Survey of churches damaged by the May 2012 Emilia-Romagna earthquake sequence

Paupério, E.[1], Romão, X.[2], Tavares, A.[3], Vicente, R.[4], Guedes, J.[5], Rodrigues, H.[6], Varum, H.[7], Costa, A.[8]

[1] *Construction Institute, Faculty of Engineering of the University of Porto, Porto, Portugal; pauperio@fe.up.pt*

[2] *Faculty of Engineering of the University of Porto, Porto, Portugal; xnr@fe.up.pt*

[3] *Faculty of Engineering of the University of Porto, Porto, Portugal; tavares.c.alice@ua.pt*

[4] *University of Aveiro, Aveiro, Portugal; romvic@ua.pt*

[5] *Faculty of Engineering of the University of Porto, Porto, Portugal; jguedes@fe.up.pt*

[6] *University of Aveiro, Aveiro, Portugal; hrodrigues@ua.pt*

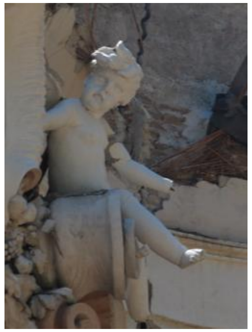
[7] *University of Aveiro, Aveiro, Portugal; hvarum@ua.pt*

[8] *University of Aveiro, Aveiro, Portugal; agc@ua.pt*

Cite as:
Paupério, E., Romão, X., Tavares, A., Vicente, R., Guedes, J., Rodrigues, H., Varum, H., Costa, A. (2012) Survey of churches damaged by the 2012 Emilia-Romagna earthquake sequence. Faculty of Engineering of the University of Porto and University of Aveiro, Portugal. Available at https://dl.dropbox.com/u/8147292/FEUP_UA_Emilia-Romagna_earthquake_report.pdf

Table of Contents

1. Introduction



This report presents an overview of the damage that was observed in fourteen churches that were hit by the May 2012 Emilia-Romagna earthquake sequence. The data was collected over the course of a two-day reconnaissance mission that took place on the 9th and 10th of July 2012, and that involved researchers from the Civil engineering Department of the Faculty of Engineering of the University of Porto and of the University of Aveiro, both institutions from Portugal.

It is noted that the current report only focusses the post-seismic damage assessment of churches and does not address the cultural and artistic losses associated to movable or immovable heritage. Furthermore, it is also referred that since the reconnaissance mission took place after the major earthquakes of the 20th and the 29th of May, the source of the reported damages is not assigned to a particular event and must be seen as the cumulative effect of several ground motions.

2. Brief review of the 2012 Emilia-Romagna earthquake sequence

On the 20th of May 2012, at 04:04 (local time), a magnitude $M_w = 5.9$ earthquake hit the Emilia-Romagna region of northern Italy. The epicentre was found to be approximately 30km northwest of Ferrara (Fig. 1) and the depth of the hypocentre was found to be around 6km. The focal mechanism indicates that the earthquake was a result of thrust faulting, with a north-south direction of compression, on a fault plane trending west-east (USGS, 2012). This earthquake resulted in 7 deaths, significant damage to historical constructions, churches and industrial buildings. The 20th of May event was followed by several aftershocks, namely two with a magnitude M_w higher than 5.0 on the same day.

On the 29th of May 2012, at 09:00 (local time), a magnitude $M_w = 5.8$ earthquake hit the same region. The epicentre of this new event was determined to be approximately 40km west of Ferrara, around 15km southwest of the epicentre of the 20th May event (Fig. 1), and the depth of the hypocentre was found to be around 10km. This earthquake had a similar mechanism to that of the 20th May event. This new earthquake caused further damage to the locations hit by the 20th May earthquake and extended the affected area to the East-side of the province of Modena. This event resulted in another 17 deaths and increased the level of damage of the historical constructions, churches and industrial buildings already weakened by the 20th May event. The 29th May event was followed by several aftershocks, namely three with a magnitude M_w higher than 5.0, two on the same day and another on June 3.

According to data from the Italian *Istituto Nazionale di Geofisica e Vulcanologia*, peak ground accelerations of around 0.30g were recorded in the vicinity of both epicentres (INGV, 2012).

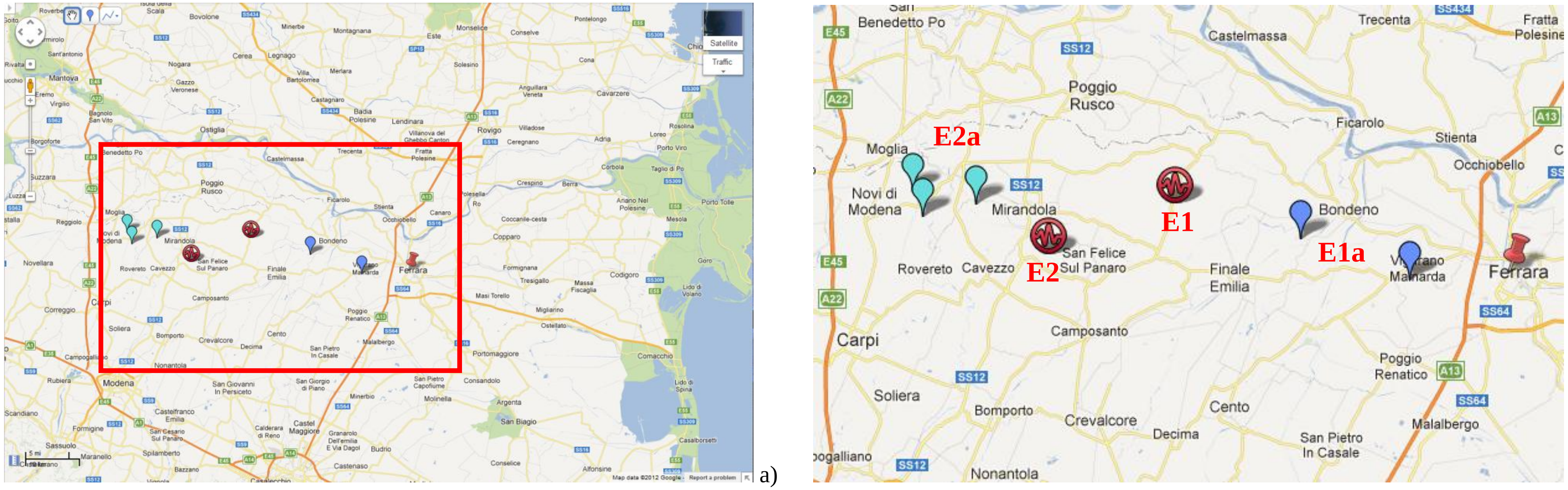


Fig. 1 – Location of the epicentres of the main events of the Emilia-Romagna earthquake sequence: general overview (a); detailed view (b): E1) earthquake of the 20th May, E1a) aftershocks of the 20th May earthquake with magnitude $M_w > 5.0$, E2) earthquake of the 29th May, E2a) aftershocks of the 29th May earthquake with magnitude $M_w > 5.0$.

3. Context of the presented church damages

The damage assessment that was carried out on fourteen churches surveyed during the reconnaissance mission is presented in the following. The churches that were surveyed are presented in Table 1 and their location relative is represented in Fig. 2.

Table 1 – Churches surveyed.

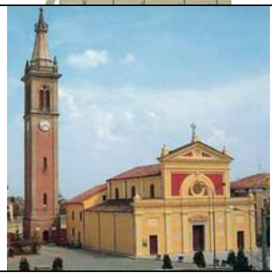
Reference number	Name	Location	Undamaged church	Reference number	Name	Location	Undamaged church
I1	Cathedral of San Paolo	Mirabello		I2	Oratorio Ghisilieri	San Carlo	
I3	Church of San Martino	Buonacompra		I4	Church of San Lorenzo	Casumaro Finalese	
I5	Church in Bondeno	Bondeno		I6	Church of Sacro Cuore	Bondeno	
I7	Church of San Geminiano Vescovo	Massa Finalese		I8	Church of Santa Maria Maggiore	Mirandola	

Table 1 (continued) – Churches surveyed.

Reference number	Name	Location	Undamaged church	Reference number	Name	Location	Undamaged church
I9	Church of San Francesco	Mirandola		I10	Church of SS Apostoli Giacomo e Filippo	San Giacomo di Roncole	
I11	Church of Montalbano	Montalbano, Medolla		I12	Church of Cavezzo	Cavezzo	
I13	Church of San Nicola di Bari	Cortile, Carpi		I14	Cathedral of Santa Maria Assunta	Carpi	

Fig. 2 – Location of the churches surveyed with respect to the main events of the Emilia-Romagna earthquake sequence.

The surveys are presented in the form of visual damage report worksheets that are included in the end of this report. For churches that were more heavily damaged, the damage report worksheets only present the more significant damages. The damage report worksheets also include additional information such as:

- The church identification (name, location, GPS coordinates)
- The period of construction of the church
- The main dimensions of the church (and of the tower if it exists)
- The materials of the main construction elements
- The type of access that was available for the survey
- The overall damage state of the church
- The type of emergency interventions that were already in place (if any)

Aside from a few exceptions, the surveys were generally performed from the exterior. Therefore, the presented damage levels should be seen as mainly qualitative. The damage grading was carried out for all the churches using the list of damage types presented in Table 2. The Italian postearthquake damage survey form, e.g. see Lagomarsino (2012), and its corresponding list of damage mechanisms, was not considered in this analysis due to difficulties in identifying such mechanisms as the result of two aspects:

- The available access for the survey was rather limited in most cases.
- The level of damage exhibited by most churches results from the cumulative effect of more than one major earthquake event.

Table 2 – List of considered damage types.

Damage type	Damage number
Cracking	D1
Collapse of the facade (partial or total)	D2
Collapse of the roof/vaults (partial or total)	D3
Collapse of walls (partial or total)	D4
Out-of-plane detachment of walls	D5
Detachment of the outer layer of masonry	D6
Masonry crushing at the tie rod anchorage	D7
Masonry crushing in compression	D8
Pounding	D9
Fall of spire (facade/tower)	D10
Collapse of the tower (partial or total)	D11
Collapse of reinforced concrete elements	D12

For each church, only the more important damage types are reported, based on the *in situ* observations. The intensity of each damage type was then graded as *Low*, *Medium* or *High*. Based on the individual grading of the damage types, the global state of damage of each church was also graded as *Low*, *Medium* or *High*.

4. General characterization of the churches surveyed

The churches and towers surveyed are mostly made of brick masonry. The different brick masonry bonds of the masonry walls that were observed among the existing debris of some of the churches are presented in Figs. 3 to 8. The bond type of Fig. 3 represents an example of single header bond masonry along with the corresponding sketch of the bond type according to Borri (2006). The block dimensions of this wall are $28 \times 14 \times 3.5$ cm according to *in situ* measurements.

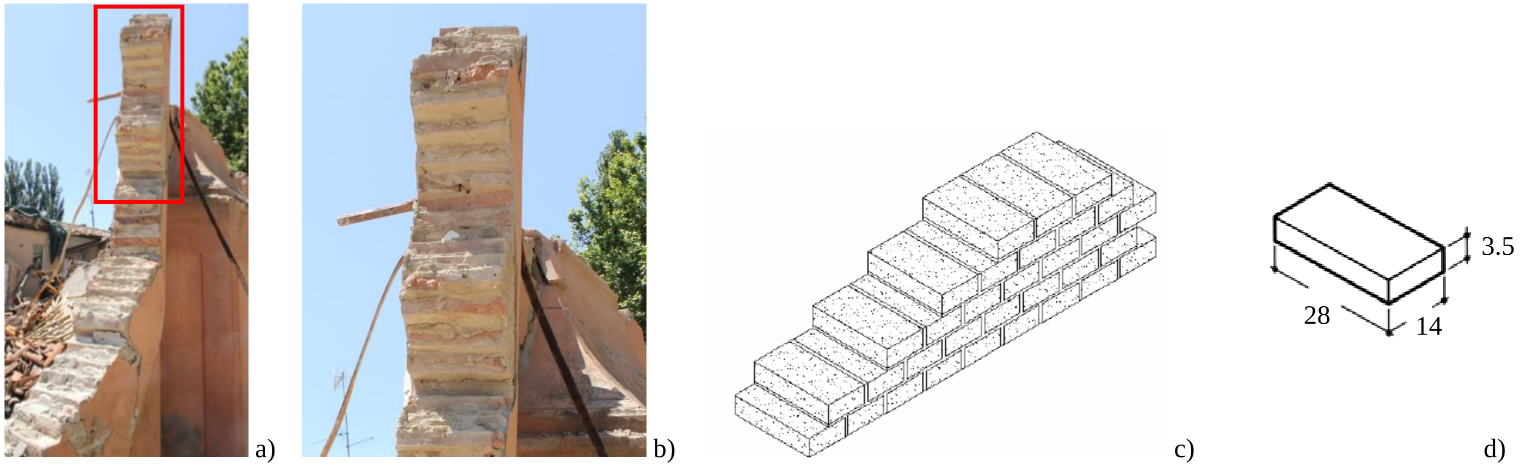
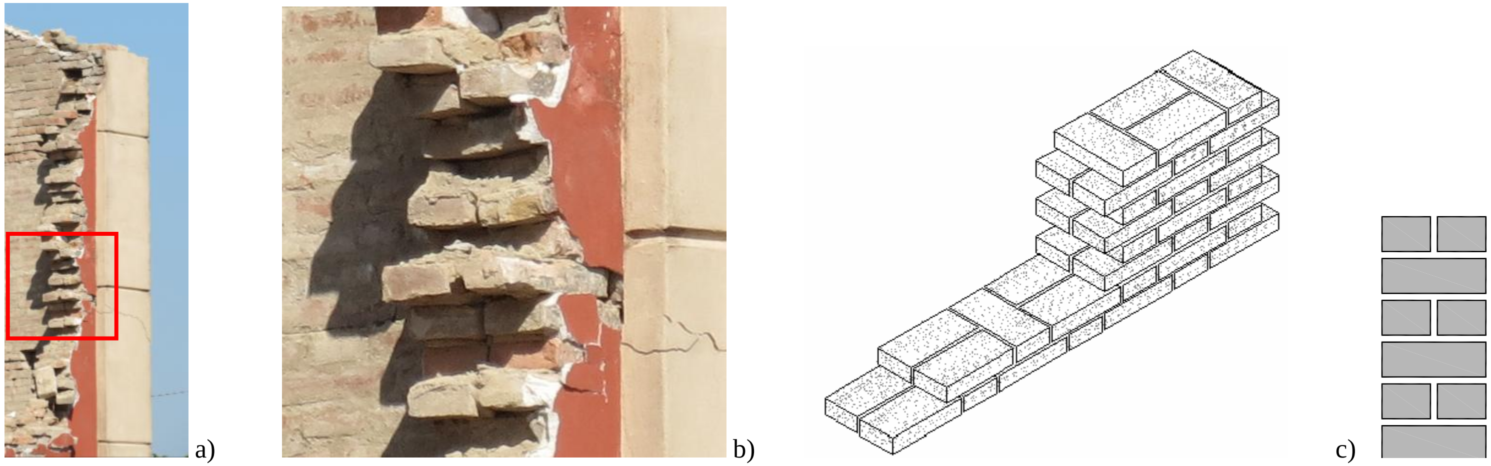


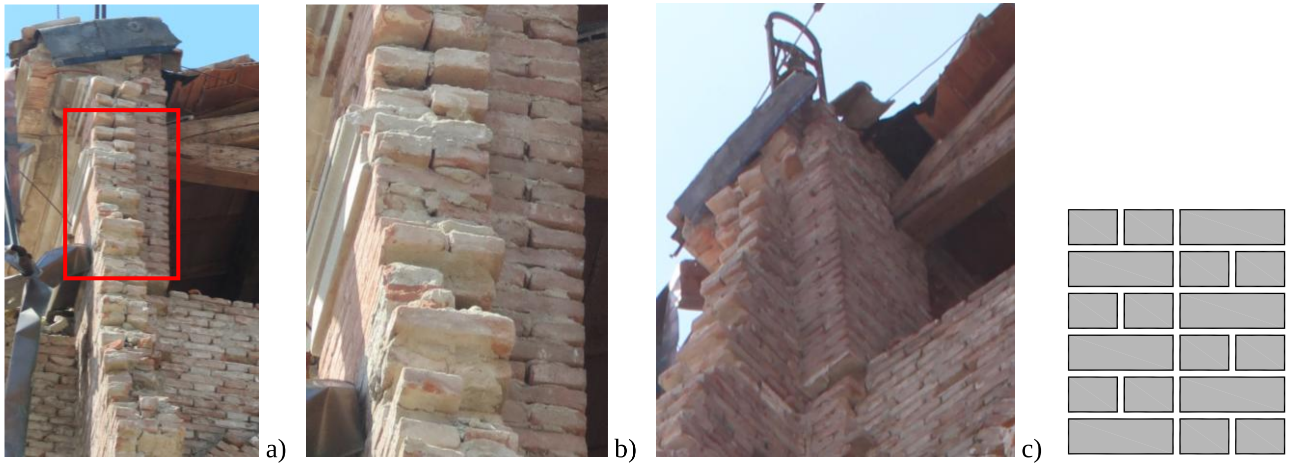
Fig. 3 – Single header brick masonry bond in church I2: general view (a), detail (b) and sketch of the bond type adapted from Borri (2006) (c), brick dimensions in cm.

The bond type of Figs. 4 and 5 is a double header bond masonry similar to the Flemish bond and was observed in churches I1 and I3. Figure 4 also presents a sketch of the bond type according to Borri (2006) and a sketch of the cross section view of the wall. In this case, the brick dimensions were not able to be measured. In church I1, it was also observed that the region of the timber truss supports was reinforced by duplicating the wall, Figs. 5b) and c). Although it was not able to be observed, it is believed that both walls must be connected to the truss by timber or metallic elements.



a) b) c) d)

Fig. 4 – Double header brick masonry bond in church I3: general view (a), detail (b), sketch of the bond type adapted from Borri (2006) (c) and sketch of the cross section view of the wall (d)

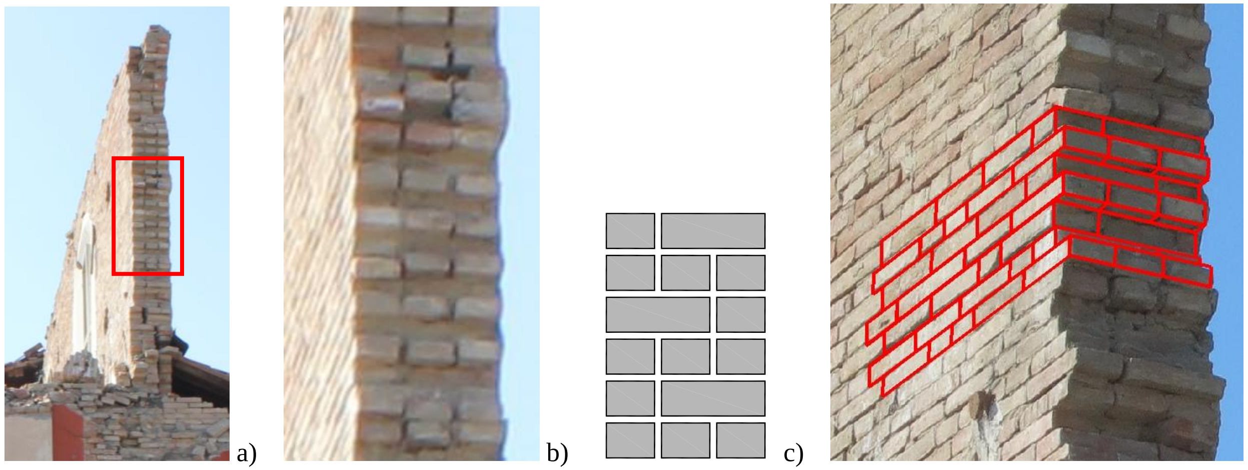


a) b) c) d)

Fig. 5 – Double wall made of double header brick masonry bond in church I1: general view (a), detail (b), view from the back side which supports a timber truss (c) and sketch of the cross section of the duplicated wall in the region of the truss support (d).

The bond types of Figs. 6 and 7 are examples of triple header masonry bonds. The several examples that were observed show the existence of different triple header bonds. Figure 6 presents an example of a more regular bond found in church I3, as can be seen from the pattern of the cross section view of Fig. 6c). However, the side view of Fig 6d) shows the inexistence of a regular pattern over the several courses of masonry. Figure 7 presents another example of this type of masonry bond also from church I3.

The examples of triple header masonry bonds presented in Fig. 8 were found in churches I9 and I10 and represent cases of a more irregular bond of this type. As can be seen, both the cross section views and the side views show the inexistence of a regular pattern. Furthermore, it is noted that, according to the detail of Fig. 8d), this irregularity promotes the detachment of the three leaves in some localized regions of the wall.



a) b) c) d)

Fig. 6 – Example of a triple header brick masonry bond in church I3, general view (a), detail (b), sketch of the cross section view of the bond type (c) and highlighted detail of the side and the cross section view of the bond type (d).

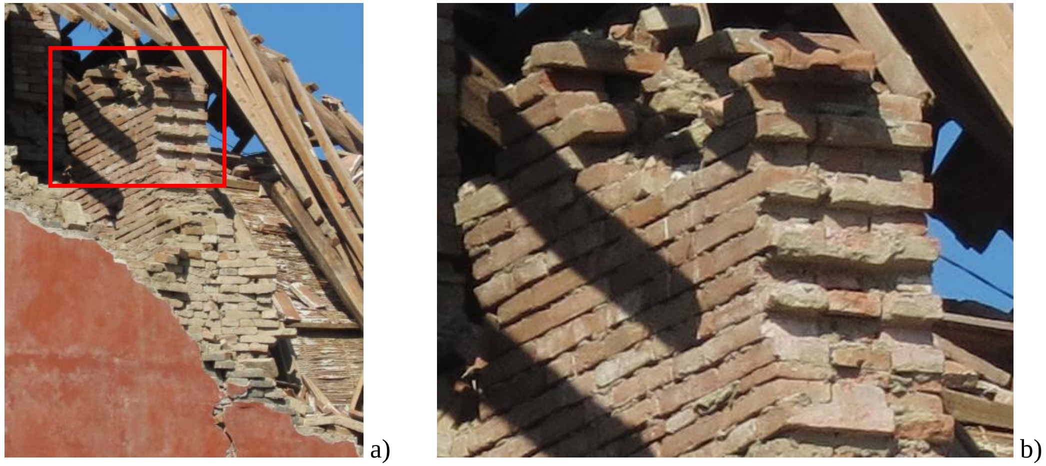
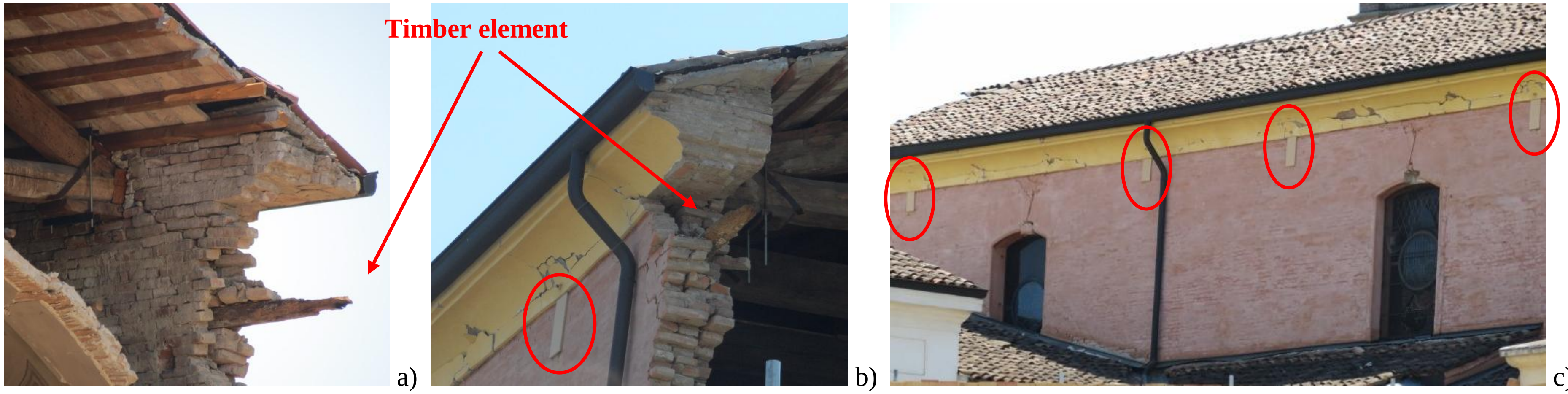


Fig. 7 – Example of regular triple header brick masonry bond in church I3, general view (a) and detail (b).

Fig. 8 – Irregular triple header brick masonry bond in church I9, general view (a) and detail (b), and in church I10, general view (c) and detail (d), and sketch of the highlighted part of the cross section bond (e).

With respect to the walls, it is also referred that, in church I10, timber elements were found inside the triple header masonry lateral walls in the anchorage region of the tie rods with the purpose of enhancing their efficiency (Fig. 9).



a) b) c)

Fig. 9 – Timber elements inside the walls of church I10 to enhance the efficiency of the tie rods, (a) and (b), and exterior view showing the tie rod anchoring plates (c).

The roof structure of the churches was generally seen to consist of timber trusses (Fig. 10). Timber battens run transversal to the trusses over which there is a roof sheeting made of masonry elements, either hollow, Fig. 11a), or solid, Fig 11b). The roof tiles are then fixed to this masonry sheeting by mortar, Fig. 11b).

Fig. 10 – Examples of roof structures made of timber trusses in churches I9 (a), I10 (b) and (c), I3 (d), and I1 (e).

 a)  b)

Fig. 11 – Example of roof sheeting made of hollow masonry elements in church I9 (a), and made with solid masonry elements in church I3 (b).

Three types of vaults were observed in the churches: vaults made of brick masonry laid flatwise (Fig. 12), reed mat false vaults hanging from the roof timber trusses (Fig. 13), and vaults made of timber elements imbedded in mortar/plaster (Fig. 14).

Fig. 12 – Examples of vault structures made of brick masonry laid flatwise in church I1.

a) b) c) d)

Fig. 13 – Examples of reed mat false vaults in churches I2 (a) and I10 (b) and (c), and detail of a reed mat (d).

Fig. 14 – Example of a vault made of timber elements imbedded in mortar/plaster in church I11.

With respect to the arches, those that were able to be observed were made of vertically stacked brick masonry (Fig. 15). The interior columns that were surveyed were also seen to be made of brick masonry (Fig. 16).

Fig. 15 – Examples of arches made of vertically stacked brick masonry in church I1.

Fig. 16 – Example of an interior column made of brick masonry in church I1.

Finally, it is also referred that in church I1, the debris of a collapsed reinforced concrete element were found. The debris are believed to be part of a large reinforced concrete beam that existed over the transept area (Fig. 17). As can be seen, the beam reinforcement was made of smooth rebars and the transverse reinforcement was almost inexistent. It is also noted that the beam appeared to be supported by the brick masonry walls.

Fig. 17 – Collapsed reinforced concrete beam in church I1.

Whenever possible, general dimensions of the churches and towers were measured (Fig. 18). However, since the surveys were performed from safe positions, such dimensions should be considered to be approximate. Additional measures and data were also obtained from Decanini *et al.* (2012), Ioannou *et al*. (2012) and Rossetto *et al.* (2012).

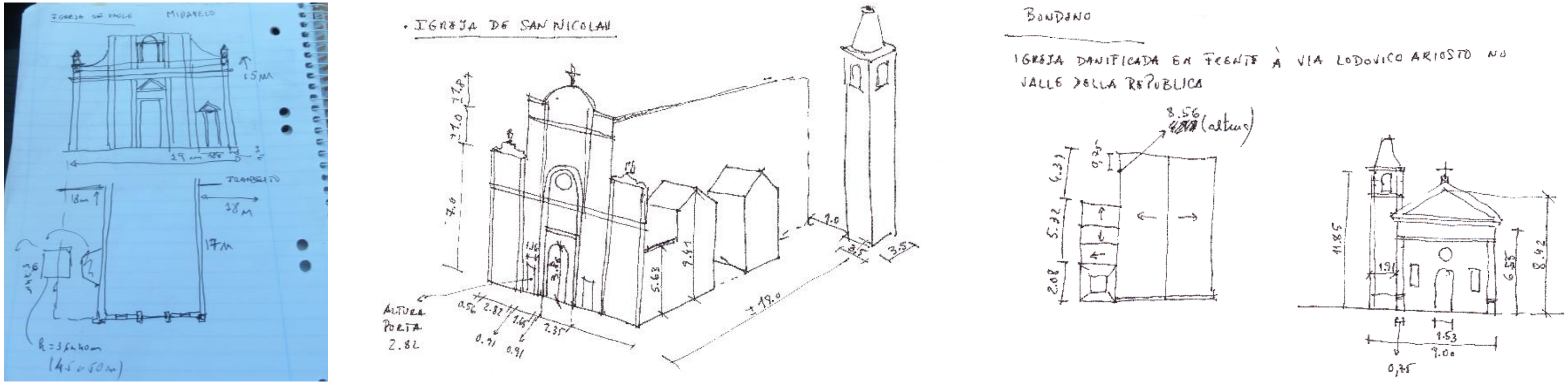


Fig. 18 – Examples of general dimension surveys carried out for the churches and towers.

5. Emergency interventions

With respect to the emergency interventions that were observed in some of the churches, these were grouped according to the typologies presented in Table 3. Nonetheless, information was also obtained regarding some churches in which elements were either removed or demolished for safety reasons. For example, it was found that the tower of church I3 was demolished after the 20th May earthquake while the spire of the tower adjacent to church I1 was removed from its location also after the 20th May earthquake.

Table 3 – List of considered emergency intervention types.

Emergency intervention type	Emergency intervention number
Steel raker shoring of walls	i1
Wood raker shoring of walls	i2
Wood shore at the openings	i3
Confinement of the facade with steel cables	i4
Confinement of the tower	i5
Confinement of the frontispiece with polyester-nylon strips	i6
Confinement of the spire with polyester-nylon strips	i7

Acknowledgements

The authors would like to thank the financial support of the Portuguese Foundation for Science and Technology and the *Centro de Estudos da Construção* research centre of the Civil Engineering Department of the Faculty of Engineering of the University of Porto for sponsoring their participation in this reconnaissance mission. The authors would also like to thank don Giancarlo Mignardi, priest of the church of San Carlo, for the information provided and Manuel Carvalho for his help in preparing the church damage report worksheets.

References

Borri, A. (2006) Allegato 3b.1_UR06_2. Progetto di recerca Nº1, Valutazione e Riduzione della Vulnerabilità di Edifici in Muratura, Rendicontazione Scientifica 1º anno. Rete dei Laboratori Universitari di Ingegneria Sismica (RELUIS).

Decanini L.D., Liberatore D., Liberatore L., Sorrentino L. (2012) Preliminary report on the 2012, May 20th, Emilia earthquake. v.1. Available at http://www.eqclearinghouse.org/2012-05-20-italy-it/ (Accessed July 2012).

INGV (2012) Istituto Nazionale di Geofisica e Vulcanologia. Available at http://terremoti.ingv.it/it/ultimi-eventi/842-terremoti-in-pianura-padana-emiliana.html (Accessed July 2012).

Ioannou, I., Borg, R., Novelli, V., Melo, J., Alexander, D., Kongar, I., Verrucci, E., Cahill, B., Rossetto, T. (2012) The 29th May 2012 Emilia Romagna Earthquake. EPICentre Field Observation Report No. EPI-FO-290512. Available at http://www.eqclearinghouse.org/2012-05-20-italy-it/ (Accessed July 2012).

Lagomarsino, S. (2012) Damage assessment of churches after L'Aquila earthquake (2009). *Bulletin of Earthquake Engineering* **10**(1), 73-92.

Rossetto, T., Alexander, D., Verrucci, E., Ioannou, I., Borg, R., Melo, J., Cahill, B., Kongar, I. (2012) The 20th May 2012 Emilia Romagna Earthquake. EPICentre Field Observation Report No. EPI-FO-200512. Available at http://www.eqclearinghouse.org/2012-05-20-italy-it/ (Accessed July 2012).

USGS (2012) M 6.0, 5.8, and 5.4 Northern Italy Earthquakes of May 2012. ftp://hazards.cr.usgs.gov/maps/sigeqs/20120529/20120529.pdf (Acessed July 2012).