C/D that would be obtained from a detailed assessment.
For the following two case studies, namely the hospitals of Tolentino and San Severino Marche, the recorded strong motions accelerations and relevant seismological parameters have been listed and discussed with reference to the seismic events having a magnitude higher than 5.0 (ML). They are nine, even though, the most severe seismic events, as already mentioned, are those already named 1^{st} (24 August 01.36), 2^{nd} (26 October, 19.18) and 3^{rd} (30 October), for which also the response spectrum functions (5% damping) are shown. Particularly, the N-S and E-W PGA values relevant to the accelerometric stations placed in Tolentino on soil type B (CEN 2004) and in Matelica (16.4 km away from San Severino, being the site of San Severino Marche not provided with an accelerometric station) have been considered. Moreover, the epicentral distances, the Housner (1975) intensity values, the predominant periods, the significant durations and the Cosenza-Manfredi index values are reported. The last one is computed as

$$I_D = \frac{2g}{\pi} \frac{I_A}{PGA \cdot PGV}$$

where I_A is the Arias intensity (Arias, 1970). This index is correlated with the number of plastic cycles sustained by the structure during a seismic event (Cosenza and Manfredi, 1997).

4. CASE STUDIES

4.1 "San Salvatore" hospital, Tolentino

The “San Salvatore” hospital (Fig. 4.1) is located in the suburbs of Tolentino, a small town with about 20.000 inhabitants belonging to the province of Macerata in the Marche region. The hospital has 65 beds capacity and provides basic services such as radiology (CT), surgery, medicine, psychiatry, dialysis and chemotherapy (Tab. 2.2). Furthermore, the hospital provides some outpatient service such as, for example, analysis laboratories. The authors made a complete survey after the 1^{st} event and before seismic events occurred on October 2016. An additional survey was carried out in the first months of 2017, when the seismic sequence was fading.

Description of the hospital, structural types and material

The healthcare complex is made-up of five buildings, all reinforced concrete structures. Its buildings were built in different periods according to healthcare needs of the town as well as of the surrounding small villages. Table 4.1 reports the main characteristics of the buildings as well as the result of the WHO procedure in terms of the S coefficient.

a) b)

Fig. 4.1 – a) Front view and b) rear view of the Tolentino hospital

Table 4.1.1. Main features of the Tolentino hospital buildings

Building	Structural type	N. of storeys	Mean floor area (m^2)	Construction period	ERD	Usability 1^{st} event	Usability $2^{nd}/3^{rd}$ event	S
A	RC f1d	5	450	1962-71	n/a	Yes	No	0.60
B	RC f1d	5	350	1962-71	n/a	No	No	0.60
C	RC f1d	4	400	1972-75	n/a	Yes	No	0.60
D	RC f2d	5	450	1976-81	n/a	Yes	Yes	0.66
E	RC f2d	2	380	1982-86	Yes	Yes	No	0.80

1^{st} event: August 24, 2016
2^{nd} event: October 26, 2016
3^{rd} event: October 30, 2016

f1d, f2d: frames along one or two plan directions, respectively; ERD: earthquake resistant design.

The municipality of Tolentino is currently classified as seismic zone 2 (on a scale of 4 seismic hazard grades), namely, it is a medium to high seismicity zone. The law that for the first time recognized the seismic hazard of Tolentino was the Ministry Decree *D.M. 10 Febbraio 1983*. Consequently, only building E, out of the five buildings of the complex, should have been designed referring to also seismic actions, while the other buildings were designed and built without any seismic provision. In fact, buildings A, B and C (fig. 4.1.2) have structure with frames in only one plan direction, while the more recent buildings, namely D and E, have RC structure with frames in both the plan directions. The above mentioned Ministry Decree *D.M. 10 Febbraio 1983* included only three seismic grades: Tolentino belonged to intermediate grade, with a design spectral acceleration of 0.07g. Note that this was the spectral design value accounting also for the behaviour factor, thus it cannot be directly compared with the spectral values of the current Italian seismic code.

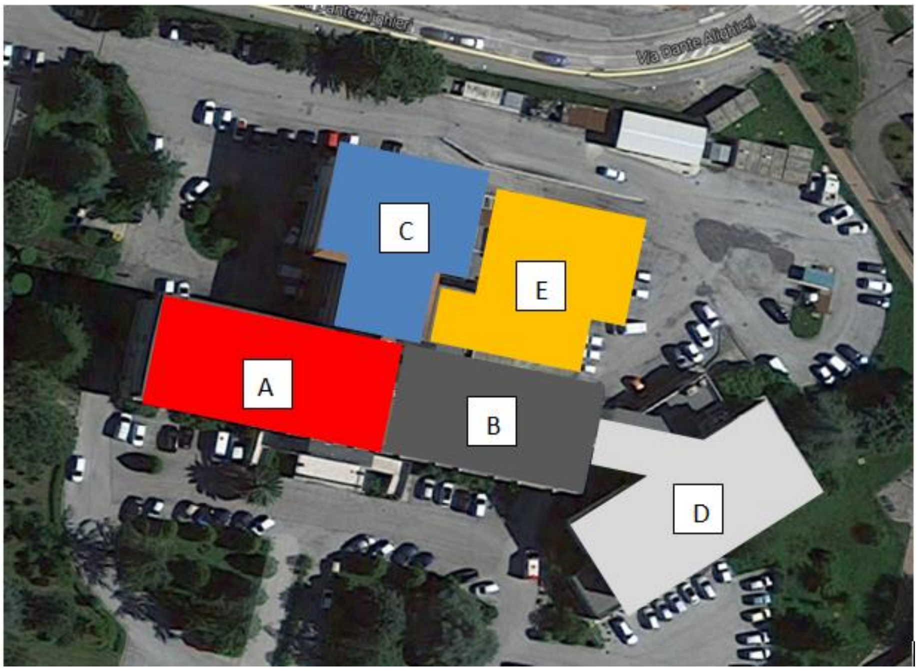


Fig. 4.1.2 - Tolentino hospital layout (Gps coordinates N 43.213972, E 13.295300)

According to the construction period, buildings A, B and C have smooth bars as well as very distant hoops (around 30 cm spaced), as shown in Fig 4.1.3a, displaying a zone of a column with exposed reinforcement due to concrete spalling. In buildings A, B and C expansion joints are generally insufficient to accommodate seismic displacements, while larger joints were found at the borders of the more recent building E, being specifically seismic joints.

None of the buildings of the complex were subjected to seismic upgrading or retrofitting in the aftermath of the Umbria-Marche earthquake that occurred in 1997.

Fig 4.1.3 - a) Spalled concrete of a column b) Insufficient expansion joints

Soil condition of the site

From the point of view of geology and geotechnics, the territory of the Tolentino's municipality was subjected to a seismic microzonation campaign whose documents and reports are available through the web site *http://www.urbanisticatolentino.it/microzonazione-sismica/.* The suburb area of the town, where the hospital is located, is flat, therefore no topographic amplification effect is expected. This campaign included geotechnical tests that made available a lot of information about the nature of the soil from the geological and seismic point of view. Specifically, the stratigraphy nearby Tolentino's hospital shows a first layer about 10 m thick of clay and sandy lime having an undrained cohesion of about 50-120 kPa. Underneath this latter, a layer of sandstones gravel is present with a thickness of about 5-7 m directly in contact with the substrate. According to the microzonation documents, the area where the hospital is located is advised to be subjected to seismic amplification even though the soil type according to Eurocode 8 and Italian seismic code (NTC2008) is not reported.

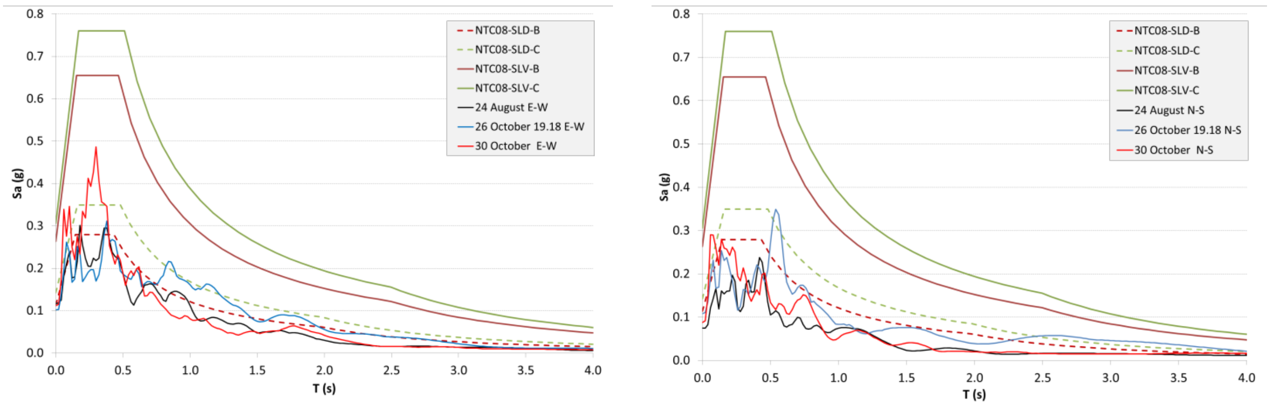
2016-2017 Seismic sequence: recorded acceleration strong motions accelerations and relevant seismological parameters

Tolentino's hospital was subjected to nine main seismic events as reported in Tab. 4.1.2. The accelerations records were derived from the Italian Strong Motion Network (RAN) managed by the National Civil Protection Department (Zambonelli et al., 2011). The Tolentino accelerometric station is 3 km east from the hospital, founded on a soil tentatively classified as type "B" in agreement with Eurocode 8 (CEN, 2004).
As can be seen, the event with the closest epicentre is the 2b occurred on October 26, 19.18 (UTC). Events 1a, 2b and 3 generated almost the same maximum PGA values. Events 1a and 3 caused PGA values equal to 0.122g and 0.117g, respectively, in the E-W direction, while event 2a caused a PGA of 0.122g in N-S direction.

Tab 4.1.2 Main properties of the strong motion records measured at Tolentino

Event	Date/time	Epicentral distance (km)	Magnitude (Ml)	PGA (g)		Housner intensity (cm)		Cosenza-Manfredi Index		Significant duration (s)		Predominant period (s)	
(Id)				N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W
1a	24/08/2016 (01.36)	56.7	6.0	0.075	0.122	21.17	32.06	8.97	9.15	13.11	12.24	0.42	0.18
1b	24/08/2016 (02.33)	47.7	5.4	0.018	0.023	2.97	4.22	22.64	19.27	14.59	17.34	0.14	0.16
2a	26/10/2016 (17.10)	38.9	5.4	0.032	0.036	4.71	8.26	15.60	17.83	14.13	16.96	0.06	0.08
2b	26/10/2016 (19.18)	35.2	5.9	0.122	0.105	37.86	50.27	5.29	8.46	10.41	12.72	0.54	0.38
3	30/10/2016	43.53	6.1	0.093	0.117	25.09	35.66	13.85	21.54	15.67	16.13	0.06	0.3
4a	18/01/2017 (09.25)	74.37	5.3	0.02	0.023	3.98	4.46	11.73	11.83	14.99	13.88	0.14	0.16
4b	18/01/2017 (10.14)	76.29	5.4	0.018	0.022	3.47	4.74	14.52	13.07	14.38	35.57	0.16	0.12
4c	18/01/2017 (10.25)	80.31	5.3	0.019	0.022	2.54	3.41	0.39	0.64	19.73	20.34	0.16	0.12
4d	18/01/2017 (13.33)	82.09	5.1	0.012	0.014	2.49	3.21	6.75	8.99	13.55	13.09	0.2	0.16

With respect to Housner intensity, whose ability to effectively represent the damage potential of a ground motion is well known (e.g. Masi et al., 2011), the highest value was caused by the E-W component of the event 2b, reaching I_H = 50.27 cm. Moreover, the same event showed the highest values of the predominant periods, equal to 0.54s and 0.38s for the N-S and the E-W component, respectively. It is worth noting that, taking into account that the Tolentino hospital buildings are RC framed structures with 4-5 storeys, their fundamental vibration period ranges around the predominant periods of the seismic event under consideration. As a result of the event 2b, the hospital suffered significant damage forcing the Regional healthcare authority to close the hospital, moving the inpatients to other structures.



a) b)

Fig. 4.1.4 - Pseudo-acceleration response spectrum functions of three main earthquakes for the Tolentino hospital site: a) E-W direction, b) N-S direction and code-based design response spectrums.

Fig 4.1.4 displays the elastic response spectrum functions (5% damping) in terms of pseudo-acceleration of the three main events in comparison with the code based spectra computed for soil types B and C. This latter are computed for the Life Safety limit state (SLV) and for the Damage limit state (SLD) taking into account that hospitals are structures with strategic functions in the aftermath of a seismic event. This leads to an increase in the design return period from 475 to 949 years for SLV and from 50 to 101 years for SLD, with respect to ordinary buildings, as prescribed by the Italian seismic code (NTC08) that considers a return period twice in respect of ordinary buildings.
It is worth mentioning that the highest spectral accelerations are obtained from the E-W component of the event 3 (October, 30), the N-S component of the event 2b (October, 26) and from the E-W component of event 1a (August, 24), according to the PGA values of Tab. 4.1.2. Spectral pseudo-accelerations are lower than the code based values for the SLV limit state, even though the previously mentioned seismic events provided values between 0.3g and 0.5g, which should be considered significantly high for structures essentially designed only considering gravity loads. This justifies the structural damage occurred to the Tolentino hospital. Regarding the SLD limit state, the code based spectrum values are exceeded for some period values especially for the E-W components of the seismic events. This means that even for seismically designed structures, some damage to non-structural components could be expected.

Observed damage

A full survey of the hospital complex was carried out by some of the authors on October 2016, when only the first event (August 24, 2016) had occurred. A second survey was performed in the first months of 2017. The first survey was focused on filling the AeDES form (Baggio et al., 2007). Damage was essentially concentrated on non-seismically designed buildings A, B and C, with minor non-structural damage to building D and no damage to building E.
The result of the damage conversion from AeDES to EMS 98 classification gave damage grades D1, D3 and D2 for buildings A, B and C respectively, while, the more recent buildings (D and E) a damage grade equal to D1 and D0 was assigned, respectively.
As a result of the first survey, building B was declared unusable, while the remaining ones were declared usable. After the seismic events occurred on October 2016, also buildings A and C were declared unusable and consequently evacuated due to structural damage. Building E was declared partially unusable not due to its own damage but being unfortunately close to the other damaged buildings. Building D, where outpatient services are currently provided, is at the moment the only usable one.

a)

b)

c)

d)

Fig. 4.1.5 Damage to Tolentino hospital: a) flexure crack in a beam of building B, b) partition wall cracks in building B, c) interaction between building A and C, d) interaction between building D and B due to insufficient structural joints.

However, the part of building D interacting with building B was closed due to damage occurred to the infills near the expansion joint as a result of hammering. It is worth noting that no significant damage was reported on medical components. In summary, Tolentino hospital lost its serviceability mainly due to structural damage and to some damage to architectural components (infills, partitions). The presence of more recently designed (and safer) buildings was frustrated by the risk induced on them by the older buildings that suffered structural damage. This means that the advantages of constructing new seismically designed buildings in old hospital complexes can be hindered by the risk deriving from the older ones. Even when new buildings are far from the older ones, the serviceability can be seriously limited by the unusability of these latter, in case they host essential services or equipment or in case that both roads and parking have to be restricted due to older building collapse risks.

Application of the WHO procedure

The Safety Index has been evaluated for the five buildings belonging to the Tolentino hospital. Buildings A, B and C have similar characteristics and were built in the same period. Thus, only one value of the I_{STR} has been calculated. For buildings D and E two separate evaluations were carried out. The Safety Index and, then, coefficient S have been computed based on a simplified version of the procedure set-up by Aiello et al. (2012), and reported in Tab. 4.1.1.

An S value near to 1.0 means that the risk can be assumed as acceptable and similar to newly built structures, while cases of S going to zero are representative of very high-risk situations. For Tolentino hospital S values range from medium to low risk and are sort in relative terms as expected (i.e., the older buildings have a higher risk with respect to the newer). In fact, buildings A, B, and C are the older ones. However, the absolute value would give the indication that upgrading or retrofitting interventions are not urgently needed. For example, a seismic capacity/demand ratio equal to 0.6 is the lower bound limit for upgrading interventions (following the Italian usual practice and guidelines), meaning that an intervention on buildings A, B and C could be avoided or at least postponed. On the contrary, damage suffered during the Central Italy earthquakes shows that such an evaluation was misleading. Finally, the very low risk predicted for building E is not in agreement with the fact that, as a result of the seismic sequence, it was declared not usable due to the risk induced by buildings B and C, having structural damage. This aspect (i.e., the external or induced risk) appears totally neglected in the WHO approach and not specifically analysed in AeDES form according to the particular (hospital) function of these buildings.

4.2 "San Bartolomeo Eustachio" Hospital, San Severino Marche

San Bartolomeo Eustachio Hospital is a multi-storey RC hospital building located in the outskirt of San Severino Marche (see Fig. 4.2.1), a village with about 13.000 inhabitants in the province of Macerata, in Marche region, Central Italy. The hospital has a total capacity of 83 beds.

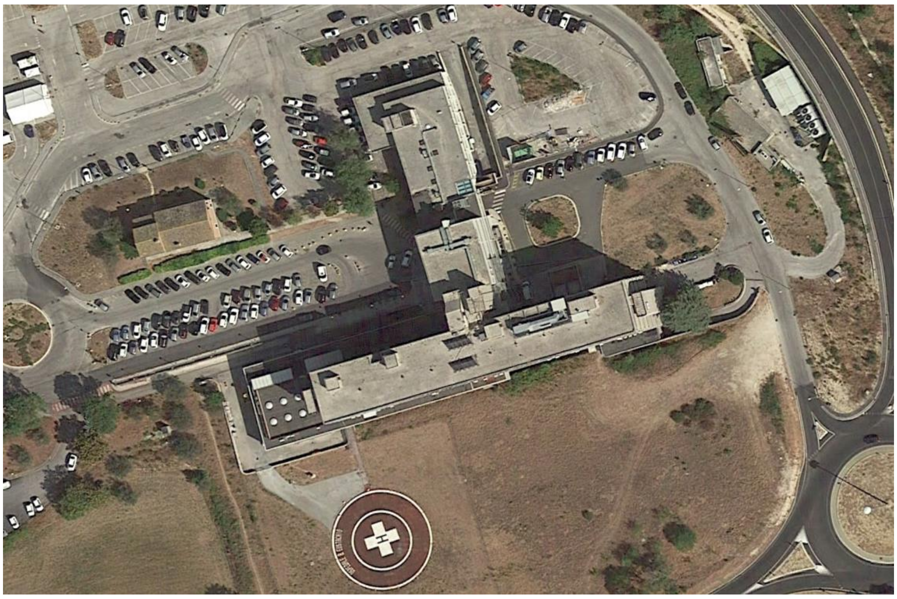


Fig. 4.2.1 - Aerial view of the San Severino Marche Civil hospital (Gps coordinates N 43.140945, E 13.112260)

The location of the hospital is flat (see also aerial view in Figure 4.2.1), hence topographic amplification effects are not expected. The geological properties of the site are very similar to Tolentino. Technical reports and thematic maps with the site-specific seismic zonation are not available for public consultation.
The hospital building, which is a critical facility serving the province of Macerata, has been surveyed twice in the aftermath of the 24th August 2016 earthquake, and of the seismic sequence occurred on October 2016. The hospital, which has an irregular structural configuration, as displayed in Figure 4.2.2, remained operational during the seismic sequences as minor non-structural damage was identified primarily on partitions located at the upper floors, as better described hereafter.

Description of the hospital, structural types and material

The healthcare complex comprises four main RC buildings and an independent office building (A) located in the area opposite the main hospital, close to the car park (*see* Fig. 4.2.1). The RC buildings have different plan (*see* Fig. 4.2.2) and elevation layouts. The building heights also vary significantly: Building A has three storeys, Building B has 5 storeys, Building C has 2 storeys (1 storey located underground), and Building D has 6 storeys. The building complex has global T-shaped layout which makes the RC structural system irregular in plan. Besides, the building complex is also irregular in elevation because of the presence of low to medium-rise systems, namely from 2 to 6 storeys. However, during the on-site visit it was observed that

Building A (low-rise) and Building B (medium-rise) are provided with a structural joint where a typical Gerber saddle is present.

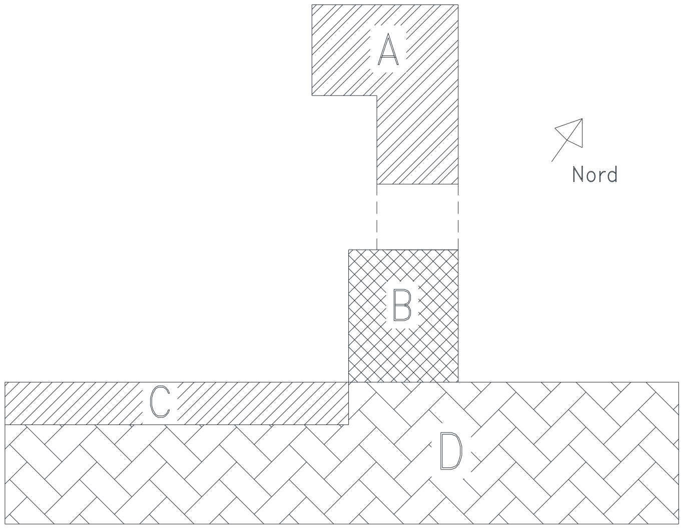


Figure 4.2.2. – Plan layout of the San Bartolomeo Eustachio Hospital.

Table 4.2.1 summarizes the main properties of the buildings. Each block of the T-shaped building complex is regular having rectangular geometry. Building block D is 90m long, 14m wide and 15m high. Building block C is 56m long and 6m wide. For both the tall main building block D and secondary building block C the length-to-width ratio is larger than 6, which can be detrimental for the seismic response of the structural system due to possible torsional effects. Specifically, asynchronous motions at the base and accidental mass eccentricities may lead to inadequate torsional performance of the structural system. In building D, stiff shear walls were used for the staircases located along the width, at the edges of the structural system, thus improving the lateral stiffness of the RC structure and limiting torsional unbalance.

Table 4.2.1. Main properties of the San Severino Marche hospital building

Building	Structural type	N. of storeys	Mean floor area (m^2)	Construction period	ERD	Usability 1st event	Usability 2nd/3rd event	S
A	RC frame/walls	3	520	1972-1975	n/a	Yes	Yes	1.0
B	RC frame/walls	5	450	1972-1975	n/a	Yes	Yes	1.0
C	RC frame/walls	2	600	1972-1975	n/a	No	No	0.8
D	RC frame/walls	6	1200	1972-1975	n/a	Yes	Yes	0.8
1st event: August 24, 2016 2nd event: October 26, 2016 3rd event: October 30, 2016								

The municipality of San Severino Marche is currently classified as Seismic Zone 2, namely the seismic area with design peak ground acceleration (PGA) ranging between 0.15g and 0.25g (10% probability of exceedance in 50 years return period), as specified in the Ordinanza del Presidente del Consiglio dei Ministri n. 3274/2003, which was updated by the Regional Decree of Regione Marche n.1046 on the 29th July 2003. In the province of Macerata there are 55 main villages and towns; 6 out of 55 places are classified as zone 1 (high seismic risk with PGA=0.35g). It is worth mentioning that San Severino Marche has been classified as seismic zone 2 since the early 80's. As mentioned earlier in Section 4.1, the local seismicity was defined in the 80's by the Ministry Decree D.M.10 Febbraio 1983.

It appears that the four main blocks of the hospital were designed primarily for gravity loads, hence seismic details are not implemented. However, the post-earthquake on-site visits showed that the structural system of the as-built RC structures shows adequate lateral stiffness and strength. For what it was possibly seen during the survey, the constituent materials of RC structural members showed good properties.

Figure 4.2.3. – Global frontal view (left) and main entrance of the Emergency Unit (right) of the San Bartolomeo Eustachio Hospital, San Severino Marche, Macerata.

Specifically, the concrete seems to have an adequate compressive resistance, and its degradation does not appear to be significant. The steel reinforcements include ribbed longitudinal and transverse bars. It was not possible to identify the spacing of the stirrups as the cover was not damaged and/or removed during the on-site visits. It is worth mentioning that none of the buildings of the surveyed hospital was retrofitted after the Umbria-Marche earthquake occurred in 1997. In summary, due to the presence of RC shear walls and an apparently good materials' quality, the S index of this hospital complex resulted very high (see Table 4.2.1), meaning that a low seismic vulnerability can be expected, despite the absence of a seismic design, due to a good material quality.

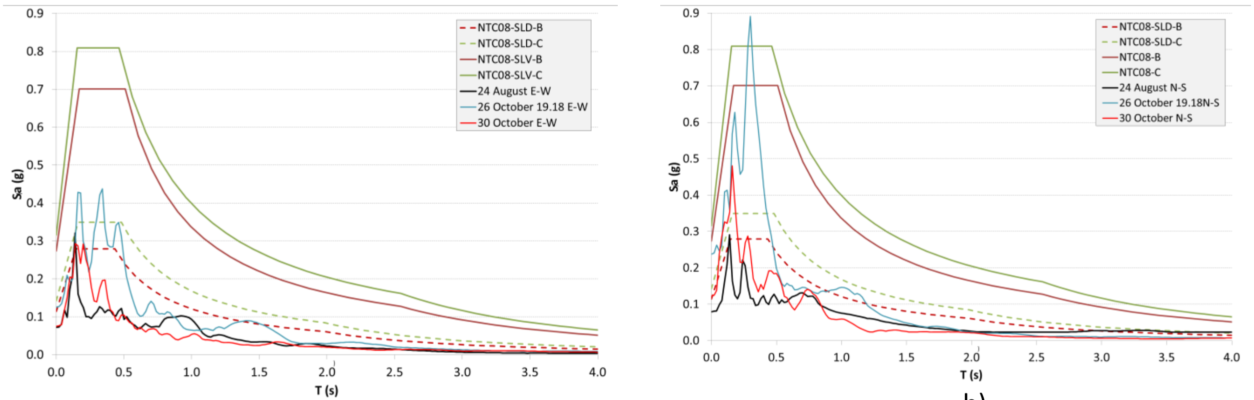
2016-2017 Seismic sequence: recorded acceleration strong motions accelerations and relevant seismological parameters

The San Bartolomeo Eustachio Hospital has experienced 9 strong motions from the 24th August 2016. There are two accelerometric recording stations of the RAN network which are located close to San Severino Marche, i.e. Tolentino and Matelica stations. Both stations are at a distance of about 15km from the location of the hospital. The maximum horizontal PGA recorded at Matelica is 0.238g, which occurred on the 26th October 2016 at 7h18 pm (event 2b, Tab. 4.2.2)

Table 4.2.2. Main properties of the strong motion records measured at Matelica (Province of Macerata, 16.4 km from San Severino Marche)

Event	Date/time	Epicentral Distance	Magnitude	PGA (g)		Housner intensity (cm)		Cosenza-Manfredi Index		Significant Duration (sec)		Predominant Period (sec)	
(id)		(km)	(ML)	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W
1a	24/08/2016 (01.36)	62.81	6.0	0.079	0.072	21.54	20.43	10.12	7.22	13.26	15.51	0.14	0.14
1b	24/08/2016 (02.33)	51.99	5.4	0.015	0.017	2.79	2.67	22.21	21.41	16.01	15.30	0.14	0.14
2a	26/10/2016 (17.10)	42.29	5.4	0.046	0.030	5.08	4.37	18.38	20.14	12.43	16.28	0.14	0.14
2b	26/10/2016 (19.18)	38.34	5.9	0.238	0.125	43.48	33.80	6.85	12.63	6.86	9.95	0.30	0.34
3	30/10/2016	46.23	6.1	0.122	0.075	21.33	17.48	18.26	21.29	13.66	20.43	0.16	0.14
4a	18/01/2017 (09.25)	80.73	5.3	0.009	0.031	2.51	2.36	24.40	6.50	17.13	17.62	0.16	0.14
4b	18/01/2017 (10.14)	83.03	5.4	0.007	0.007	2.50	1.84	15.55	14.48	18.69	15.76	0.14	0.14
4c	18/01/2017 (10.25)	87.46	5.3	0.007	0.007	1.71	1.63	28.03	20.22	19.02	19.65	0.14	0.14
4d	18/01/2017 (13.33)	88.58	5.1	0.007	0.006	1.70	1.32	19.87	18.30	15.84	18.61	0.14	0.14

It is noted that the strongest seismic event recorded on October 26, at 7h18 pm (UTC) was the North-South component. During the latter event also the RAN station in Tolentino measured the highest value of horizontal PGA. During the first seismic event, i.e. 24th August 2016, the maximum horizontal PGAs were 0.07g in both North-South and East-West direction. The 30th October earthquake also caused a maximum horizontal PGA in Matelica equal to 0.122g in the North-South direction. The acceleration strong motions measured in 2017 are negligible, that is lower than 0.01g. The highest value of the Housner intensity also refers to the 2b event, with values equal to 43.48cm and 33.80cm along the North-South and the East-West direction, respectively. The Cosenza-Manfredi index computed for the sample strong motions tends to be higher than the counterpart values estimated for the records of the accelerometric station placed in Tolentino and reported in Tab. 4.2.1. As for the Cosenza-Manfredi index, the highest values were not found for the 26th October seismic event. The highest values, i.e. the strong motion with largest number of cycles, were computed for the 18th January earthquake. This could be ascribed to near-field effects, i.e. lower number of cycles of the recorded strong motion, that may cause lower values of the Cosenza-Manfredi index computed for the 26th October.
The predominant periods of the sample earthquake records vary between 0.14s and 0.34s, thus structural systems with fundamental periods of vibration close to the above values may experience resonance. The structural system of the San Severino hospital has different blocks, as displayed in Fig. 4.2.2. Building C, which is a 2-storey RC structure, may exhibit a fundamental period of vibration close to the predominant periods of the recorded accelerograms. The maximum relative displacements were recorded at the interface between Building C and Building D, where the damage has been detected as better discussed hereafter.
The comparison of the elastic acceleration response spectrum of the strong motions summarised in Tab. 4.2.2 and the relevant code based spectra computed for soil types B and C (with the same return periods as for Tolentino site), for the location of the San Bartolomeo Eustachio hospital buildings, shows that the computed spectral pseudo-accelerations are lower than the code base values for the E-W component but significantly high for the N-S component. More remarkably than for Tolentino recording station, the horizontal response spectrum leads to values of spectral accelerations that are high for RC structures designed primarily for gravity loads, as the blocks of the sample hospital.



a) b)

Fig. 4.2.4 - Pseudo-acceleration response spectrum functions of three main earthquakes for the Matelica site (16.4 km from San Severino Marche) for: a) E-W direction, b) N-S direction and code-based design response spectrums.

For many vibration period values, the design spectra for the SLD limit state are exceeded in both the horizontal components by the seismic events, thus remarking the good performance of this hospital as surveyed.

Observed damage

A full survey of the San Bartolomeo Eustachio hospital buildings was carried out in the aftermath of the 24th August 2016 and 26th October 2016 earthquakes. The AeDES form was compiled during the survey. In general it was observed that the structural systems experienced mainly non-structural damage, although it was not heavy and was primarily concentrated along the width of Building D, at top floors, as displayed in Figure 4.2.5.

Fig. 4.2.5. Non-structural damage observed along the partitions and the infills of the upper floors of building block D.

The extent of light non-structural damage was limited, as it interested a low number (less than 1/3 of the total) of partitions and infills. However, due to the occupancy type of the rooms, during the on-site visit, it was suggested to prevent the use of the rooms where light damage was detected. Additionally, to recover the full functionality of Block D of the hospital, it was suggested to repair the light cracks injecting adequate resin.

During the survey carried out in the aftermath of the 24th August 2016 earthquake, an evident damage was detected between the Block C and Block D. The adjacent RC framed structures were connected with Gerber saddles, which create discontinuity between the adjacent structures (*see* Fig. 4.2.6). Blocks C and D have different height (see also Table 4.2.1), thus relative displacements occurred under horizontal seismic forces at the location of the saddles, which, in turn, generated vertical cracks in the plaster. Initially it was believed that the cracks were caused by shear effects in beams. A close investigation of the cracking pattern and the removal of the covering plaster showed that significant hammering between the adjacent framed structures did not occur. The maximum relative displacements at the location of the saddles were accommodated by the 2.5cm thick polystyrene sheet. It is worth noting that the polystyrene was covered by the plaster and there was no joint cover, for this matter a misunderstanding in crack evaluation occurred before plaster removal.

Fig. 4.2.6. Damage observed at the location of the Gerber saddle between building Blocks C and D.

The analysis of the surveyed building blocks of the San Bartolomeo Eustachio hospital shows that the higher EM98 damage level is D1, with an extension less than 1/3. D1 damage was experienced by Building Blocks C and D while, as for the remaining buildings, damage is absent or negligible (D0 level).
The hospital complex remained operational after the seismic sequence of August and October 2016. The limited damage occurrence was localized at the ground floor of the administrative offices, which were temporarily closed to perform the above-mentioned interventions of structural repair at the saddles. The damaged partitions at the upper floors of Block D were repaired in the aftermath of the 24^{th} August earthquake.

Application of the WHO procedure

The WHO procedure for the seismic assessment of hospitals was applied also to the San Severino Marche Hospitals by estimating the Safety Index (I_{STR}) for Blocks A, B, C and D. A rough estimation of the capacity-to-demand ratio C/D, i.e. the coefficient S = (1 - Safety Index) is also computed. The values of I_{STR}, i.e. 0.20 for both Blocks C and D, leads to S=0.8, which means that the seismic vulnerability of the sample blocks can be assumed as low. The remaining building blocks, i.e. A and B, have S=1.0, i.e. their seismic vulnerability is very low. Therefore, San Severino hospital (whose buildings were all designed only for gravity loads) shows higher values of the S coefficient with respect to Tolentino hospital, even though the ERD level is practically the same. This result is determined by the presence of stiff and resistant shear walls in the San Severino hospital buildings and by the apparently better material quality in particular referring to concrete. This can explain why much less damage has been observed for San Severino hospital, despite a possibly higher felt seismic action (compare figs 4.2.4 and 4.1.4).

CONCLUDING REMARKS

The seismic sequence occurred across 2016-2017 in Central Italy demonstrated, once again, the seismic vulnerability of healthcare facilities. After the 24 August 2016 event, hospitals of small-medium capacity partially or totally lost their serviceability forcing to move the inpatients to other hospitals during the first phases of the emergency management, while facing additional problems due to the medium/severe damage affecting the roadway network. The subsequent events, heavily worsened the situation, aggravating the physical damage and structural impacts, when hospital managers were in the process of planning actions for restoring the full capacity of their facilities. A reconnaissance campaign was carried out by the authors by means of several surveys in the most important healthcare facilities for which they were able to fill out the AeDES form, for post-earthquake damage and usability assessment. As a result of the three main events, referring to the infrastructures more detailed in this paper, two hospitals (i.e. Amatrice and Amandola) were declared totally unusable, one (i.e. Tolentino) resulted almost totally unusable, and a further one (San Severino) suffered minor damage preserving its serviceability throughout the entire seismic sequence. In the case of Amatrice hospital, extensive damage significantly involved structural components, as a result of the high vulnerability of the building with masonry structure. Moreover, damage mainly to architectural components was found to the RC building. As a consequence of the 24th August seismic event, the Amandola hospital suffered damage mainly to architectural components like infill and partitions of the two more recent RC buildings, forcing to close them. The event occurred on October 2016 worsened the damage to the masonry buildings forcing to close the entire complex. As for Tolentino hospital, the closure was essentially caused by structural damage. Especially the events of August and October progressively caused the closure of the three main buildings. In addition to the high vulnerability of RC and masonry structures designed without seismic provisions during periods when seismic classification had not yet been introduced, the lack of attention to non-structural components, like infills and partitions, has been clearly shown by significant damage found also in recently constructed buildings. Moreover, the survey highlighted the limits and the weaknesses of heterogeneous hospital facilities. Indeed, they grew in agreement with the healthcare demand in the surrounding area. As a result they are hospital complexes with buildings characterized by differently expected seismic performances, where the functionality of the earthquake-resistant designed buildings might be compromised by the severe damage suffered by the more vulnerable buildings. This observation leads to the consideration that to guarantee the post-earthquake functionality of hospital complexes it is necessary to assure a uniform seismic capacity among the different buildings included in the complexes, as well as among the structural and non-structural components within each building. This should be adequately taken into account in defining priorities and sequence of the progressive strengthening program of single buildings belonging to whole hospital complexes. Further, in the design of the strengthening intervention within each building, it is advisable to target a similar level of performance for both structural and non-structural components. As a matter of fact, architectural non-structural components behaved very badly. Particularly, entire external coatings overturned, or were about to overturn, demonstrating that even in recently designed hospitals poor attention has been given to these components.

As far as the two case studies are concerned, even though most of their buildings were not provided with any seismic provision, due to their construction period, San Severino hospital performed much better that Tolentino hospital due to a stiffer and resistant structural system made of RC walls able also to reduce torsional effects. Regarding the reliability of simplified tools, such as the WHO Safety Index, for the relative estimation of seismic risk level for hospital facilities, this analysis showed that, somehow, relative sorting of hospital buildings' seismic risk can be reasonably predicted, even though absolute risk values are not in line with what could be obtained from detailed assessments. Moreover, the WHO Safety Index procedure seems to totally neglect the aforementioned critical feature of heterogeneous hospital complex, namely the external (or induced) risk, for which a safe and undamaged building could be declared unusable only because of its proximity to damaged buildings.

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