

INTEGRATED DATING OF THE CONSTRUCTION AND RESTORATION OF THE MODENA CATHEDRAL VAULTS (NORTHERN ITALY): PRELIMINARY RESULTS

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ABSTRACT. After the last damaging earthquake in 2012, an anti-seismic reinforcement project of the cathedral of Modena was designed giving us the opportunity to investigate and date the building materials. Radiocarbon (¹⁴C), optically stimulated luminescence (OSL), and thermoluminescence (TL) dating techniques were performed on the vaults with the aim to (1) clarify the construction timing, (2) define the history of the restorations, and (3) explore the possible correlation of the main restoration works to the earthquake chronology deduced from the historic catalog. Preliminary results show that medieval older bricks were reused for most of the original construction. Only lime and non-gypsum mortar was used for the original construction in the 15th century and for later repair of damage caused by earthquakes in the 16th and 17th centuries. Gypsum mortar was used for later repair in the 18th century. The results show much stronger damage due to earthquakes than previously thought.

KEYWORDS: ¹⁴C AMS dating, heritage, mortar, OSL, TL.

INTRODUCTION

The seismic event that hit the Emilian plain in 2012 caused extensive damage to the region's historical and artistic heritage (Decanini et al. 2012; Dolce et al. 2012; Indirli et al. 2012; Andreini et al. 2014; Graziani et al. 2015). The condition of the UNESCO World Heritage Site of Modena, and in particular the cathedral vaults, was alarming (Baraccani et al. 2015; Baraccani et al. 2017; Baraccani et al. 2019). An anti-seismic reinforcement project was planned with the aim of determining the vulnerability of the cathedral and analyzing the damage suffered in the past. Since historical documents leave unclear issues regarding the chronology of the construction phases, absolute dating of building materials represents the only way to obtain reliable data. The study and dating of the building materials of the cathedral were previously carried out by analyzing other parts of the building (Lubritto et al. 2015; Panzeri et al. 2019).

The construction phases of the Modena cathedral are a subject for discussion (Silvestri 2013), but the vaults were progressively added to the main framework during the 15th century (Dondi 1896; Baracchi and Giovannini 1988; Baracchi 1993).

Our survey carried out on the extrados (upper/convex surface) of the vault revealed unexpected data: the vaults were built using either a gypsum or a lime binder and carry the scars of several earthquakes, repaired using different binders, which resulted in a complex patchwork of lime and gypsum mortars (Figure 1).

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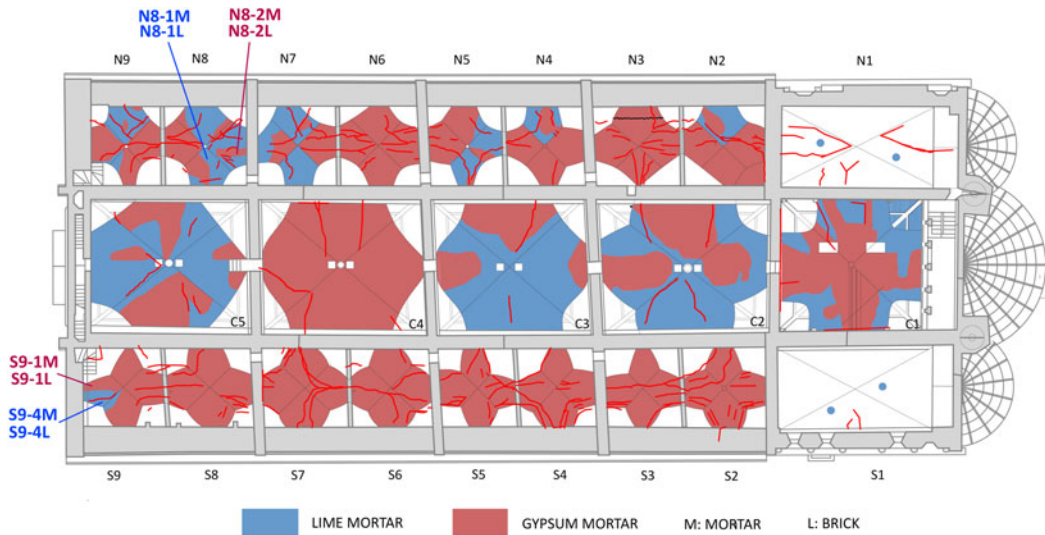


Figure 1 Modena Cathedral: vaults extrados plan with sampling points of the vaults S9 and N8. (Please see electronic version for color figures.)

The main objectives of the project were to date the original vaults' construction, restoring portions built after the main earthquakes and correlating them to the earthquake chronology deduced from the historic catalog (Rovida et al. 2016). Several damaging, moment magnitude (M_w) and high peak ground acceleration (PGA) value earthquakes occurred after the vaults were constructed, with epicenters located in various areas during the following years: 1474 (Modena, M_w 4.30, PGA 0.232), 1501 (Emilian Apennines, M_w 5.82, PGA 0.187), 1505 (Bologna, M_w 5.41, PGA 0.055), 1584 (Tuscan-Emilian Apennines, M_w 5.99, PGA 0.025), 1586 (Spilamberto, M_w 4.53, PGA 0.091), 1660 (Modena, M_w 4.25, PGA 0.172), 1671 (Rubiera, M_w 5.23, PGA 0.110), 1688 (Romagna, M_w 5.85, PGA 0.028), 1828 (Staffora Valley, M_w 5.55, PGA 0.012), and 1850 (Modena, M_w 4.53, PGA 0.144).

We applied an integrated approach using three different techniques to date the construction of the vaults' repair phases: radiocarbon (^{14}C) of mortars by sequential dissolution (Lindroos et al. 2018), optically stimulated luminescence (OSL) of the mortar sand aggregate, and thermoluminescence (TL) of the bricks bound by the analyzed mortars (Panzeri et al. 2019). This paper reviews the preliminary results from two vaults (Figure 1).

MATERIALS AND METHODS

Petrographic Analysis

The mortar samples were consolidated with epoxy resin in order to obtain thin sections for optical microscope observations. The UNI-Normal 11176 document was used as reference for the petrographic characterization of mortar in order to determine the aggregate composition, the grain size and the texture, the type of binder, the presence of underburned and overburned limestone fragments and "lime lumps" (Nawrocka et al. 2005; Elsen 2006; Pesce et al. 2012; Michalska and Pawlyta 2019).

Image analysis of thin sections was also carried out to evaluate the binder/aggregate ratio, the aggregate grain size (Carò and Di Giulio 2004; Hayen et al. 2017; Michalska et al. 2017), and for the identification of the supply sources of the aggregate (Lugli et al. 2007).

¹⁴C Dating of Mortars: Sequential Dissolution

Two lime mortar samples from the vaults N8 and S9 were prepared for ¹⁴C dating following the sequential dissolution methodology. This procedure is fundamental in order to identify the contaminants that could occur in historic mortar. Underburned limestone fragments and carbonate aggregate could contaminate the ¹⁴C dating results and provide older ages, while a rejuvenation effect can be induced by the presence of secondary calcite within the calcareous binder, produced by later exchange with the atmospheric CO₂. The dissolution method is described in detail in Lindroos et al. (2007). The bulk mortars were carefully crushed and dry sieved into decreasing grain-size fractions ranging between 75–500 µm. The grain-size fraction <100 µm was subsequently wet sieved and, since the dissolution time decreases with grain size, a narrow grain-size window (46–75 µm) was isolated and dried for ¹⁴C dating. After the mechanical separation, cathodoluminescence (CL, see e.g. Marshall 1988) analysis was carried out to identify the possible contaminants from limestone grains added in the aggregate sand and the alkalinity test with phenolphthalein (1%) dissolved in alcohol was performed on the coarser grain size fraction (301–500 µm). An alkaline reaction may indicate the presence of calcium hydroxide, which will react with the modern CO₂ in the atmosphere, leading to a younger age. Therefore, alkaline samples are rejected for AMS dating.

The chemical separation was done in a vacuum system with 85% phosphoric acid in order to release CO₂ for dating. The mortar sample S9-4M was analyzed in two CO₂ fractions, while the ¹⁴C dating of the sample N8-1M was performed only on a soft lime lump (Pesce et al. 2012) crushed before hydrolysis and analyzed in two CO₂ fractions.

The vials containing CO₂ gas were submitted to the AMS ¹⁴C Dating Centre at Aarhus University and ETH Zurich. The conventional ¹⁴C dates were calibrated using OxCal v4.3.2 program (Bronk Ramsey 2017).

All calibrated results are reported at the 95% confidence level (2 sigma).

OSL Dating of Mortars

OSL dating was performed on the same lime mortar selected for ¹⁴C dating: N8-1M and S9-4M. Mortars were sampled using a chisel and hammer under dim red light and they were put into a black plastic bag. In the laboratory, the surface layer was removed and the inner part was used for luminescence analysis. All the laboratory procedures were carried out under dim red light. The measurements were performed using the quartz inclusion technique (180–250 µm; Fleming 1970) with the single aliquot regenerative (SAR) protocol (Murray and Wintle 2000). Both multi-grain (MG) and single grain (SG) techniques were applied. OSL measurement were performed with TL-DA-20 Risø reader and photons were detected by a bialkali photomultiplier tube (EMI 9235QB) coupled to a 7.5 mm Hoya U-340 filter. More details on OSL application to mortars are discussed elsewhere (Galbraith et al. 1999; Zacharias et al. 2002; Stella et al. 2018; Panzeri et al. 2017; Urbanová et al. 2018; Panzeri et al. 2019, 2020, in this volume and other references therein).

TL Dating of Bricks

We analyzed two brick fragments for each of the two vaults (N8-1L, N8-2L, S9-1L, S9-4L). The outer layer of the brick fragments was removed in the laboratory. The polymineral fine grain technique was used and the multiple aliquot additive dose (MAAD) protocol was applied (Aitken 1985). TL dating was performed using an in-house system equipped with a photomultiplier tube (EMI 9235QB) coupled to a blue filter (Corning BG12).

Dose Rate Determination

For dose-rate determination, ^{238}U and ^{232}Th concentrations were derived from alpha counting using ZnS (Ag) scintillator discs and assuming a Th/U concentration ratio equal to 3.16 (Aitken 1985). The contribution due to ^{40}K content was obtained from the total concentration of K measured by flame photometry. The attenuation of the beta particles in coarse grain quartz used for mortar dating was taken into account (Bell 1979). For dose rate calculations, an amount of water corresponding to $20 \pm 5\%$ of saturation was assumed. The external dose rate was evaluated on site with an ionization chamber for environmental dosimetry, to avoid the problem of inhomogeneity of the building materials around the samples.

Parameters used for age determination are reported in Table 1.

RESULTS AND DISCUSSION

Petrographic Analysis of Lime Mortars

The sample S9-4M is a non-hydraulic lime-based mortar with underburned particles up to 3 mm in size. Lime lumps are scarce and small (< 1 mm). The binder/aggregate ratio is 2.2. The aggregate grain size is very fine to fine sand and moderately well sorted. The sand composition is: micritic limestone and sparry calcite, quartz, feldspar, siltstone, rare fossil fragments, serpentinite fragments, biotite, iron oxide and/or hydroxide. The provenance is probably from the Panaro River (Lugli et al. 2007; Figure 2a).

The sample N8-1M is a non-hydraulic lime-based mortar with underburned particles up to 4 mm in size. Lime lumps are frequent and up to 2 mm across. They are soft and white and of the type that Pesce et al. (2012) and Lindroos et al. (2018) recommend for dating. The binder/aggregate ratio is 1.3. The aggregate grain size is very fine to medium sand and moderately well sorted. The sand composition is as follows: micritic limestone and sparry calcite, quartz, feldspar, siltstone, fossil fragments, serpentinite fragments, biotite, iron oxide and/or hydroxide, glauconite. The provenance is probably from the Panaro River (Lugli et al. 2007; Figure 2b).

^{14}C Dating

The ^{14}C dating results are listed in Table 2. The alkalinity test reveals that the samples result with a low alkalinity and therefore are suitable to be dated. CL inspection was performed on the selected grain size fraction (46–75 μm) after sieving and on the same powder after sequential dissolution of the sample S9-4M. The powder before dissolution contained carbonate contaminants and part of silicic aggregates, while after the dissolution, the aggregate was only visible since the binder and the carbonate contaminants were dissolved.

The ^{14}C profile of the sample S9-4M is shown in Figure 3a. It displays an increasing slope, characterized by rapidly dissolving mortar binder and slowly dissolving contaminants. The ^{14}C

Table 1 Parameters used for age determination of OSL and TL dating.

Name	Sample	Technique	E.D. (Gy)	²³⁸ U (ppm)	²³² Th (ppm)	⁴⁰ K (ppm)	Saturation water content (%)	Dose rate
S9 1La	Brick	TL	4.3 ± 0.5	2.29	7.23	1.213875	21	5.52 ± 0.19
S9 1Lb	Brick	TL	3.0 ± 0.4	2.05	6.49	1.13	27	3.91 ± 0.14
S9-4L	Brick	TL	3.6 ± 0.3	2.68	8.46	1.34	19	4.67 ± 0.16
S9-4M	Mortar	OSL MG	4.2 ± 0.9	1.94	6.12	0.31	10	1.32 ± 0.04
		OSL SG	1.4 ± 0.3					
N8-1L	Brick	TL	5.3 ± 0.5	2.30	7.26	1.47	22	5.47 ± 0.19
N8-2Lc	Brick	TL	1.5 ± .1	2.29	7.23	1.26	20	5.44 ± 0.19
N8-2La	Brick	TL	1.4 ± 0.18	2.11	6.68	1.23	20	5.13 ± 0.17
N8-2Lb	Brick	TL	1.2 ± 0.3	2.38	7.52	1.34	22	5.72 ± 0.20
N8-1M	Mortar	OSL MG	2.3 ± 0.2	1.22	3.85	0.51	5	0.97 ± 0.03

Table 2 Hydrolysis data, ^{14}C results and $\delta^{13}\text{C}$ values for the dated samples.

Site	Sample subsample/ CO ₂ -fraction	Material	Grain size (μm)	Reaction time (s) from t_0	Carbon yield (tot) (%)	Fraction size (relative 1)	^{14}C age (BP)	\pm	$\delta^{13}\text{C}$ ‰ VPDB
Modena Cathedral	N8-1MLi.1.1	Lime lump	Crushed	10	3.05 % C	0–0.27	291	56	n.r.
Vault N8	N8-1MLi.1.2			24		0.27–0.52	223	66	n.r.
Modena Cathedral	S9-4M.3.1	Bulk mortar	46–75	13	2.62 % C	0–0.17	523	23	–17.4
Vault S9	S9-4M.3.2			35		0.17–0.36	1207	24	–6.4

Carbon yield (tot) (%) = total carbon yield after about 1-hr dissolution.

n.r. = not reported.

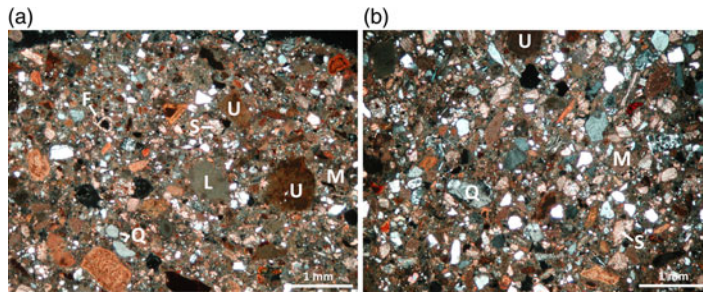


Figure 2 (a) photomicrograph in crossed polars of the mortar sample S9-4M. F: fossil fragments, L: lime lump, M: micritic limestone, S: sparry calcite, U: underburned fragment; (b) photomicrograph in crossed polars of the mortar sample N8-1M. M: micritic limestone, Q: quartz, S: sparry calcite, U: underburned fragment.

age of the first CO₂ fraction (523 ± 23 BP) of the sample S9-4M gave a calibrated calendar age 1328–1341 AD (5.2%) and 1396–1439 AD (90.2%), matching with the age provided by historical documents (1404–1433 AD, Baracchi and Giovannini 1988, Figure 3b). It follows that despite the presence of carbonate grains in the aggregate and unburned limestone fragments, the sequential dissolution procedure succeeded in eliminating the possible contaminant effect, which would have given an older age than that provided by documents.

As show in Figure 3c, the ¹⁴C profile of the sample N8-1MLi reveals that the dates seem to be inverted i.e. fraction 1 produced an age slightly older than fraction 2. However, CO₂ fractions 1 and 2 have overlapping ages and according to the Criterion I (Heinemeier et al. 2010; Ringbom et al. 2011; Lindroos et al. 2018) if the first two CO₂ fractions agree within the given error margins (and so the ages are overlapping), it demonstrates an absence of contamination and is considered a reliable result. In this case the combined calibration is assumed to give the true age of the mortar. The combined age of the CO₂ fractions 1 and 2 yields the ¹⁴C age 263 ± 43 BP corresponding with a calibrated calendar age 1487–1681 AD (79.2%), 1739–1743 AD (0.4%), 1763–1802 AD (12.4%), >1938 AD (3.5%), younger than the documented construction age (1433–1454 AD, Baracchi and Giovannini 1988, Figure 3d), indicating a later re-construction after significant damage. The catalog of earthquakes reports several seismic events that occurred after the vaults' construction. Four damaging earthquakes in 1474, 1501, 1660, and 1671 overlap with the ¹⁴C dating, and they may be the cause of the reparation works, which are not documented in the historical records. In Table 3 we report the calibrated ages and their interpretation in comparison with the TL and OSL dating results.

OSL Dating

The OSL dating results are listed in Table 3. Mortar OSL dating gives results incompatible with the construction phases. The OSL ages obtained are much older than expected, regardless of the techniques used, indicating a poor and uncomplete bleaching (Sawakuchi et al. 2011).

TL Dating

Table 3 lists the TL dating results. They provide information about the construction timing and restoration of the vaults, especially for those cases where gypsum binder was used. In these cases, the TL of bricks is the only possible dating technique. The results from vault S9

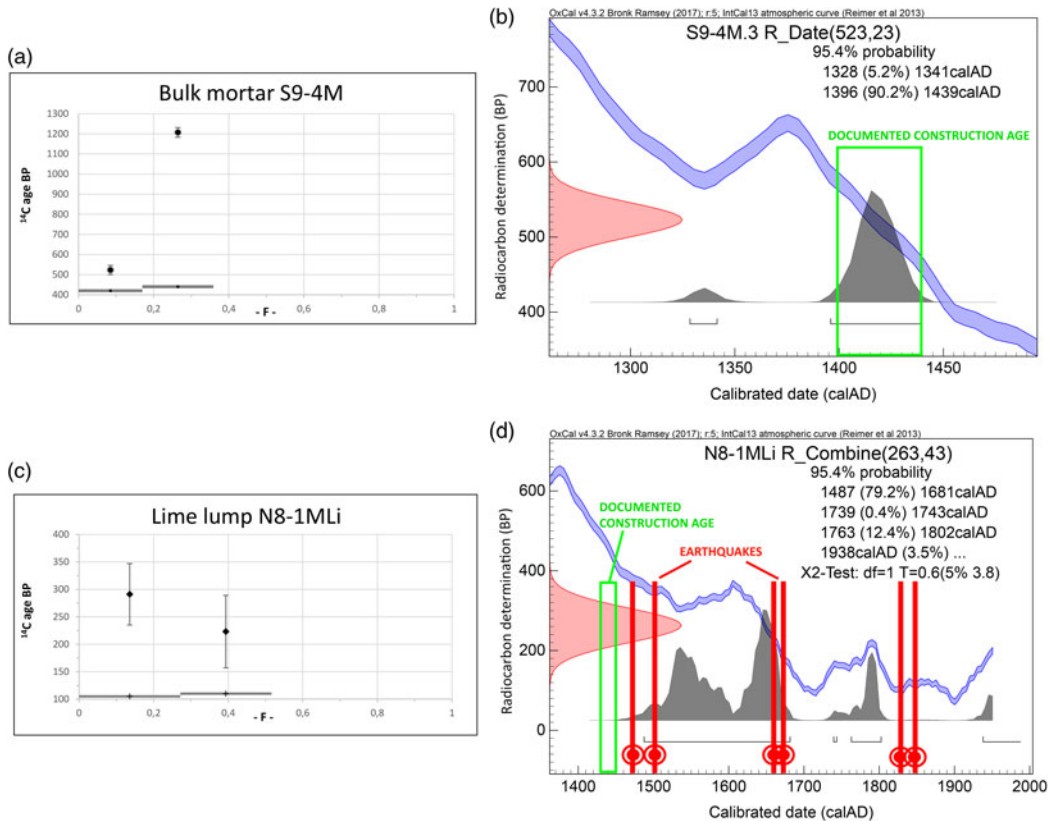


Figure 3 (a) ^{14}C age profile of the samples S9-4M. F is the fraction of reactive material transformed from carbonate to carbon dioxide. The horizontal gray bars along the x -axis denote the size of the extracted CO_2 fractions relative to the total carbon yield ($=1$); (b) calibrated result of the bulk mortar S9-4M, 1328–1341 (5.2%) and 1396–1439 (90.2%). The date coincides with the historical documents age (1404–1433) marked as a green rectangle; (c) ^{14}C age profile of sample N8-1M. F is the fraction of reactive material transformed from carbonate to carbon dioxide. The horizontal gray bars along the x -axis denote the size of the extracted CO_2 fractions relative to the total carbon yield ($=1$); (d) calibrated result of the lime lump N8-1MLi, 1487–1681 (79.2%), 1739–1743 (0.4%), 1763–1802 (12.4%), >1938 (3.5%). The dates are younger than the historical documents age (1433–1454) marked as a green rectangle. Several earthquakes, marked as red vertical lines, overlap with the ^{14}C age, indicating later repair after significant seismic damage.

suggest that the bricks were manufactured in the 13th century (1245 ± 65 and 1235 ± 80 , 1250 ± 80) and were reused later in both lime and gypsum portions of the vault.

The dates obtained from the vault N8 reveal that the lime portion of the vault was built with reused bricks from the 11th century, whereas bricks from the gypsum portion are younger (1740 ± 20 , 1740 ± 30 , 1805 ± 20) than the original construction phase of the vault. These data suggest that significant restoration works were carried out using gypsum mortar in the 18th and 19th centuries after the damaging earthquakes of 1671, 1688, 1828, and 1850.

CONCLUSION

A detailed survey of the 15th century vaults of the Modena medieval cathedral revealed a complex and unexpected structure consisting of different mortars used for multiple modifications.

Table 3 Results of absolute dating of the vaults S9 and N8.

Name	Sample	Expected age	Absolute dating techniques	Date	Notes	Interpretation
S9-1La	Brick (gypsum mortar)	1404–1433	TL	1235 AD ± 80	REUSED brick	Lime mortar for original construction (1404–1433) with reused bricks; gypsum mortar for later repair with reused bricks
S9-1Lb	Brick (gypsum mortar)		TL	1250 AD ± 80	REUSED brick	
S9-4M	Lime mortar	¹⁴ C Sequential dissolution ETH Zurigo	Bulk: [1328–1341 AD] 5.2% [1396–1439 AD] 90.2%	The date is in AGREEMENT with expected age		
S9-4M	Lime mortar	OSL multi-grain	1140 BC ± 720	The date is NOT in agreement with expected age		
S9-4M	Lime mortar		OSL single grain (MAM)	960 AD ± 200	The date is NOT in agreement with expected age	
S9-4L	Brick (lime mortar)		TL	1245 AD ± 65	REUSED brick	
N8-1L	Brick (gypsum mortar)	1433–1454	TL	1050 AD ± 90	REUSED brick	Lime mortar for later repair with reused bricks after earthquakes (1474, 1501, 1660, 1671); gypsum mortar for interventions of 18th century
N8-1M	Lime mortar		¹⁴ C Sequential dissolution Aarhus AMS Centre	Lime lump: [1487–1681 AD] 79.2% [1739–1743 AD] 0.4% [1763–1802 AD] 12.4% [>1938 AD] 3.5%	The date is YOUNGER than expected age. Later repair after earthquakes: 1474, 1501, 1660, 1671	
N8-1M	Lime mortar	OSL multi-grain	390 BC ± 220	The date is NOT in agreement with expected age		
N8-2Lc	Brick (gypsum mortar)	TL	1740 AD ± 20	Later repair after earthquakes: 1671, 1688, 1828, 1850		
N8-2La	Brick (gypsum mortar)	TL	1740 AD ± 30			
N8-2Lb	Brick (gypsum mortar)	TL	1805 AD ± 20			

The dating of mortars and bricks clarifies the chronology of the construction phases and the history of complex restorations, which are probably related to damage suffered after earthquakes.

Absolute dating results suggest that the vault S9 was originally built in 1404–1433 using lime mortar and older bricks, and was subsequently partially reconstructed with gypsum mortar and reused bricks. As gypsum mortar can not be directly dated, the reuse of older bricks does not allow us pinpoint the timing of the reconstruction and the possible triggering earthquake.

Two different restoration phases were recognized on the vault N8. A first repair by lime mortar, and reused bricks, was carried out immediately after the original construction, possibly as a result of the 1474, 1501, 1660, and 1671 earthquakes. A second intervention was then necessary to repair damage probably caused by the 1671, 1688, 1828, and 1850 earthquakes. As building materials for this second repair, new bricks were used, kept together by a gypsum mortar. The preliminary results of this study demonstrate that the vaults suffered much larger damage induced by earthquakes than previously assessed by mapping fracture and crack networks alone.

REFERENCES

- Aitken MJ. 1985. Thermoluminescence dating. London: Academic Press.
- Andreini M, De Falco A, Giresini L, Sassu M. 2014. Structural damage in the cities of Reggiolo and Carpi after the earthquake on May 2012 in Emilia Romagna. *Bulletin of Earthquake Engineering* 12(5):2445–2480.
- Baraccani S, Palermo M, Silvestri S, Gasparini G, Trombetti T, Silvestri E. 2015. The structural strengthening of the Cathedral of Modena. SEWC 2015, 5th Structural Engineers World Congress:1–5.
- Baraccani S, Gasparini G, Palermo M, Silvestri S, Trombetti T. 2017. The structural behavior of the masonry vaults of the Cathedral of Modena. *Proceedings of the 5th International Conference on Architecture and Civil Engineering*, Singapore, 8–9 May. p. 550–556.
- Baraccani S, Palermo M, Trombetti T, DeJong M. 2019. Seismic modelling of a masonry monument including the interaction of the vaults, longitudinal walls and soil. In Aguilar R, Torrealva D, Moreira S, Pando MA, Ramos LF, editors. *Structural analysis of historical constructions*. RILEM Bookseries, Vol. 18. Springer. p. 1099–1107.
- Baracchi O, Giovannini C. 1988. Il duomo e la torre di Modena: nuovi documenti e ricerche. Modena: Aedes Muratoriana. p. 304.
- Baracchi O. 1993. Volte a crociera e affreschi del Duomo: nuovi documenti del '400 e '500. *Atti e memorie della Deputazione di storia patria per le antiche provincie modenesi* 11(15): 131–156.
- Bell WT. 1979. Attenuation factors to absorbed dose in quartz inclusions for thermoluminescence dating. *Ancient TL* 8:2–13.
- Bronk Ramsey C. 2017. OxCal [WWW program] version 4.3. Oxford Radiocarbon Accelerator Unit: University of Oxford. Available at <https://c14.arch.ox.ac.uk/oxcal/OxCal>.
- Carò F, Di Giulio A. 2004. Reliability of textural analysis of ancient plasters and mortars through automated image analysis. *Materials Characterization* 53:243–257.
- Decanini L, Liberatore D, Liberatore L, Sorrentino L. 2012. Preliminary report on the 2012, May 20, Emilia earthquake. Vol. 1. 70 p.
- Dolce M, Nicoletti M, Ammirati A, Bianconi R, Filippi L, Gorini A, Marcucci S, Palma F, Zambonelli E, Lavecchia G, de Nardis R, Brozzetti F, Boncio P, Cirillo D, Romano A, Costa G, Gallo A, Tiberi L, Zoppé G, Suhadolc P, Ponziani F, Formica A. 2012. The Ferrara arc thrust earthquakes of May–June 2012 (northern Italy): strong-motion and geological observations. *The National Civil Protection Department Report II*. 11 p.
- Dondi A. 1896. *Notizie storiche ed artistiche del Duomo di Modena raccolte ed ordinate dal can. A. D. con l'elenco dei codici capitolari in appendice*. Modena: Edizione Aldine. 301 p.
- Elsen J. 2006. Microscopy of historic mortar: A review. *Cement Concrete Research* 36:1416–1424.
- Galbraith RF, Roberts RG, Laslett GM, Yoshida H, Olley JM. 1999. Optical dating of single and multiple grains of quartz from Jinnium rock shelter, northern Australia: Part I, experimental design and statistical models. *Archaeometry* 41:339–364.
- Graziani L, Bernardini F, Castellano C, Del Mese S, Ercolani E, Rossi A, Tertulliani A, Vecchi M. 2015. The 2012 Emilia (northern Italy) earthquake sequence: an attempt of historical reading. *Journal of Seismology* 19: 371–387.
- Hayen R, Van Strydonck M, Fontaine L, Boudin M, Lindroos A, Heinemeier J, Ringbom Å,

- Michalska D, Hajdas I, Hueglin S, Marzaioli F, Terrasi F, Passariello I, Capano M, Maspero F, Panzeri L, Galli A, Artioli G, Addis A, Secco M, Boaretto E, Moreau C, Guibert P, Urbanova P, Czernik J, Goslar T, Caroselli M. 2017. Mortar dating methodology: Assessing recurrent issues and needs for further research. *Radiocarbon* 59(6):1859–1871.
- Heinemeier J, Ringbom Å, Lindroos A, Sveinbjörnsdóttir AE. 2010. Successful AMS ^{14}C dating of non-hydraulic lime mortars from the Medieval churches of the Åland Islands, Finland. *Radiocarbon* 52(1):171–204.
- Indirli M, Marghella G, Marzo A. 2012. Damage and collapse mechanism in churches during the Pianura Padana Emiliana earthquake. *Energia Ambiente Innovazione* 4/5:69–94.
- Lindroos A, Heinemeier J, Ringbom Å, Braskén M, Sveinbjörnsdóttir Á. 2007. Mortar dating using AMS ^{14}C and sequential dissolution: Examples from medieval, non-hydraulic lime mortars from the Åland Islands, SW Finland. *Radiocarbon* 49(1):47–67.
- Lindroos A, Ringbom Å, Heinemeier J, Hodgins G, Sonck-Koota P, Sjöberg P, Lancaster L, Kaisti R, Brock F, Ranta H, Caroselli M, Lugli S. 2018. Radiocarbon dating lime lumps and/or binder carbonate in historical mortars?. *Radiocarbon* 60(3):875–899.
- Lubritto C, Caroselli M, Lugli S, Marzaioli F, Nonni S, Marchetti Dori S, Terrasi F. 2015. AMS radiocarbon dating of mortar. The case study of the medieval UNESCO site of Modena. *Nuclear Instruments and Methods in Physics Research B* 361:614–619.
- Lugli S, Marchetti Dori S, Fontana D. 2007. Alluvial sand composition as a tool to unravel late quaternary sedimentation of the Modena Plain, northern Italy. In: Arribas J, Critelli S, Johnsson MJ, editors. *Sedimentary provenance and petrogenesis: perspectives from petrography and geochemistry*. United States: Geological Society of America. p. 57–72.
- Marshall DJ. 1988. *Cathodoluminescence of geological materials*. Boston: Unwin Hyman.
- Michalska D, Czernik J., Goslar T. 2017. Methodological Aspect of Mortars Dating (Poznań, Poland, MODIS). *Radiocarbon*. 59 (6): 1891–1906.
- Michalska D, Pawlyta J. 2019. Modelled and measured carbon isotopic composition and petrographically estimated binder-aggregate ratio-recipe for binding material dating?. *Radiocarbon* 61(3):799–815.
- Murray AS, Wintle AG. 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements* 32:57–73.
- Nawrocka DM, Michniewicz J, Pawlyta J, Pazdur A. 2005. Application of radiocarbon method for dating of lime mortars. *Geochronometria* 24:109–115.
- Panzeri L, Cantù M, Martini M, Sibilìa E. 2017. Application of different protocols and age-models in OSL dating of earthen mortars. *Geochronometria* 44:341–351.
- Panzeri L, Caroselli M, Galli A, Lugli S, Martini M, Sibilìa E. 2019. Mortar OSL and brick TL dating: The case study of the UNESCO world heritage site of Modena. *Quaternary Geochronology* 49: 236–241.
- Panzeri L, Maspero F, Galli A, Sibilìa E, Martini M. 2020. Luminescence and radiocarbon dating of mortars at Milano-Bicocca laboratories. *Radiocarbon*:1–10. DOI: [10.1017/RDC.2020.6](https://doi.org/10.1017/RDC.2020.6)
- Pesce GL, Ball RJ, Quarta G, Calcagnile L. 2012. Identification, extraction, and preparation of reliable lime samples for ^{14}C dating of plasters and mortars with the “pure lime lumps” technique. *Radiocarbon* 54 (3–4):933–942.
- Ringbom Å, Heinemeier J, Lindroos A, Brock F. 2011. Mortar dating and Roman Pozzolana, results and interpretation. In: Ringbom Å, Hohlfelder R, editors. *Proceedings of the Building Roma Aeterna, Conference, Rome, 23–25 March 2008*. *Commentationes Humanarum Litterarum, Societas Scientiarum Fennica* 128:187–208.
- Rovida A, Locati M, Camassi R, Lolli B, Gasperini P. 2016. CPT115, the 2015 version of the Parametric Catalogue of Italian Earthquakes. Istituto Nazionale di Geofisica e Vulcanologia (INGV).
- Sawakuchi AO, Blair MW, DeWitt R, Faleiros FM, Hyppolito T, Guedes CCF. 2011. Thermal history versus sedimentary history: OSL sensitivity of quartz grains extracted from rocks and sediments. *Quaternary Geochronology* 6:261–272.
- Silvestri E. 2013. Una rilettura delle fasi costruttive del Duomo di Modena. *Atti e Memorie. Deputazione di Storia Patria per le Antiche Provincie Modenesi* 11(35):117–149.
- Stella G, Almeida L, Basilio L, Pasquale S, Dinis J, Almeida M, Gueli AM. 2018. Historical building dating: a multidisciplinary study of the convento of Sao Francisco (Coimbra, Portugal). *Geochronometria* 45: 119–129.
- Urbanová P, Michel A, Cantin N, Guibert P, Lanos P, Dufresne P, Garnier L. 2018. A novel interdisciplinary approach for building archaeology: The integration of mortar “single grain” luminescence dating into archaeological research, the example of Saint Seurin Basilica, Bordeaux. *Journal of Archaeological Science: Reports* 20:307–323.
- Zacharias N, Mauz BT, Michael C. 2002. Luminescence quartz dating of lime mortars. A First research approach. *Radiation Protection Dosimetry* 101(1–4):379–382.