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Non-contact based photogrammetric technique for testing of rigid blocky masonry arch

Pratyusha Naik [1, *], Shibu Samson [2], Arun Menon [3]

[1] Department of Civil Engineering, PhD Research Scholar, Indian Institute of Technology Madras, Chennai, India
[2] Department of Civil Engineering, MS Research Scholar, Indian Institute of Technology Madras, Chennai, India
[3] Department of Civil Engineering, Associate Professor, Indian Institute of Technology Madras, Chennai, India

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Abstract

In case of dry jointed stone structural systems, the stone blocks can be assumed to be rigid with relative predominant displacements occurring along the joints giving rise to geometric non-linearity in these systems. The testing of such discontinuous systems becomes challenging task with contact-based measuring instruments such as LVDTs as the blocks are free to displace and/or rotate with six degrees of freedom. This technique is more often used for surveying of large existing structures in the field of civil engineering and its applicability to testing of structural systems has not been explored to a larger extent yet. The photogrammetry with motion module has been observed to be the one of the most reliable and feasible methods of instrumentation for dry jointed stone structural systems. With few quality control measures adopted from taking photos to the processing stage, sufficient accuracy of measurements can be achieved. In the present study, non-contact-based technique, photogrammetry is used for testing of a typical dry-stone corbel vault taking a scaled down model of an existing vaulted gallery of Ta Prohm, Cambodia. The findings from the study have been in agreement with the observed distress in the existing corbel vaulted galleries. It has been proved to be efficient, low cost method that uses simple handheld digital cameras giving reliable results with an accuracy up to 0.4 millimetres. Thus, photogrammetry is a way forward for testing of discontinuous structural systems such as dry-stone masonry.

Keywords: Rigid block, dry-stone masonry, dry-jointed masonry, corbel arch, non-contact measurement, photogrammetry

1. Introduction

1.1 Introduction to non-contact-based measurement methods:

Understanding the structural behaviour of any system can be through laboratory/field tests conducted on the structural elements in isolation or on system as a whole, analytical/numerical methods. While the experimental/numerical studies carried out on model involves idealization and making of certain assumptions, that carried out on the prototype/actual structure on field does not involve any idealizations. Experiments definitely form an important part of the study that is always reliable, provided the exact conditions are simulated. The experimental technique can be grouped into two methods based on measurement technique; viz, contact and non-contact measurements. Most commonly, the contact measurement methods involve use of deflection gauges, strain gauges, optical fibres, pressure gauges and load cells etc. Non-contact measurements using the classical method of transmission photoelasticity [1], [2] and modern Digital Image Correlation (DIC) techniques allow accurate measurement of deformation and quantification of stress in the test model [3]. The complete stress distribution obtained using these methods allows identification of critical locations such as that of principal stresses, maximum shear stresses indicating failure. In transmission photoelasticity technique, light is passed onto an optically sensitive material subjected to loading. The isochromatic fringes are observed through polariscope which help identify stress concentrations and locations of zero stress. This can help in the product manufacturing stage in order to achieve optimum shape and dimensions. The principle of Digital Image Correlation (DIC) on the other hand, is based on the correlation of digital images of the experimental model in consideration. The advantage of high speed DIC technique is that it can be applied to objects in motion as well. Unlike the transmission photoelasticity technique, this method can be used to obtain all the stress fields such as principal stresses, shear stresses, normal stresses and equivalent stresses from strain fields.

Another such no-contact based technique is Photogrammetry that is low cost and effective tool to map the locations of a real object in a 3D space with reasonable accuracy. Digital photogrammetry hence has been increasingly used to generate a 2D/3D CAD model of the structure that can then be used for development of a numerical model [4]. Digital photogrammetry combined with laser scanning is an effective tool to model complex surfaces and obtain a complete 3D model reconstruction. With recent advances in high resolution digital cameras and drones, the application of this technique has become more reliable. It has been successfully used to document the heritage sites ([5], [6]), digitization of historic cartography [7] and in geomorphological research applications [8], [9], [10]. Some of the recent studies report application of digital photogrammetry to motion problems [11] where the author has applied the technique of photogrammetry to study the aero-dynamic performance of wings of a mini–Unmanned Aerial Vehicle in a wind tunnel. The spectra of deflected shapes were obtained for stiff and flexible wings.

*Corresponding author. Tel: +918056862570; E-mail address: pratyushamnaik@gmail.com

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1.2 Digital photogrammetry method:

The basis for photogrammetry is the digital images, taken by a camera, drone or a smartphone. When light rays hit on an object, they get reflected and the image is captured on the camera's image sensor or film. Multiple photos of this object are taken by cameras at different known positions and angles, to carry out a 3D reconstruction of the object. The position of a point can be located in 3D space when the point is imaged in two or more photos, with known camera parameters and position and angles of the cameras capturing the images. The camera parameters such as focal length, lens distortion can be obtained from the camera calibration. The process of finding positions and angles of cameras is handled by a key algorithm called 'Bundle Adjustment' in photogrammetric software such as Photomodeler Premium ® to arrive at a solution, such that the bundle of light rays between all points and cameras are optimal. A reference scale then needs to be defined by the user to obtain the exact measurements in real units with one known measurement in the object. Target detection and marking tools of Photomodeler are used to obtain the location of key points in 3D space, identified using coded targets. Coded targets provide additional ability to automatically reference targets between photos. A RAD coded target is an efficient one with a high contrasting dot and a unique pattern around it. The resulting points can be used for line, curve, and surface modelling, or measurement and export as needed. Referencing helps the matching points in different images to be tied together. The coded target with offsets provides an automated method for obtaining the location of a point where a target cannot be placed (such as in a corner or under a lip). For objects in motion, the position of key points can be tracked by synchronizing multiple cameras using a simple infrared remote. one such set of images taken from multiple cameras at a time accounts to one epoch, thus 'n' number of epochs corresponds to positions of points calculated at 'n' intervals of time. The commercial Photomodeler Premium® [12] software has a unique motion module with automated tracking tool to carry out such measurements over several epochs with sets of images from multiple cameras as input. Also, all the cameras used in the project are pre-calibrated which is also an input for the project.

Digital photogrammetry technique has been applied to a scaled down 2D model of one of the vaulted entrance galleries of Ta Prohm temple, Cambodia to study its structural response under support in-plane rotations. The efficacy of this technique to measure accurate displacements over time using consumer grade digital cameras has been highlighted. An image processing photogrammetric software Photomodeler Premium ® [12] has been used for this purpose. Earlier numerical study on one of the corbelled dry-stone vaulted galleries of Ta Prohm, Cambodia carried out by Chandran et. al [13] showed the vulnerability of such systems to support rotations based on the observations of structural failures of temple vaulted galleries due to tree root penetration (see Figure 1). The numerical study was carried out in ANSYS 5.6, units modelled as two-dimensional plane stress elements with 4 nodes and joints as non-linear contact elements to capture possible sliding and rotational movements at the joints. The predominant failure mechanism was found to be overturning of the arch by hinging in case of outward rotation. Outward rotations as small as 10^{-4} radians was found to be enough to open up the horizontal joints followed by large rotation of blocks.

(a)

(b)

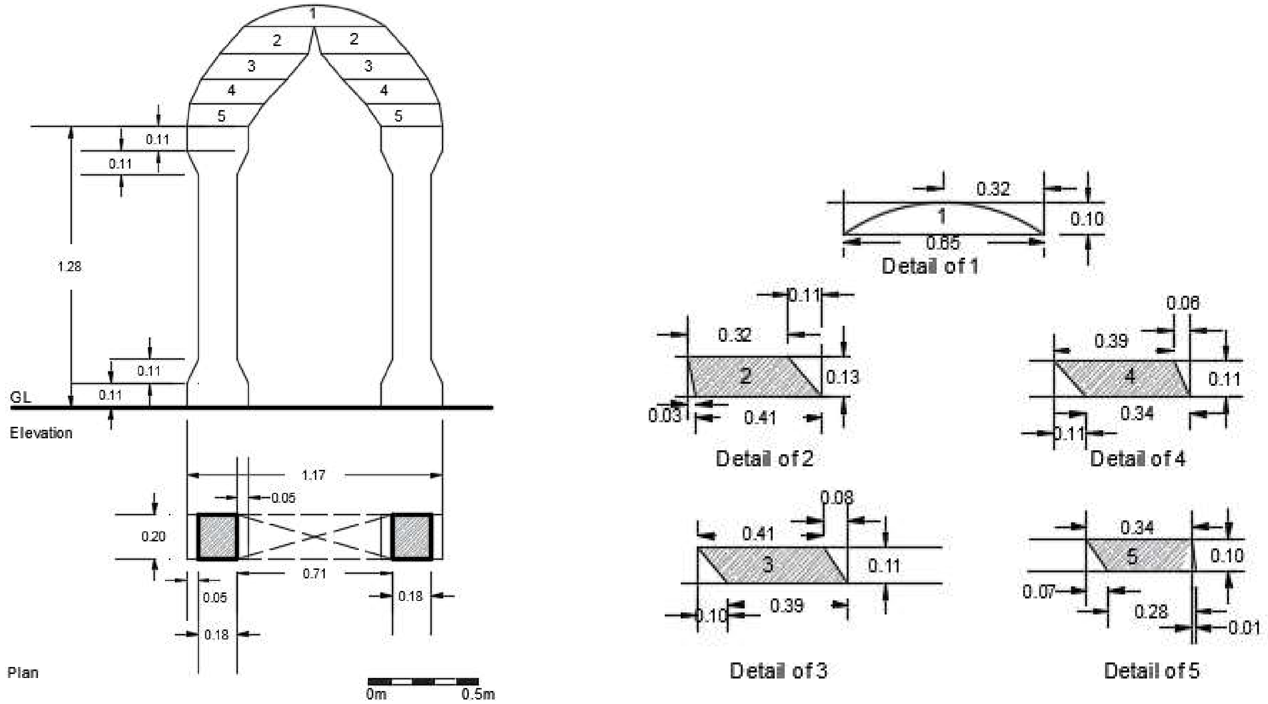
Figure 1: (a) Distress in corbel vaulted galleries of Ta Prohm due to support outward rotation (b) Damages due to support inward rotation (Chandran et. al [12])

Experimental study

2.1 Test setup and specimen details:

The test specimen is a 1:3 scaled down model of one of the corbelled vaulted galleries of Ta Prohm, Cambodia. It is dry stack masonry made of charnockite granite blocks due to the abundance of constructions in granite in the south east India. The granite used in the present study constitutes of about 40-45 percent of plagioclase feldspar, about 20-25 percent of quartz with about 5-10% of mafic minerals and about 5% of biotite, without any mortar in the assembled arch configuration. The density of blocks was 2700 kg/m^3 with an elastic modulus ranging between 8000-12000 N/mm^2 and compressive strength on cubes [14] varying between 67 and 107 MPa as obtained from the material characterization tests carried out by authors. The joint characterization study was also carried out by Naik et. al [15].

The cut stone blocks were assembled one above the other without any mortar. The details of the specimen are as shown in Figure 2.



(a) **(b)**

Figure 2: Details of test specimen (in metres)

The experimental study carried out to study the effect of relative support outward rotation involved fabrication of a specially designed test setup as shown in figure 3.

The test setup consisted of a steel beam of C-section bolted on to the strong floor. The right support was fixed with the base stone blocks resting on the steel platform with four pedestals bolted to the steel beam. On the left end, the base stone blocks rested on a steel platform that was in-turn welded on to a hinge mechanism specially fabricated to aid smooth rotation of the base platform above it (see Detail 'A' in Figure 3). The horizontal rod welded to the steel platform was designed with a socket for ball bearing arrangement that was connected to a vertical threaded rod to aid free rotation of the vertical rod and the base platform as well. Every cycle of rotation of vertical threaded rod led to in-plane rotation of steel base platform about the centre of the hinge at its base at the left end.

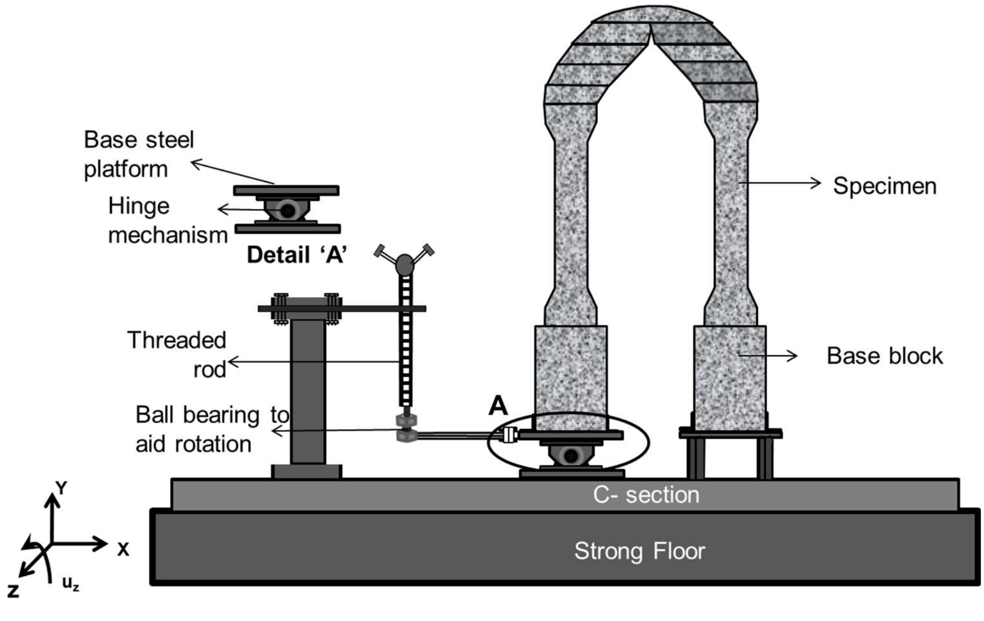


Figure 3: Schematic sketch of the test setup for relative support in-plane rotation

2.2 Test procedure and data processing:

Two tests were carried out with the same test setup. The support block at the left end was subject to in-plane outward rotation by turning knob of the vertical threaded rod in anti-clockwise direction, each rod giving 0.1 degrees. In another test, the support block at left end was subjected to inward rotation by turning the knob of vertical threaded rod in clockwise direction. In both the cases, the input rotation was measured in terms of inclination of the base steel platform with a digital laser inclinometer glued on to

the base steel platform in addition to the two LVDTs on either ends of the base platform. Photographs were taken at an interval of 0.1 degrees input inclination simultaneously from 3 cameras

that were stationed at 3 differentlocations using a remotely connected shutter remote. Three high-resolution cameras, namely one NIKON D5200, with a maximum resolution of 6010 ×4000 pixels (24.1 effective megapixels) and two NIKON D5300 cameras with a maximum resolution of 6000×4000 pixels (24.1 effective megapixels) were used in the study. Markers were pasted on the surface of each block at every corner to monitor the block's displacement right up to collapse (see Figure 4).

A grey coloured non-reflecting cloth was used as the back drop enhancing the quality of images. Sufficiently bright LED lights were positioned so that the targets could be captured distinctly preventing problems with marking and referencing in the processing stage. For the purpose of referencing and measurements a steel box section with coded targets was fixed at a position throughout the test (see Figure 4). Figure 5 shows a schematic sketch of the positions of cameras and lights to capture the images of the specimen. ‘CS’ refers to camera station, ‘L’ refers to LED lighting stand.

Each photograph taken by three cameras at every interval of time constitutes one test frame. The images of the all the chosen frames were processed to obtain the displaced geometry of each unit in every frame up to the collapse. From the processed set of images at each frame, the coordinates of the markers were located and the measurements were obtained based on the user defined coordinate system with

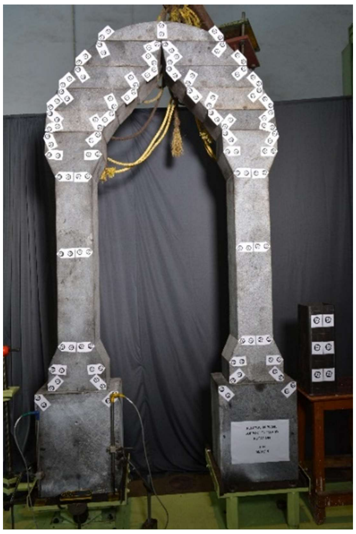
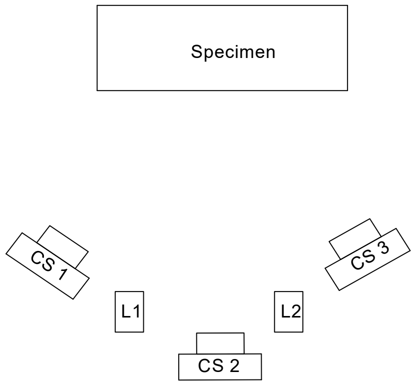
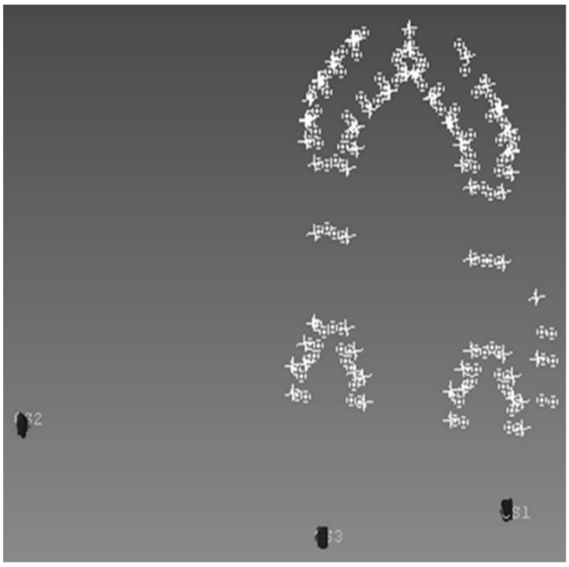


Figure 4: Test specimen with coded target markers



(a)



(b)

Figure 5: (a) Schematic sketch showing the positions of camera, lights and specimen (b) Positions of markers and camera stations evaluated by Photomodeler internal algorithm

measurement between the reference points on the reference block that remains unchanged throughout the test. Thus, the position of every marker on the block to the actual scale was obtained and evolution of a deformation mechanism was obtained quantitatively. Figure 6 depicts the procedure of image processing in Photomodeler Premium software to arrive at the results of displaced block positions.

2.3 Test results:

2.3.1 Under relative support in-plane outward rotation:

The corbel arch was found to be susceptible to support outward rotations with predominant failure mechanism being overturning by hinging at the springing level. It was evident from the tests that the increasing support outward rotation causes reduction in normal thrust as found out by Chandran et. al [12]. This leads to reduction in the frictional resistance of joints followed by large rotation of blocks and hence collapse by overturning. The displaced configurations processed in Photomodeler are shown in Figure 7. As seen in Figure 7, the half arch at the free end designated as ‘F’ overturned with blocks 2F, 3F, 4F and 5F as a single unit until there was restraint available at the opposite end. The out-of-plane displacements were found to be negligible. The input rotation needed to cause collapse was found to be 4.1 degrees.

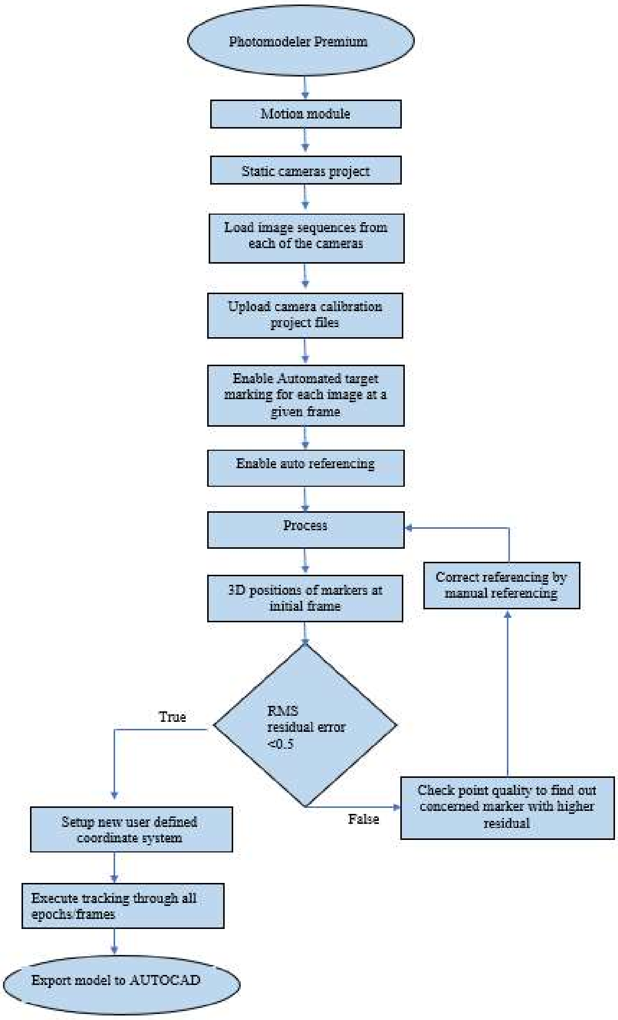
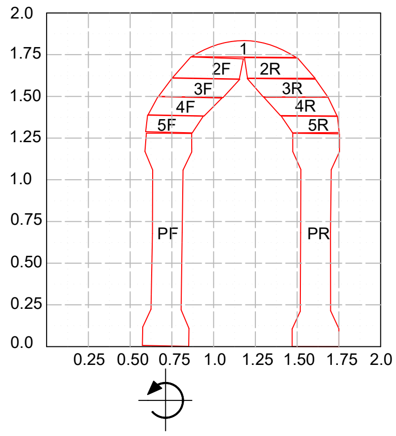
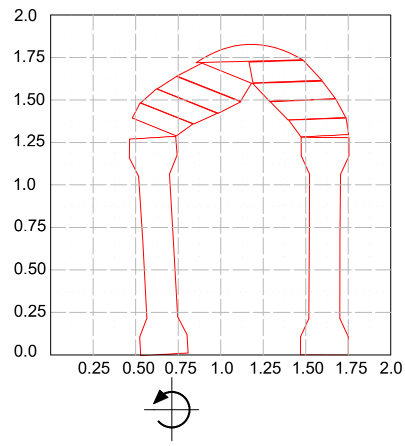


Figure 6: Image processing in Photomodeler



(a)



(b)

Figure 7: (a) Initial configuration at no rotation (b) Displaced geometry at an input rotation of 4 °

The corbel arch at the verge of collapse is shown in Figure 8. The downward Y displacement trend of right top most vertex of block 2F, point ‘A’ is shown in Figure 9 as the overturning mechanism evolves.

Figure 8: Corbel arch in the verge of collapse at an input outward rotation of 4 º

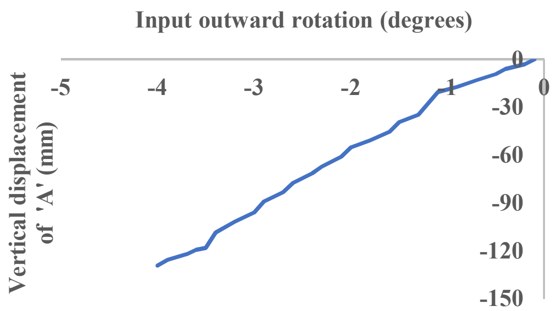
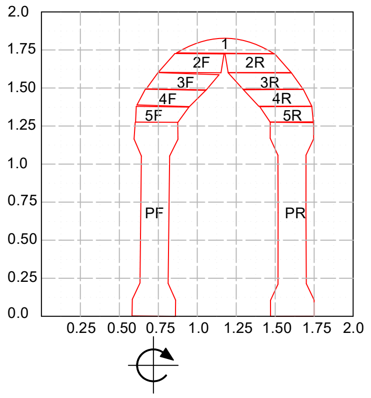


Figure 9: Input outward rotation vs response vertical displacement of ‘A’

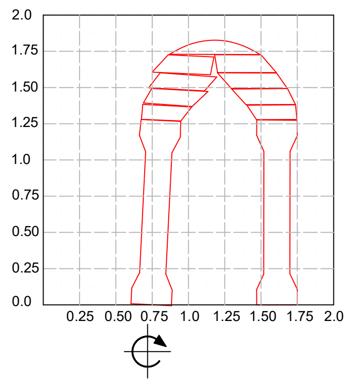
2.3.2 Under relative support in-plane inward rotation:

The support when subjected to inward rotation, the predominant failure mechanism observed was shear sliding failure mechanism along the joints. With the in-plane inward support rotation, the thrust along the joints increased leading to exceedance of the frictional resistance of the joint. The top joints were more vulnerable due to the lower normal stress, and hence lesser shear resistance. Therefore, the increased thrust resulted in shear sliding failure in the top joint between blocks 2F and 3F(see Figure 10b) , followed by failure in successive joints as shown in the Figure 10c. Figure 10 shows evolution of sliding shear failure along the joints from the processed images.

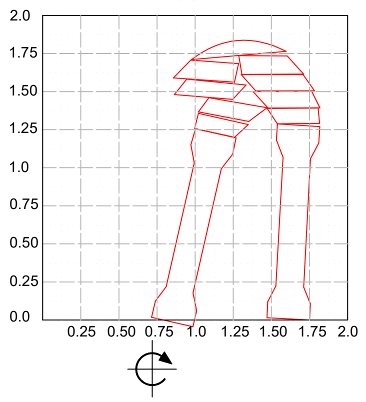
The test was stopped at an input rotation of 12.5 degrees, as the arch was found to be in a precarious condition (see Figure 11). Also, the intent of these tests was to assess the type of



(a)



(b)



(c)

Figure 10: (a)Initial geometry at zero rotation (b) Displaced geometry at input rotation of 2.3°(c) Displaced geometry at input rotation of 12.5°

Figure 11: Corbel arch in the verge of collapse at 12.5 ° input inward rotation

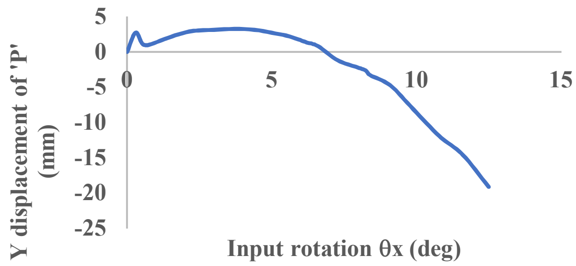


Figure 12: Input inward rotation vs response vertical displacement of 'P'

failure mechanism and its evolution rather than evaluating the values of collapse rotation. The response displacement of top left vertex of the free pedestal PF 'P' as seen in Figure 11 is presented in Figure 12.

Clearly, as seen in figure 12, the free pedestal 'PF' rotated with the support block without any restraint. The accuracy of measurements obtained from the processed images in Photomodeler for the present project was 0.4 millimetres.

3. Conclusions:

It is found that the dry jointed corbel arches are more susceptible to support outward rotations that could lead to collapse of the system. Even slightest of outward inclination can lead to opening up of the joints followed by overturning of blocks with further increase in the rotation. In case of shear sliding mechanism along joints caused due to support inward rotation, the relative displacement of the blocks occurs. This re-adjustment of the blocks continues with the joint of lowest normal stress, hence least frictional resistance giving away initially, until the frictional resistance of the lowest joint is exceeded. The results obtained from the current study reinforce the observations on structural distress in the corbelled vaulted galleries of Ta Prohm. From the study, it can be concluded that Photogrammetry can be adopted as an efficient method to measure and track the displacements, particularly in a discrete block system where large displacements and rotations are expected to occur. It proves to be a simple and cost-effective method to measure displacements that can be applied to tests on dry-jointed masonry systems. The only limitation can be some critical data can be lost if certain markers are not captured in minimum of two cameras for image processing, say in case of out-of-plane displacements. Hence number of cameras and their angles and positions should be accordingly adjusted so as to capture the images of all the markers at any time interval.

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Disclosures

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