

# Modelling Medieval Vaults: Comparing Digital Surveying Techniques to Enhance our Understanding of Gothic Architecture

Nicholas Webb<sup>1</sup>, Alexandrina Buchanan<sup>2</sup>, John Robert Peterson<sup>3</sup>

<sup>1,2,3</sup>University of Liverpool

<sup>1,2,3</sup>{njwebb|alexandrina.buchanan|j.r.peterson}@liverpool.ac.uk

*Surveying tools such as laser scanning and photogrammetry are increasingly accessible, providing opportunities as digital mediators to enhance our understanding of architectural heritage. Here we discuss and compare the use of both techniques as starting points to analyse medieval vaults at two sites in England: Chester Cathedral and Exeter Cathedral. The project is inspired by the work of Robert Willis, a Victorian scholar who hypothesised how medieval vaults were designed and constructed; however, he did not have sufficient survey data to fully prove his theories. We will discuss the accuracy of each digital survey method in relation to our research that occurred at two distinct scales: the overall geometry of vault rib arcs where vault bays were several metres in length and width, as well as more detailed investigations of individual rib profiles where millimetre accuracy is required. We will compare laser scanning with photogrammetry in terms of their methodological and practical applications to architectural heritage in the particular context of medieval vault design, in order to assess the relative merits of each and aid decision-making as to which method should be used in specific circumstances.*

**Keywords:** *Photogrammetry, laser scanning, point cloud modelling, medieval vaults, digital heritage*

## INTRODUCTION

At the University of Liverpool a team of researchers are studying medieval vault design and construction in the British Isles (Webb and Buchanan 2016), and consequently the most appropriate applications of digital techniques to enhance our understanding of this topic. Both laser scanning and photogrammetry offer the ability to create point cloud models and digital mesh models to a high level of accuracy in defined environments (Corns 2015, Tallon 2014) and

we are investigating how these techniques compare based on our specific lines of enquiry.

This paper describes a pilot study to digitally document the medieval vaults at Chester Cathedral, and a later study at Exeter Cathedral, both in England (Figure 1). The investigation forms part of a larger project, where vaults at Wells Cathedral, Ely Cathedral, Nantwich St Mary's Church and Ottery St Mary Church have also been documented. The study is inspired by the research of the Victorian scholar Robert

Willis who encouraged members of the Royal Institute of British Architects to survey medieval vaults in order to gain enough information to develop theories regarding their design and construction (Willis 1842). However, due to the limitations of manual surveying techniques in comparison to the significant task of documenting the vaults, usually high up in the cathedral interior, his challenge was not answered.

The introduction of digital techniques makes it possible to survey existing buildings accurately and rapidly, and additionally offers the potential to provide a new analysis of significant works of architecture through the exploitation and manipulation of this data (Di Mascio 2015, Giannattasio et al 2013). In the context of medieval vaults, this has enabled us to gather data for analysis in a matter of days, as opposed to the same task that would have taken many weeks if completed manually, not to mention the added risk of human error (Richens and Herdt 2009). Nevertheless, the digital process still requires careful planning and documentation, not only to deliver transparency in relation to the methodology used, but also to ensure that accuracy is provided and that any errors or deviations are kept to an acceptable minimum (Mitchell 1992). This is important, as investigations into vault geometry should be assessed against the precision of the digital survey data, as like physical copies, there is a risk they may become a faded facsimile with each version, such as creating a digital mesh model from a point cloud model. Consequently, for the purposes of transparency and accuracy it is important to be able to verify any data against an equivalent dataset derived by alternative means.

Medieval vault design and construction is synonymous with the conference call of 'complexity and simplicity'. Whilst medieval vaults may appear to have simplicity and clarity in terms of their geometry when analysed visually, the use of digital surveying and modelling techniques has revealed an underlying complexity demonstrating this is not necessarily the case. For example, Willis discusses in his original article different methods of establishing a vault

rib's curvature based on its association with a floor plan, its radius, its centre point(s) and the relationship of the centre point(s) to the rib's impost line. He also hypothesises how the profile of vault ribs may be distorted on tas-de-charge stones, where ribs diverge to form individual elements, which is unreliable to establish by eye. The use of digital surveying techniques makes this complexity apparent.



Figure 1  
Vaults from the  
Chester Cathedral  
Chapter House (left)  
and Exeter  
Cathedral Lady  
Chapel (right) for  
the large scale  
investigation.

## LINES OF ENQUIRY FOR COMPARISON

Although Willis made many suggestions for future research on the design and construction of the vaults, we will focus on two lines of enquiry to demonstrate the potential advantages and disadvantages of both photogrammetry and laser scanning at different scales. In order to examine the curvature of the vault ribs and relate these to the linear geometry of the plan, the line of enquiry at a larger scale documented the overall geometry of vault rib arcs, where vault bays were several metres in length and width, at the two case study sites; the Chapter House at Chester Cathedral, generally dated to c.1250-1260 (Hartwell et al 2011), and the Lady Chapel at Exeter Cathedral, dated c.1280-1290 (Cherry and Pevsner 2004). To do this we created orthophotos in plan and section to assess any significant features that were not apparent when studying the vaults by eye. The line of enquiry at a smaller scale investigated Willis's hypothesis that the rib profile of

tas-de-charge stones were distorted for ease of construction, where millimetre accuracy was required to obtain satisfactory results. A respond supporting a tas-de-charge comprised of three courses of worked blocks in the Chapter House at Chester Cathedral and a two-course tas-de-charge above one of the piers of the south nave arcade at Exeter Cathedral, generally dated as 1332-1334 (Erskine 1983), were used (Figure 2). For this investigation we used a combination of orthophotos and point cloud models to ascertain the profiles of the ribs as they met at the springing point as accurately as possible. These studies relating to scale are vital as it may be apparent that the survey data becomes more or less reliable depending on whether photogrammetry or laser scanning is used, and reiterates the need for accuracy in such research (Kersten 2007).

Figure 2  
A pier (right foreground) in the south nave arcade at Exeter Cathedral was used for the small scale study.



## PHOTOGRAMMETRY PROCESS

The first method used to digitally document the medieval vaults was photogrammetry. The only piece of equipment required besides the camera was a tripod; therefore they were logistically simple to transport to the two sites. A 24MP Sony a77ii camera was used to take photographs with approximately 200 images captured at each site. Lenses with 35mm equivalent lengths of 24mm, 45mm, 75mm and 150mm were used for different elements of the surveys. Targets were positioned in the cathedral interiors as common reference points between photographs (Figure 3), and several measurements were taken between distinctive features as a method of scaling the images once they were imported into the photogrammetry software. A level ground plane was also desirable; different methods such as plumb lines and spirit levels were tested, however, as yet we have been unable to find a definitive solution to accurately plot this.

Next the photographs were processed using Adobe Lightroom, where RAW files were converted into high quality JPEGs and unsuitable photographs removed. Following this, the photographs were imported into Agisoft Photoscan to begin the procedure of creating three-dimensional digital models. Photoscan automatically locates the targets positioned in the cathedral interiors during photography, and the measurements taken are input as scale bars and full three-dimensional co-ordinates for known points on the ground plane. An accurate camera alignment is then performed, and tensions between the targets and scale bars are calculated. Finally, a bounding box is drawn around the area to be investigated, which is then processed into and exported as a high-density point cloud or mesh model. With photogrammetry, getting the correct settings when photographing the spaces was particularly important; this was an issue at the Chester Cathedral pilot study, which will be discussed later on. We also found that capturing the geometry of the spaces carefully could be problematic and had to be well planned in advance; too many photographs resulted in the Photoscan software crashing on a MacBook Pro with

16GB of RAM, whereas using too few photographs produced poor results.



### LASER SCANNING PROCESS

The laser scanning was performed using a Faro Focus 3D X330, mounted on a tripod for most scans (Figure 3). The tripod and the two cases holding the scanner and its proprietary spherical targets can be carried by one person if necessary, or comfortably between two people. Several scans were taken of the medieval vaults; at the Exeter Lady Chapel and Chester Chapter House two scans were taken in each vault bay with an additional scan in the centre of each space for context. Two scans per bay were taken to ensure that details were captured along the entire width of the rectangular bays. Two scans were taken of the column in the nave arcade at Exeter. Similarly to the photogrammetry process, all laser scans were taken from ground level. This did result in some small areas of the scan being obscured or less detailed as they could not be seen from below, however, these were not significant enough to affect our research questions and justify using scaffolding or a basket crane. Spherical targets were placed in the interior for processing later on. At Chester we chose not to capture colour data, whereas at Exeter we decided on full

colour scans, where the laser scanner captures colour using the available light.

Faro's own scan software, Scene, was used to create point cloud and mesh models. Once imported, the spherical targets were tagged in each scan, and through a registration process they were combined into a single point cloud model. We could then create orthophotos; orthographically correct images in plan and section, as a method of analysing the overall geometry of the two spaces studied at Exeter and Chester. Following this, point cloud models of the combined scans were exported for further analysis, as well as mesh models. Faro Scene can directly export mesh models of a single scan only, and tests using other software such as Meshlab to convert point clouds to mesh models proved unsatisfactory, therefore mesh models of single scans were imported into Rhino and combined when necessary for the research. One of the main issues we had with the laser scanning process was that resulting orthophotos produced by combining several scans often depicted areas of shadow as well as changing light levels that sometimes occurred across different scans; a downside not considered by the medieval masons in their quest for light, well-lit spaces.

### LINES OF ENQUIRY: LARGE SCALE SURVEYS

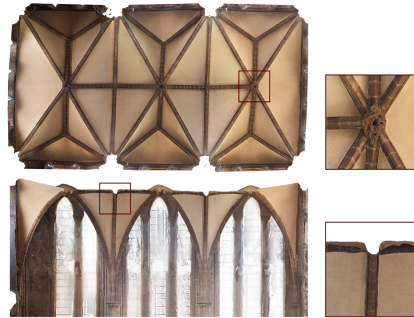
The first line of enquiry investigated the overall geometry of the vaults at the Chester Chapter House and Exeter Lady Chapel in plan and section, focusing on the position and curvature of the ribs. It is widely accepted that masons first traced the plan of the vault full scale on a tracing floor and then projected arcs upwards to form the three dimensional geometry, rather than making scale drawings or plotting the full design beforehand (Porter 1997). Therefore, having access to orthographically correct plans and sections enabled us to interrogate the design and construction processes. As mentioned previously, we used orthophotos created from both photogrammetry and laser scanning.

Figure 4 shows orthophotos in plan and section

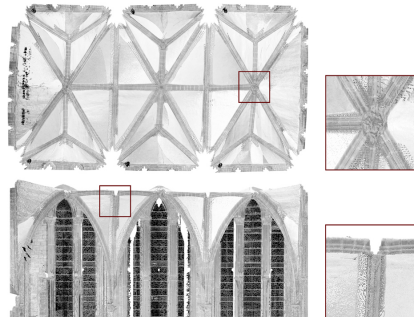
Figure 3  
Photogrammetry targets positioned on the wall of the Chapter House at Chester Cathedral, with the laser scanner also capturing data in the foreground.

Figure 4  
Comparative  
images of surveys  
taken at Chester  
Cathedral (left) and  
Exeter Cathedral  
(right), with the  
photogrammetry  
survey shown  
above, the laser  
scan survey in the  
centre and the two  
surveys overlaid to  
demonstrate their  
accuracy below.

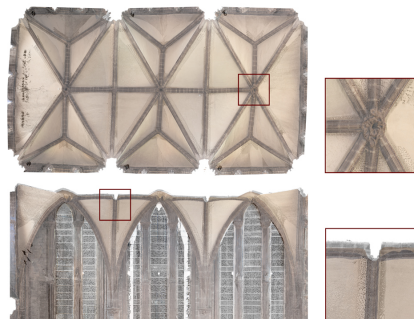
### Chester Cathedral Chapter House



Photogrammetry

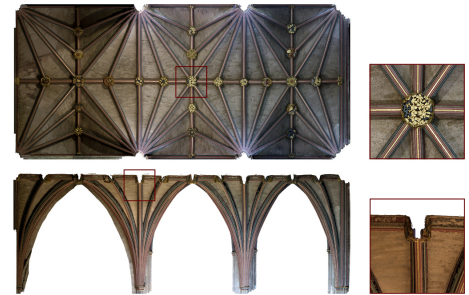


Laser scanning



Overlay of both techniques

### Exeter Cathedral Lady Chapel



Photogrammetry



Laser scanning



Overlay of both techniques

of the Exeter Lady Chapel and the Chester Chapter House. Overlaying the two and looking at the spaces as a whole demonstrated that photogrammetry and laser scanning produce almost identical results, which could be used for accurate measurement and investigation of the building features at a large scale. The fact that both methods produced similar results provides mutual validation, especially as this occurred at both case study sites. However, in some scenarios the usability of the orthophotos becomes less successful at a detailed scale, as can be seen from the highlighted areas in Figure 4. Graining is apparent on the laser-scan produced images due to the overlap of scans as mentioned previously, and the sectional photogrammetry models have a lack of accuracy in depicting the rib curvature in section, which appears to be faceted rather than smooth. The photogrammetry models were most successful in plan as photographs were taken from the cathedral floor capturing surfaces directly above. These images leave us with a precise record of building elements for analysis, such as sizes of individual rib stones, or voussoirs, as well as sculptural details on rib bosses.

The plan images of Chester show us how the apparently rectangular bays are actually parallelograms, and the sectional images reveal how the ridgeline rises considerably at each end to meet the window and vestibule respectively; both factors that are difficult to see by eye. The plan images at Exeter demonstrate that each bay gets progressively longer moving from east to west, suggesting poor setting out at the start and/or a need to meet with an existing feature, and the sectional images show that the vaults have a flat ridge line.

## **LINES OF ENQUIRY: SMALL SCALE SURVEYS**

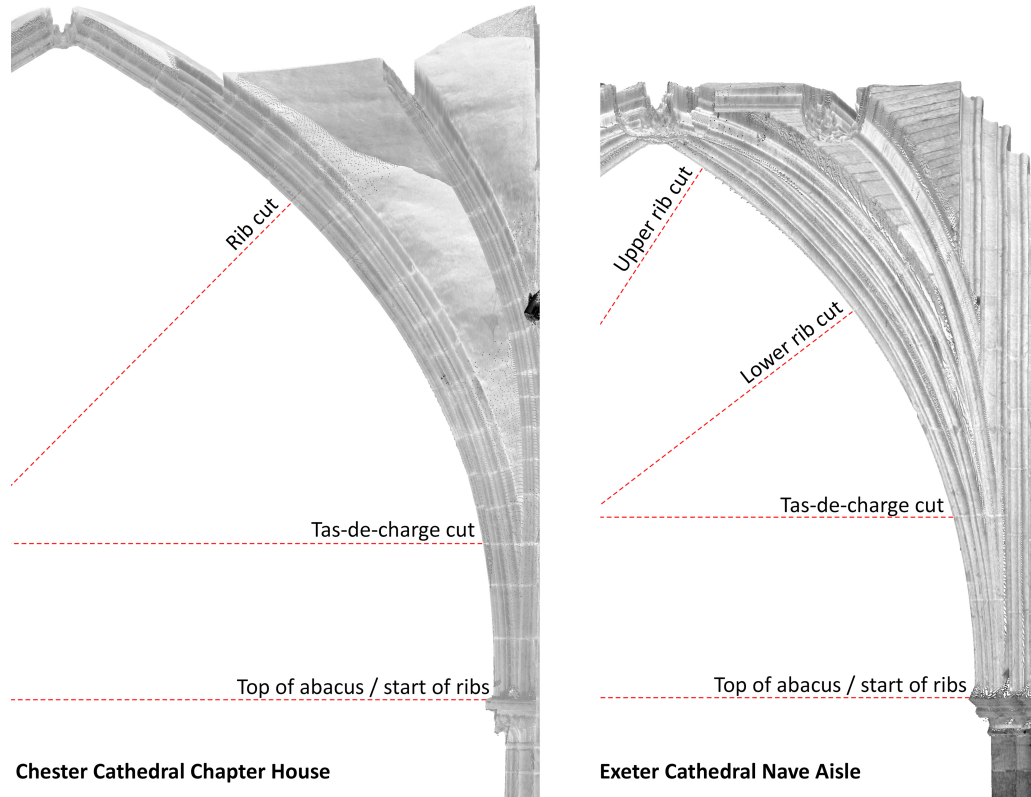
The second line of enquiry utilised a Chester Chapter House springer and Exeter South Nave springer to review small-scale surveys. This follows up on Willis's hypothesis that the templates (moulds from which the ribs were cut) used for the *tas-de-charge*, where the ribs are worked from a single block as they begin

to diverge, did not use projection techniques (Willis 1842). By studying marks on a stone from a ruined vault at Canterbury Cathedral, Willis suggested that the masons might create a distorted springing. This is because some of the individual *tas-de-charge* blocks were cut horizontally, rather than radially from the rib arc's centre as expected from typical arch design (Figure 5). Consequently, if the rib template is not adjusted when laid horizontally, it results in a distorted rib profile along the *tas-de-charge* stone. Investigating this is of particular interest as, besides the initial studies by Willis at Canterbury, *tas-de-charge* distortions have also been documented by Pérez De Los Ríos and Rabasa (2014) at Narbonne cloister vaults, Valdecristo Charterhouse, La Trinidad Convent, Perpignan Chapter Hall and Lonja de Palma, as well as documentation by Vidal (2011) at Santa María de Huerta Monastery. However, it is yet it is unknown whether this was universal practice.

To test whether or not this occurred at our case study sites, we firstly had to study the orthophotos created previously to ascertain whether or not cuts were radial or horizontal. Working with the colour images for Exeter made mortar joints unclear, therefore the colour data was discarded for this line of enquiry. Examining the orthophotos of a selected springing in the Chester Chapter House and another in the nave aisle at Exeter clearly showed in both cases that their *tas-de-charge* blocks were cut horizontally (Figure 5).

The next step used the digital data to take sections through the diagonal cuts, or mortar joints, of the transverse ribs to establish the profile and then test these against the *tas-de-charge* horizontal section. If the two matched, this would support Willis' theory that the ribs were distorted based on the masons not adjusting the rib templates. For this investigation the point cloud models were most effective as the mesh models had a faceted profile making them less reliable. Once flattened, the points were traced in red using MicroStation V8i to create the rib profiles, and then compared by overlaying the different examples over each other. Figure 6 shows comparative data captured at Chester using both laser scanning

Figure 5  
At both Chester and Exeter, horizontal cuts are apparent in tas-de-charge stones when studying the orthophotos created from the survey data. In addition to tas-de-charge stone cuts, the images also demonstrate the locations of radial rib cuts.

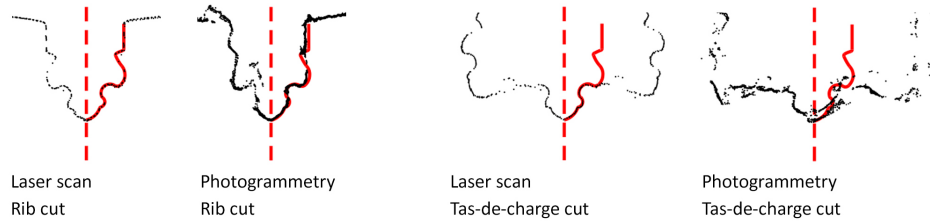


and photogrammetry. The images show that results for the photogrammetric study at Chester were unreliable, whereas the laser scanned version produces an accurate rib profile for tracing. It is important to state that the data captured at Chester was intended for the large-scale investigations only, and whilst the laser scan data also proved adequate for more detailed investigations, we realised that for photogrammetry to be effective a more strategic approach was required.

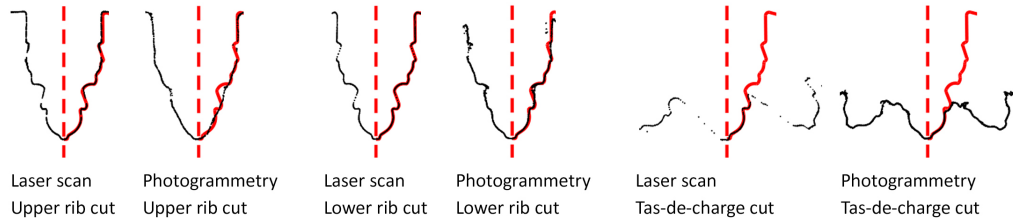
At Exeter, based on our previous findings, we selected a single pier and produced a photogrammetric survey of it. As a strategy, the images of the

tas-de-charge and vault ribs springing from the abacus were more focussed, and consequently the wider context was ignored. The data was then processed alongside the laser scanned version of the pier. Data from Exeter in Figure 6 shows that the laser scanned tracing of rib profiles was still more accurate than the photogrammetric survey. This is particularly noticeable for the upper rib cut, where the laser scan data shows all the intricacies of the rib profile, while the photogrammetry data shows the general shape of the rib profile, but the details of the ribs are lost. However, when we compare the profiles of the main pier below the abacus line, we can see that the pho-

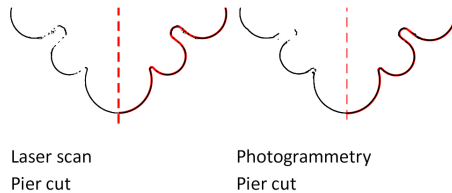
### Chester Cathedral Chapter House



### Exeter Cathedral South Nave Arcade



### Exeter Cathedral South Nave Arcade



ogrammetry version is comparable to the laser scan version (Figure 6). This is because of two factors, firstly the pier shafts are lower than the ribs and secondly the pier itself features in the majority of digital images used for photogrammetry, therefore it is documented much more thoroughly than the ribs. This tells us that photogrammetry could be a viable method of investigating tas-de-charge distortions if we could get close enough to the ribs using scaffolding or a basket crane, however, as we have the use of a laser scanner this method is still the most successful in terms of both results and logistics.

Based on the results obtained primarily from

laser scanning we can state that the standard rib cuts matched those of the tas-de-charge blocks in the selected features at both Chester and Exeter. This supports Willis's theory that the overall rib profile is distorted at the springing, probably, according to his interpretation, for ease of constructive practice when this construction shortcut would be invisible to the viewer.

### RECOMMENDATIONS AND REFLECTIONS

The surveys captured at Chester Cathedral were part of a pilot study, whereas those captured at Exeter

Figure 6  
Cuts taken through mortar joints of vault ribs and tas-de-charge stones are compared. As the most accurate representation, the laser-scanned profile is then traced in red and overlaid with the photogrammetry-produced images.



Cathedral occurred after further trials at several other sites. Therefore we had the chance to refine our methods and consequently, we should take into account that the photogrammetry data at Chester could be improved if we were to survey it again. For example, Chester showed us that to study the tas-de-charge using photogrammetry required an in depth survey of the feature itself, rather than relying on wider contextual data. Consequently, the photogrammetry data at Chester was not representative of that developed at additional sites such as Exeter. On the other hand, the laser scan data proved to be successful at all scales and incidentally, we decided to lower the resolution of our scans for later sites from approximately one point every one and a half millimetres to one point every three millimetres, as the datasets we were producing were too large. This again demonstrates the accuracy that the laser scans provide.

As a methodology, particularly when scans of cathedral interiors are taken from the floor, we propose that both laser scanning and photogrammetric survey methods are viable for producing orthophotos to investigate the overall geometry of medieval vaults, and that photogrammetry provides higher quality orthophotos to study vault details such as rib bosses. However, when using point clouds in three-dimensional modelling software it is clear from the research presented here, as well as data from other sites such as Wells Cathedral, that photogrammetry is not sufficient at capturing the intricacies of rib profiles when photographs are taken from the cathedral floor. Therefore, the use of laser scanning is the superior option, particularly as it gives very accurate results from several metres away.

We intend to continue documenting sites for the project using both methods, since they can be carried out in parallel and essentially, each technique can be used as validation of the other in terms of accuracy. Our next step is to investigate using the photogrammetric models as wrap around images for the laser scan models, therefore combining the superior visual images of the photogrammetry with

the accuracy of the laser scans. Most importantly to the project, the use of both laser scanning and photogrammetry has enabled us to enhance understanding of medieval vaults, and support arguments regarding of their design and construction initially put forwards by Willis over 175 years ago.

## ACKNOWLEDGEMENTS

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## REFERENCES

- Cherry, B and Pevsner, N 2004, *Devon (Pevsner Architectural Guides)*, Yale University Press, New Haven and London
- Erskine, A (Ed) 1983, 'The accounts of the fabric of Exeter Cathedral, 1279-1353', *Devon and Cornwall Record Society*, 26, p. xxxi
- Giannattasio, C, Grillo, SM and Vacca, G 2014, 'The medieval San Francesco convent in Cagliari: From the architectural, Material and Historical-Stratigraphical analysis to the information system', *International Journal of Heritage in the Digital Era*, 3(2), p. 413-429
- Hartwell, C, Hyde, M, Hubbard, E and Pevsner, N 2011, *Cheshire (Pevsner Architectural Guides)*, Yale University Press, New Haven and London
- Kersten, T 2007, 'Virtual Reality Model of the Northern Sluice of the Ancient Dam in Marib/Yemen by Combination of Digital Photogrammetry and Terrestrial Laser Scanning for Archaeological Applications', *International Journal of Architectural Computing*, 5(2), pp. 340-354
- Di Mascio, D 2015 'Analytical drawings of architectural built heritage', *Proceedings of EAEA12*, pp. 199-208
- Mitchell, W 1992, *The Reconfigured Eye*, Massachusetts Institute of Technology
- Porter, T 1997, *The Architect's Eye*, Taylor & Francis, New York
- Richens, P and Herdt, G 2009 'Modelling the Ionic Capital', *Proceedings of eCAADe 2013*, pp. 809-816
- Pérez De Los Ríos, C and Rabasa, E 2014 'Stretched templates in gothic tas-de-charge construction', *Pro-*

*ceedings of the First Construction History Society Conference*, pp. 333-342

Tallon, A 2014, 'Divining Proportions in the Information Age', *Architectural Histories*, 2(1), pp. 1-14

Vidal, RM 2011 'Bóvedas sexpartitas: Traza, estereotomía y construcción. Monasterio de Santa María de Huerta', *Actas del Séptimo Congreso Nacional de Historia de la Construcción*, pp. 821-832

Willis, R 1842, 'On the Construction of the Vaults of the Middle Ages', *Transactions of the Royal Institute of British Architects*, 1(2), pp. 1-69

[1] Corns, A 2015, '3D Icons Ireland', <http://www.3dicons.ie/process>

[2] Webb, N and Buchanan, A 2016, 'Tracing the Past', <http://www.tracingthepast.org.uk>