13TH CANADIAN MASONRY SYMPOSIUM
HALIFAX, CANADA
JUNE 4TH – JUNE 7TH 2017

ANALYSIS OF THE 15TH CENTURY BELL TOWER, ST. NICHOLAS CATHEDRAL, NEWCASTLE UPON TYNE

Righetti, Luca[1]; Corradi, Marco[2]; Lim, Michael[3]; Charlton, James[4]; Dundas, Matthew[5] and Amess, Leon[6]

ABSTRACT

This paper reports the first results of an accurate three-dimensional survey and structural analysis of the historic bell tower of St Nicholas Cathedral, Newcastle Upon Tyne. It presents detailed analysis of the geometry, masonry state, the morphology and overall structural stability of the bell tower. The bell tower was completed in 1474 and is of particular interest (Grade I listed). Extending vertically 61.24 m from the base (12.03 x 11.99 m) to the top of the steeple the generally perfectly-cut large sandstone blocks, cemented with lime-based mortar, are supported by four stonemasonry pillars resulting in high compressive stresses. The analysis also considers the historic construction phases and analyses the consequences in terms of structural behavior. Key findings relate to the particular significance of the wall-to-wall connections and altered stonemasonry style during the repair and subsidence and settlement mitigation work undertaken on the east face of the tower. A dynamic analysis has been also conducted to understand the structural behavior of this iconic stonemasonry landmark.

KEYWORDS: *structural analysis, historic masonry, tall structures*

[1] PhD candidate, Dept. of Mechanical & Construction Engineering, Northumbria University, Wynne-Jones Building, NE1 8ST Newcastle Upon Tyne, United Kingdom, luca.righetti@northumbria.ac.uk

[2] Associate Professor, Dept. of Mechanical & Construction Engineering, Northumbria University, Wynne-Jones Building, NE1 8ST Newcastle Upon Tyne, United Kingdom, marco.corradi@northumbria.ac.uk and Dept. of Engineering, Perugia University, Via Duranti, 92 06125 Perugia, Italy marco.corradi@unipg.it

[3] Senior Lecturer, Dept. of Mechanical & Construction Engineering, Northumbria University, Wynne-Jones Building, NE1 8ST Newcastle Upon Tyne, United Kingdom, michael.lim@northumbria.ac.uk

[4] Lecturer, Dept. of Architecture & Built Environment, Northumbria University, Sutherland Building, NE1 8ST Newcastle Upon Tyne, United Kingdom, j.charlton@northumbria.ac.uk

[5] Assistant Technician, Faculty of Engineering and Environment, Northumbria University, Ellison Building, NE1 8ST Newcastle Upon Tyne, United Kingdom, matthew.dundas@northumbria.ac.uk

[6] Senior Technician, Faculty of Engineering and Environment, Northumbria University, Ellison Building, NE1 8ST Newcastle Upon Tyne, United Kingdom, leon.amess@northumbria.ac.uk

INTRODUCTION

A significant portion of European architectural heritage is accounted for by religious buildings (churches, monasteries, etc.). Many of these structures were designed to impress, using tall and imposing constructions. In England, the strong association between religion and political power enhanced this effect; religious constructions were not only places to worship, but also public buildings where the authority was demonstrated. Prominent among these structures are bell towers. In Christianity, bell towers were designed to contain one or more bells to be rung to signify time or to call people to worship. Consequently, architects often designed structures close to their limits and limit stresses, utilising relatively low strength materials based on stone masonry and lime-based mortars. Therefore, historic masonry bell towers have often proven particularly susceptible to damage and collapse, not only during catastrophic events (earthquakes, storms, etc.), but also under ordinary loading conditions. On 17 march 1989, the 11th century civic tower next to Pavia Cathedral in Italy collapsed into 8000 m^3 of brick, sand and granite rubble, killing four people and injuring fifteen (Fig. 1). The famous bell tower of Pisa is another stonemasonry construction at risk of collapse due to progressive tilt that originated during construction. On Monday 14 July 1902 the bell tower of St. Mark Cathedral in Venice collapsed completely on a calm, sunny summer day (Fig. 2).

a) b)

Figure 1: The Civic Tower next to Pavia Cathedral Collapsed in 1989: a) Before Collapse, b) After

a) b)

Figure 2: The Bell Tower Next to Venice Cathedral Collapsed in 1902: a) Before Collapse, b) After

These structures have recently attracted increasing focus from researchers and several studies can be found in the literature on the static and dynamic assessment of masonry towers. In Europe, where there is particular interest in the conservation and protection of architectural heritage, several analysis methods have been proposed. Interesting examples of these researches include: the bell tower of the Monza Cathedral, Italy [1], the masonry bell tower of St. Andrea church in Venice, Italy [2], the eighth-century masonry tower known as Torre Sineo of Alba, Italy [3], the bell tower of Nuestra Señora de la Misericordia church in Valencia, Spain [4] and the bell tower of the St. Justa and Rufina Church in Orihuela, Spain [5].

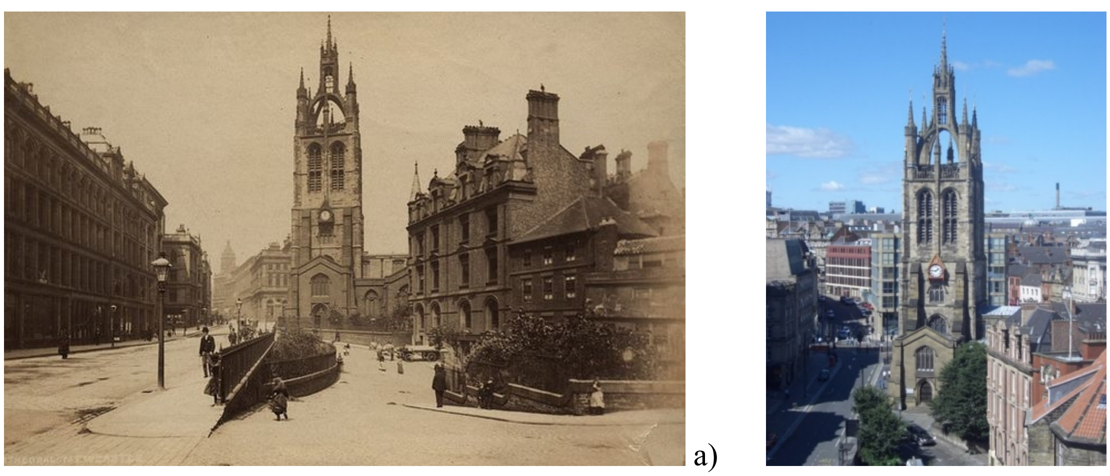
The analysis of these structures is inherently a multidisciplinary task, involving not only structural engineers but also architects, material engineers, surveyors and historians. Constructions phases, historic repair works, material properties, crack patterns and degradation, internal forces analysis and static and dynamic loading conditions are critical data when such analyses are approached. However, the interactions between these aspects have remained poorly constrained until recently. Examples of accurate experimental analyses and investigation surveys can be found in the literature ([6], [7], [8]). On-site testing is an important preliminary step in order to assess the mechanical properties of historic masonry. Destructive (compression tests, diagonal tension tests), slightly destructive (flat-jack tests) or non-destructive tests (dynamic tests, sonic pulse velocity tests, thermography) are typical examples of experimental analysis, which aims to establish strengths and elastic moduli for use in the tuning of numerical models employed to assess the vulnerability of the tower, usually through non-linear analyses.

Dynamic analyses have been also carried out with increasing frequency and accuracy, as a consequence of the availability on the market of new instruments and software capable of addressing these aspects. Interesting dynamic identifications of masonry towers can be found in [9], [10], [11], [12] and [13]. Non-contact methods for conducting ancient and modern building surveys have advanced considerably over the last few decades, permitting the accurate survey of as-built dimensions, the image gathering of qualitative and quantitative information and the 3D (Three-Dimensional) modelling of complex buildings. These innovative methods have become particularly useful as 3D modelling tools where structural elements and surfaces are complex. Terrestrial Laser Scanner (TLS) systems are widely used to obtain large number of data points distributed across the observed target surface with rapid acquisition rates and high precision. TLS technologies have been applied in different fields such as archeology ([14] and [15]), geology ([16], [17], [18] and [19]), civil engineering ([20]) and documentation and monitoring of heritage sites ([21] and [22]).

Laser scanners can be categorized into three types, reducing in range but increasing in precision: time of flight scanners, phase-based scanners and triangulation scanners. Scanners based on the principle of time of flight emit a pulse of laser light, which, after hitting the target and returning, is detected by the photo-detector. The distance is evaluated considering the time spent by the signal between the scanner and the target. The second type (phase comparison scanner) produces a constant wave of laser energy and then the instrument evaluates the phase shift of the returning laser energy to compute distances. These two systems are most appropriate for building surveys at long (< 10 m) and short (< 30 m) range respectively. A coordinate system centred on the instrument can be created, linking the distance measurements with two internal angle measurements associated with the rotating mirrors with the laser scanner. The raw data obtained through TLS are collectively displayed as a point-cloud that requires cleaning, registering and processing.

CONSTRUCTION OF THE BELL TOWER

Following destruction in the year 1216 by fire, St. Nicholas church is said to have been rebuilt in 1359. However, according to historic records preserved in the Church, it appears only to have been part-finished at this time [23]. The steeple, a later addition to the original tower, was built by Robert de Rhodes, a prominent member of the Newcastle community during the reign of Henry VI (1421-1471). His name is carved in Latin at a bottom on the bell tower on a stone (*Orate pro anima Roberti Rhodes*) and original documents demonstrate his involvement with this construction between 1447 and 1451. The construction of the bell tower lasted for several centuries. The tower originally contained five bells; of these three are very old and coeval with the completion of the bell tower. Of particular interest is the inscription in black-letter characters round the 3rd bell: "When this tower's court to this height yow see it was built when - 1658" [24]. At the time of the English Civil War (1642-1651) the bell tower was probably completed as, according to historical records, the Mayor of Newcastle ordered that a certain number of Scottish soldiers to be imprisoned in the tower below the *Lanthorne* [25].



a) b)

Figure 3: The Bell Tower Next to Newcastle Upon Tyne Cathedral: a) in 1900s, b) Today

About the year 1832 the church authorities became alarmed at the condition of the bell tower, which was leaning approx. 0.30 m to the south and 0.23 m to the west. Architect John Green designed some undersetting and ordered the construction of two large buttresses with ranking (inclined) joints on the south side. Green also added a porch on both south and north sides. The tower previously had no footing, but the wall rested on the clay at a depth of approx. 1.2- 1.5 m. Restorations were again conducted in 1868 by Gilbert Scott. At that time the arches carrying the lanterns were tied in at the springing by an arrangement of ties of flat bar-iron. Scott also extended and reinforced the existing foundation of the tower to a depth of approx. 4.3 m below the nave floor level, putting in a concrete foundation (Fig. 3).

SURVEY OF BELL TOWER GEOMETRY

In order to obtain accurate and detailed information on the bell tower's geometry, a 3D geometric survey investigation has been conducted using terrestrial laser scanning. The bell tower contains four stories. At ground level the entire structure rests on four massive pillars. Three terrestrial laser scanning instruments (Fig. 4) have been used for the survey: a Riegl LMS-Z620, a Faro Focus^{3D} 20 Scanner and a GeoSLAM ZEB1 3D Scanner. The Riegl was used to capture the long-range external structure of the bell tower. The Riegl laser can measure distances in the range of 2–2000 m, with a claimed accuracy of 10 mm at 100 m and a beam divergence of 0.15 mrad. The scan angle range is 80° vertically from the horizontal plane and 360° horizontally, with a measurement rate of up to 11,000 points/sec. The Faro was deployed to survey the internal structure of the four floors within the bell tower. The Faro Focus can transmit a continuous beam of 905 nm laser light and measures distances in the range of 0.60–20 m, with a measurement accuracy of 2 mm at 10 m and a beam divergence of 0.19 mrad. The field of view covers 305° vertically and 360° horizontally. The narrow spiral stair connections have been surveyed with the GeoSLAM handled mobile mapping system. GeoSLAM is a mobile mapping system with a range distance of 30 m and a relative accuracy of 20-30 mm. Laser wavelength is 905 nm and data acquisition rate of 43,200 points/sec.

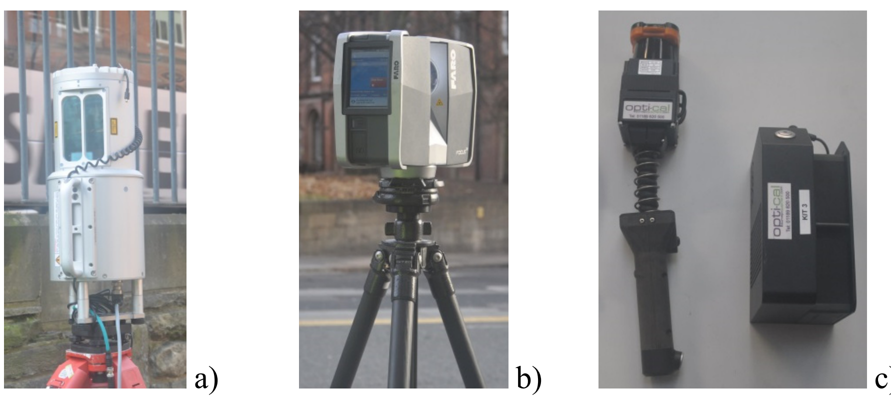


Figure 4: Scanners Used for the St. Nicholas Cathedral Survey: a) Riegl LMS-Z620, b) Faro Focus3D 20, c) GeoSLAM ZEB1 3D Scanner

After an initial analysis, four positions (Fig. 5a) were chosen for the outdoor scans. This was necessary in order to record a full panoramic view of the steeple. Six scans (Fig. 5b) were necessary to capture the geometry of the internal ground floor. Two more were carried out for the first floor (Fig. 5c) and one each for the second (Fig. 5d) and third floors (Fig. 5e). Finally, three scan trajectories have been recorded within the spiral staircase. All survey stations have been selected to optimise data coverage and achieve sufficient overlap to register scans into a coherent model. Table 1 summarises the survey strategy used to model the bell tower. The acquisition and storage of data were performed using the following software: 1) Riscan Pro for the acquisition and analysing of data from the Riegl; 2) Scene Faro for the acquisition and analysing of data from the Faro; 3) GeoSLAM Cloud for acquisition of the GeoSLAM.

All scans have been manually cleaned of erroneous points not structurally part of the bell tower. The registration process methodology is summarised in Figure 6. The results of the four external scans are shown in Figure 7. Figure 8 shows a view of the registered internal ground floor. The bell tower is 61.24 m high and, at ground level, has planimetric external dimensions of 12.03 x 11.99 m. Above the main tower is a lantern tower (17.65 m in height), supported by pinnacles at each corner. Two openings are present in the west side of the steeple: the doorway (2.53 m wide and a maximum height of 3.85 m) and a large stained glass window (4.40 x 7.2 m) above the door. The spiral staircase is enclosed within the north-west pier and connects the upper stages of the building. It has a nominal diameter of 1.65 m, but varies with height. In the north wall, an iron strap has been bolted to the wall across the whole of the internal width just below windowsill level. There is a similar strap to the south elevation wall but this is a little higher, being part way up the window opening. This also extends into the nave, fixed to the walls just below clerestory windowsill level.

Table 1: Scan Positions

Scan Position	Scanner	No. of Scans	Label
Outdoor	Riegl LMS-Z620	4	EX1, EX2, EX3, EX4
Indoor (Ground floor)	Faro Focus3D 20	6	IN1, IN2, IN3, IN4, IN5,IN6
Indoor (1st floor)	Faro Focus3D 20	2	IN7, IN8
Indoor (2nd floor)	Faro Focus3D 20	1	IN9
Indoor (3rd floor)	Faro Focus3D 20	1	IN10
Indoor (Stairs)	GeoSLAM ZEB1	3	ST1, ST2, ST3

The first and second floors are separated by a wood-boards floor supported by I-shaped steel beams. Both floors have internal dimensions of 10.78 x 10.88 m. There are also metal ties running around the internal perimeter of the walls to the window openings, coinciding with the ties noted externally. The thickness of the first and second floor walls ranges from 2.04 to 2.06 m. In the north, west and south walls three glazed window openings give light to the first floor (1.96 m x 3.59 m). Adjacent to the south elevation there is timber partitioning around the stair access to the second floor.

The third floor houses twelve bells, hung for full circle ringing. The floor dimensions are 9.99 x 10.20 m. The composite frame supporting the bells is mainly composed of timber and cast iron; horizontal timber sills within cast iron frames. The bottom sills of the bell frame run east-west and are supported on timber wall plates supported on corbels inserted into the tower walls. The thickness wall varies from 1.57 to 1.71 m. Double louvre window openings are present in all the four sides of the bell chamber, each with a width of 2.82 m and a height of 9.28 m.

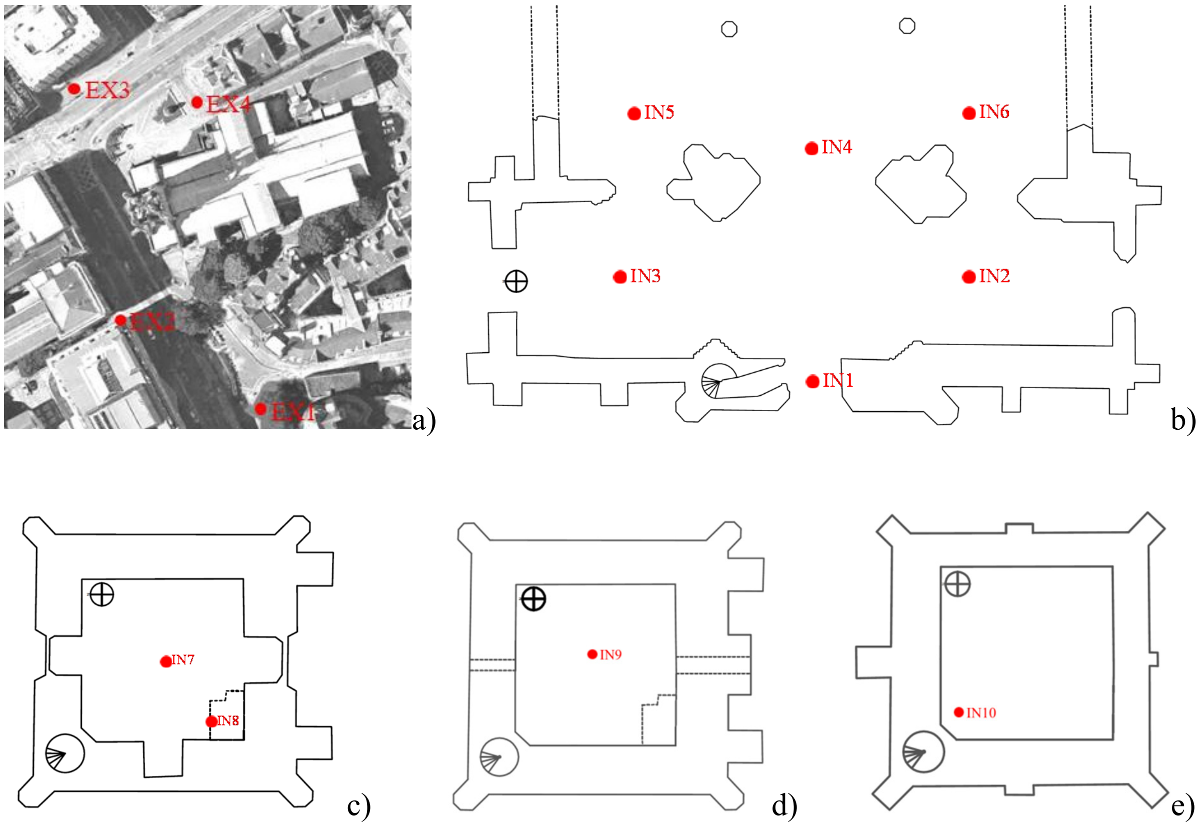


Figure 5: Scan position: a) Outdoor (EX1, EX2, EX3 and EX4), b) Ground Floor (IN1, IN2, IN3, IN4, IN5, IN6), c) 1st Floor (IN7 and IN8), d) 2nd Floor (IN9), e) 3rd Floor (IN10)

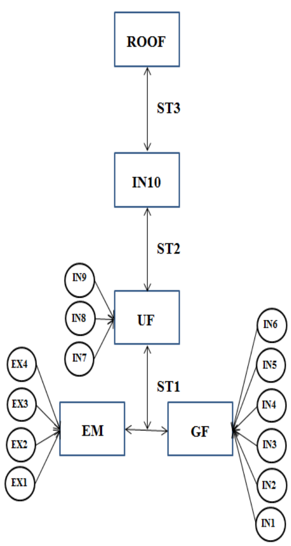


Figure 6: Outline of the Registration Phase Methodology

Figure 7: View of the Registered External Part (EM) of the Bell Tower

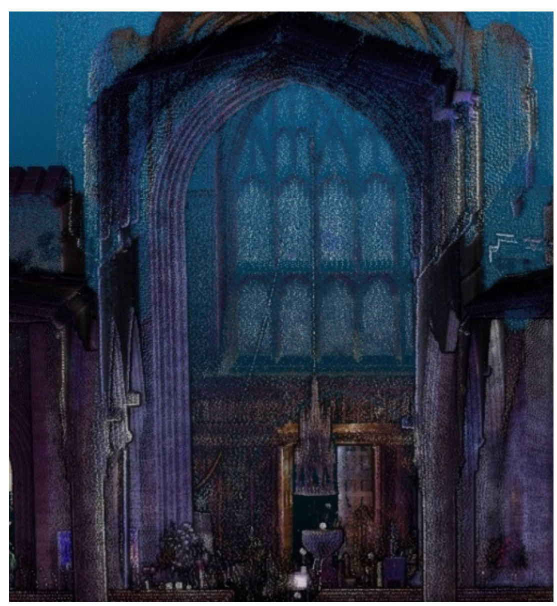


Figure 8: View of the Registered Internal Ground Floor (GF)

ANALYSIS OF MASONRY QUALITY

The bell tower construction phase lasted approximately 200 years (from 1447 to 1658) and consequently reflects a heterogeneous mix of masonry types and qualities. The entire bell tower has been constructed using sandstone, but its arrangement and quality differ significantly with height. Rocks from the Northumberland Fell Sandstone Formation have been included widely as a construction material from Roman times to the late 19th century in Newcastle Upon Tyne. Its mechanical properties have been analysed and studied by geologists [26] and found to be strongly dependent on both the quarry where the stone was mined and on the depth of excavation.

In order to assess the mechanical properties of the historic masonry a non-destructive visual method has been applied. This method, described in detail in [27], assumes an initial state of perfect integrity within the masonry wall. This as-built condition is assigned a numerical value of 10. The analysis directs the engineer to observe seven critical parameters: the conservation state and the mechanical properties of bricks or stones (SM); Stone/Brick dimensions (SD), Stone/Brick shape (SS); connection between adjacent wall leaves (for multi-leaf walls; WC); Horizontal bed joint characteristics (HJ); Vertical joint characteristics (VJ); and Mortar mechanical properties (MM). The estimation requires knowledge of historical construction methods to categorise each parameter into either: Fulfilled (**F**), Partially Fulfilled (**PF**) or Not Fulfilled (**NF**).

Table 2: Numerical Values of the 7 Parameters [27]

	Vertical Loading (V)			**Horizontal In-Plane Loading (I)**			**Horizontal Out-of-Plane Loading (O)**		
	NF	PF	F	NF	PF	F	NF	PF	F
HJ	0	1	2	0	0.5	1	0	1	2
WC	0	1	1	0	1	2	0	1.5	3
SS	0	1.5	3	0	1	2	0	1	2
VJ	0	0.5	1	0	1	2	0	0.5	1
SD	0	0.5	1	0	0.5	1	0	0.5	1
MM	0	0.5	2	0	1	2	0	0.5	1
SM	0.3	0.7	1	0.3	0.7	1	0.5	0.7	1

The numerical values reported in Table 2 have been used to calculate the Masonry Quality Index (MQI) according to Eq. (1). The numerical values of the seven parameters have been calibrated by the authors of [28] and [29] on a large number of destructive tests on masonry wall panels. The application of this method holds significant potential for historic masonry , but should be applied with caution in this instance because the Northumberland Fell Sandstone has not been verified experimentally.

$$MQI = SM(SD + SS + WC + HJ + VJ + MM) \tag{1}$$

A different MQI value can be derived depending on the loading conditions under consideration. This is because some parameters have larger influences under a particular loading conditions. Three potential loading conditions can be considered: vertical compression loads (mainly static;

V), in-plane horizontal (I) and out-of-plane loads (mainly seismic, wind-generated, foundation subsidence, etc.; O).

The bell tower of St. Nicholas has been constructed using perfectly cut sandstone blocks. However, variations exist in both the dimensions and in the state of the blocks. The visual analysis has identified three different masonry typologies relating to the ground level, the lower section and the upper section of the bell tower. The quality of the masonry material at the base of the tower is high, and likely to relate to 19th century restoration (Typology A). It comprises large and consistently sized blocks (up to 100 cm in width), perfectly cut with no signs of degradation (Fig. 9a). The vertical mortar joints are well spaced and the bed joints are perfectly horizontal. The masonry Typology B is found between the restored base levels and the clock, located at approximately half of the total height of the bell tower (Fig. 9b). It shows signs of degradation, the stones span a range of dimensions and some vertical joints are aligned, resulting in a potential strength reduction. Finally, in the section above the clock is masonry Typology C (Fig. 9c). This phase contains a better arrangement in the stone blocks, which may result in a slight increase in structural and mechanical integrity.


a)


b)


c)

Figure 9: Typologies of Masonry: a) Ground Level, Typology A, b) Under the Clock Level, Typology B, c) Over the Clock Level, Typology C

Table 3 shows the numerical values assigned to the seven parameters for all the three loading conditions (V, I and O). By using eq. (1) has been was possible to calculate the MQI value (Table 3). High values were found for masonry Typology A. However, it should be noted that this only refers to the visible masonry, added during the 19th restoration. It is likely that the restoration only affected the outer layer of external stones and there is a stark contrast between the original and later restored stone blocks (Fig. 10). It is also possible that diffuse cracking caused the out-of-plane rotation noted in the south wall as a result of foundation subsidence. In order to mitigate the subsidence a masonry buttress was added in 1832 (Fig. 11). The blocks of this structural element are inclined of approx. 26° into the subsiding south face of the tower. With regard to the behavior under static compressive loads (V), the application of the method reported in [27] gives an estimated compressive strength of 10.2, 4.8 and 5.8 MPa for typologies A, B and C, respectively.

A first attempt to estimate the mechanical properties of the sandstone used to construct St. Nicholas bell tower has been made. A Schmidt hammer (rebound hammer test), orientated horizontally against the vertical stone surfaces, has been used to characterise masonry hardness (Tab. 4). Any loose particles were rubbed off from the stone surface with a carborundum stone and, as a result, the tested stones were smooth, clean and dry.

Table 3: Assigned Numerical Values of the 7 Parameters and MQI Overall Values

	Loading	**HJ**	**WC**	**SS**	**VJ**	**SD**	**MM**	**SM**	**MQI**
Typology A	(V)	2-F	1-PF	3-F	1-F	1-F	2-F	1-F	**10**
	(I)	1-F	1-PF	2-F	2-F	1-F	2-F	1-F	**9**
	(O)	2-F	1.5-PF	2-F	1-F	1-F	1-F	1-F	**8.5**
Typology B	(V)	2-F	1-PF	3-F	0.5-PF	0.5-PF	2-F	0.7-F	**6.3**
	(I)	1-F	1-PF	2-F	1-PF	0.5-PF	2-F	0.7-F	**5.25**
	(O)	2-F	1.5-PF	2-F	0.5-PF	0.5-PF	1-F	0.7-F	**5.25**
Typology C	(V)	2-F	1-PF	3-F	0.5-PF	1-F	2-F	0.7-F	**6.65**
	(I)	1-F	1-PF	2-F	1-PF	1-F	2-F	0.7-F	**5.6**
	(O)	2-F	1.5-PF	2-F	0.5-PF	1-F	1-F	0.7-F	**5.6**

The correlation between compressive strength of the stone and rebound number was obtained using the Eq. 2 experimentally evaluated and formulated in [30].

$$q_u = 0.094 \times R_n - 0.383 \tag{2}$$

where q_u is the uniaxial compressive strength and R_n is the Schmidt hammer rebound number.

Test results differ by 31.6% from data reported for the sandstone of Shirlawhope well [26] in Northumberland. Direct compression tests conducted on a large number of specimens have been used to calculate a compressive strength of 6.5 MPa, with a CoV (Coefficient of Variation) of 29.2 %.

Figure 10: The Original and New Stone Block Added After 19th Century Restorations

Figure 11: The Buttress with Inclined Stone Blocks Added to Prevent the Out-of-Plane Mechanism of the South Wall

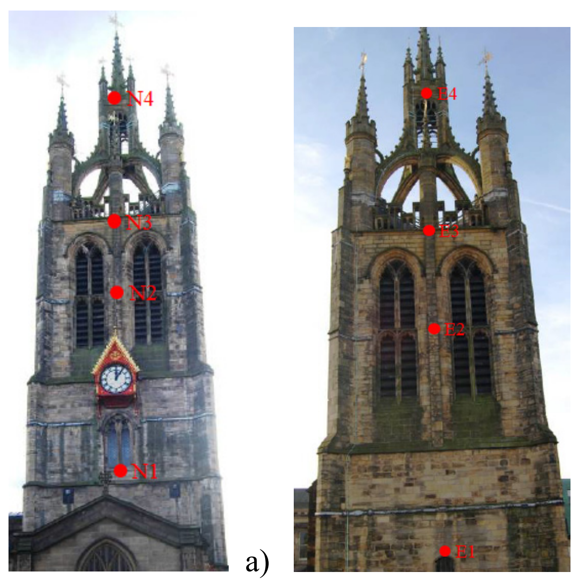
Table 4: Results of Rebound Hammer Tests.

	Typology **A**	Typology **B**	Typology **C**
Number of Tests	36	36	36
Average Rebound Value	44.1	32.8	37.6
Estimated Compressive Strength (MPa)	14.0	9.5	11.42
Standard Deviation (MPa)	3.2	2.2	2.4

REMOTE SENSING VIBROMETER (RSV) MEASUREMENTS

In order to identify the dynamic characteristics of the tower under environmental loads (wind and vehicular traffic), an initial RSV survey was planned to record the ambient vibrations of the bell tower.

The measurements were carried out on the north and east façades. The purpose of the measurement was to study the movement of the structure at several heights (four points for each façade). Because all measurements were carried out at different times, possible changes on the environmental conditions (weather conditions, noise sources, etc.) could happen and affect the displacement amplitude. The key equipment used in the experiment was a RSV. The Polytec RSV-150 single-point scanning laser vibrometer used can measure velocities up to 24 m/s with the maximum frequency bandwidth equal to 2 MHz.



a) b)

Figure 12: Points Analyzed Using RSV: a) North Façade, b) East Façade

First results of the dynamic tests indicated 6 distinct natural frequencies in the 2 directions North-South and West-East. For North-South direction, natural frequencies were 1.98, 3.87 and 5.76 Hz (Figs. 13-14). For West-East direction, these were 2.64, 7.73 and 8.65 Hz. Measurements were made using the laser vibrometer over an inclination to the horizontal varying from approx. 15° (points N1 and E1 in Figure 12) to 43° (N4 and E4). More analysis is needed for these results before a conclusion can be drawn.

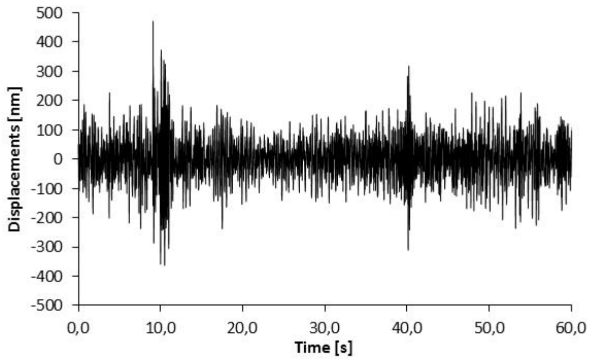


Figure 13: North-South Direction (N4): Time History

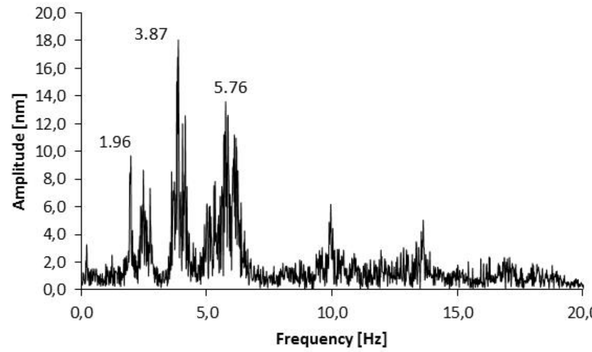


Figure 14: North-South Direction (N4): Fast Fourier Transform

CONCLUSIONS

St. Nicholas Bell Tower is one of the most impressive and iconic attractions in the northeast. Dating back to 1447, this grade I listed monument is composed entirely of sandstone blocks bonded together with low-strength lime-based mortar. Here we present the first results of an historical analysis into the construction and restoration phases of this historic landmark. The tower has undergone several structural interventions in 19th century in order to remediate differential movements of the tower's foundations and out-of-plane rotations of perimetral walls.

An accurate 3D digital survey has highlighted currently satisfactory structural conditions, with crack patterns and out-of-plane wall rotations evident but limited in their development. The analysis of masonry quality also provided an estimated compressive masonry strength of 5.8 MPa. Sandstone blocks throughout the tower and in association with specific construction phases have been subjected to non-destructive testing (rebound test). Finally, a dynamic investigation is underway to find out the dynamic behavior of the bell tower in terms of natural frequencies and vibration modes.

ACKNOWLEDGEMENTS

The authors thank L. Gao for assistance which made this work possible. R. Blong provided helpful suggestions and the EGU Editorial Office provided support. Northumbria University provided the funding which made this research possible through the PhD project "Structural Identification of St. Nicholas Cathedral and Northumberland religious historic constructions". Thanks to Mr. David

Heslop and Mr. Scott Gordon for their willingness in survey permissions to the St. Nicholas Cathedral bell tower.

REFERENCES

[1] Gentile, C. and Saisi, A. (2007). "Ambient vibration testing of historic masonry towers for structural identification and damage assessment." *Constr. Build. Mater*., 21(6), 1311-1321.

[2] Russo, G., Bergamo, O., Damiani, L. and Lugato, D. (2010). "Experimental analysis of the "Saint Andrea" Masonry Bell Tower in Venice. A new method for the determination of "Tower Global Young's Modulus E"." *Eng. Struct*, 32(2), 353-360.

[3] Carpinteri, A. and Lacidogna, G. (2006). "Structural monitoring and integrity assessment of medieval towers." *J. Struct. Eng.-ASCE*, 132(11), 1681-1690.

[4] Ivorra, S. and Pallares, F.J. (2006). "Dynamic investigations on a masonry bell tower." *Eng. Struct.*, 28(5), 660-667.

[5] Ivorra, S., Pallarés, F.J., Adam, J.M. and Tomás, R. (2010). "An evaluation of the incidence of soil subsidence on the dynamic behaviour of a Gothic bell tower." *Eng. Struct.*, 32(8), 2318-2325.

[6] Binda, L., Zanzi, L., Lualdi, M. and Condoleo, P. (2005). "The use of georadar to assess damage to a masonry bell tower in Cremona, Italy." *NDT. & E. Int.*, 38(3), 171-179.

[7] Anzani, A., Binda, L., Carpinteri, A., Invernizzi, S. and Lacidogna, G. (2010). "A multilevel approach for the damage assessment of historic masonry towers." *J. Cult. Herit.*, 11(4), 459-470.

[8] Castori, G., Borri, A., De Maria, A., Corradi, M. and Sisti R. (2017). "Seismic vulnerability assessment of a monumental masonry building", *Eng. Struct.*, 136: 454-65.

[9] Gentile, C., Saisi, A. and Cabboi, A. (2015). "Structural identification of a masonry tower based on operational modal analysis." *J. Cult. Herit*, 9(2), 98-110.

[10] Saisi, A., Gentile, C. and Guidobaldi, M. (2015). "Post-earthquake continuous dynamic monitoring of the Gabbia Tower in Mantua, Italy." *Constr. Build Mater*, 81, 101-112.

[11] Júlio, E.N.B.S., da Silva Rebelo, C.A. and Dias-da-Costa, D.A.S.G. (2008). "Structural assessment of the tower of the University of Coimbra by modal identification". *Eng. Struct.*, 30(12), 3468-3477.

[12] Borri, A., Castori, G., Corradi, M, Sisti R. and De Maria, A. (2016). "Seismic analysis of artistic assets: The Piero della Francesca's fresco called 'Resurrection'." *Proc., 10th International Conference on Structural Analysis of Historical Constructions (SAHC2016),* Leuven, Belgium, on USB.

[13] Pieraccini, M., Dei, D., Betti, M., Bartoli, G., Tucci, G. and Guardini, N. (2014). "Dynamic identification of historic masonry towers through an expeditious and no-contact approach: application to the "Torre del Mangia" in Siena (Italy)." *J. Cult. Herit.*, 15(3), 275-282.

[14] Lerma, J.L., Navarro, S., Cabrelles, M. and Villaverde, V. (2010). "Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study". *J. Archaeol. Sci.*, 37(3), 499-507.

[15] Lambers, K., Eisenbeiss, H., Sauerbier, M., Kupferschmidt, D., Gaisecker, T., Sotoodeh, S. and Hanusch, T. (2007). "Combining photogrammetry and laser scanning for the recording and modelling of the Late Intermediate Period site of Pinchango Alto, Palpa, Peru." *J. Archaeol. Sci.*, 34(10), 1702-1712.

[16] Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A. and Allison, R.J. (2005). “Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion”. *Q. J. Eng. Geol. Hydrog.*, 38(4), 363-375.
[17] Abellán, A., J. M. Vilaplana, and J. Martínez. (2006). “Application of a long-range Terrestrial Laser Scanner to a detailed rockfall study at Vall de Núria (Eastern Pyrenees, Spain).” *Eng. Geol.*, 88(3), 136-148.
[18] Lim, M., Petley, D.N., Rosser, N.J., Allison, R.J., Long, A.J. and Pybus, D. (2005). “Combined digital photogrammetry and time-of-flight laser scanning for monitoring cliff evolution.” *Photogramm. Rec.*, 20(110), 109-129.
[19] Nguyen, H.T., Fernandez-Steeger, T.M., Wiatr, T., Rodrigues, D. and Azzam, R., (2011). “Use of terrestrial laser scanning for engineering geological applications on volcanic rock slopes–an example from Madeira island (Portugal)”. *Nat. Hazards Earth. Syst. Sci*., 11(3), 807-817.
[20] González-Aguilera, D., Gómez-Lahoz, J. and Sánchez, J. (2008). “A new approach for structural monitoring of large dams with a three-dimensional laser scanner.” *Sensors*, 8(9), 5866-5883.
[21] Rüther, H., Chazan, M., Schroeder, R., Neeser, R., Held, C., Walker, S.J., Matmon, A. and Horwitz, L.K. (2009). “Laser scanning for conservation and research of African cultural heritage sites: the case study of Wonderwerk Cave, South Africa.” *J. Archaeol. Sci*., 36(9), 1847-1856.
[22] Guidi, G., Beraldin, J.A. and Atzeni, C. (2004). “High-accuracy 3D modeling of cultural heritage: the digitizing of Donatello's ‘Maddalena’.” *IEEE T. Image Process.*, 13(3), 370-380.
[23] Mackenzie, E. (1827). *A descriptive and historical account of the town and county of Newcastle upon Tyne: including the borough of Gateshead* . Mackenzie and Dent.
[24] Bourne, H. (1736). *The History of Newcastle upon Tyne: or, the Ancient and Present State of that Town.* J. White.
[25] Wood, W.H. (1905). *A description of the tower and spire of St. Nicholas cathedral, Newcastle on Tyne*, Northern Architectural Association.
[26] Bell, F.G. (1978). “The physical and mechanical properties of the fell sandstones, Northumberland, England.” *Engineering Geology*, 12, 1-29.
[27] Borri, A., Corradi, M., Castori, G., & De Maria, A. (2015). “A method for the analysis and classification of historic masonry.” *Bull. Earthq. Eng.*, 13(9), 1-19.
[28] Corradi, M., Borri, A., Castori, G. and Sisti, R. (2014). “Shear strengthening of wall panels through jacketing with cement mortar reinforced by GFRP grids.” *Compos. Part. B.-Eng*, 64, 33-42.
[29] Borri, A., Castori, G., Corradi, M. and Speranzini, E. (2011). “Shear behavior of unreinforced and reinforced masonry panels subjected to in situ diagonal compression tests.” *Constr. Build. Mater*, 25(12), 4403-4414.
[30] Haramy, K.Y. and DeMarco, M.J. (1985). “Use of the Schmidt hammer for rock and coal testing.” *Proc., 26th US Symposium on Rock Mechanics (USRMS)*. American Rock Mechanics Association.