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Title:

Simplified measurement technique for rigid-body deformations of two masonry blocks

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Abstract: (Your abstract must use Normal style and must fit in this box. Your abstract should be no longer than 1200 words. The box will ‘expand’ over 2 pages as you add text/diagrams into it.)

Preparation of Your Abstract

1. The title should be as brief as possible but long enough to indicate clearly the nature of the study. Capitalise the first letter of the first word ONLY (place names excluded). No full stop at the end.

2. Abstracts should state briefly and clearly the purpose, methods, results and conclusions of the work.

Introduction: Clearly state the purpose of the abstract

Methods: Describe your selection of observations or experimental subjects clearly

Results: Present your results in a logical sequence in text, tables and illustrations

Conclusions: Emphasize new and important aspects of the study and conclusions that are drawn from them

Introduction

Recently, the idea has been introduced to look beyond the limiting mechanism of the masonry arch and consider the behaviour of the mechanism itself and the role it can have on the system [1]. Initial investigations into this idea through FE analysis have shown that the arch can be strengthened, and the mechanism can be defined [2,3]. Therefore, the next stage is to begin the experimental investigation, but an efficient and effective measurement technique needs to be established.

The common failure of dry-joint masonry arches is by mechanization. This mechanization occurs through the release of a degree of freedom of motion at four or five block boundaries. Typically, the release is rotational, but it can also be the translational degree of freedom (slip) tangent to the joint. Slip can also transition to rotation after the onset of a mechanization, resulting in the eight possible motions defined in figure 1.

Under the traditional rigid-no tension assumptions of dry-stack masonry and the assumption of no out of plane motion, the displacements of the arch can be explicitly defined by the combined set of eight defined motions. The ability to identify and measure these displacements thus provide the opportunity to describe the motion of the system. The purpose of this work is to establish a simplified measurement technique for these common rigid-body displacements between two blocks of a masonry arch in contact.
**Methods**

If a 4x4 grid of points is applied across the joint and identified by lettered rows and numbered columns (figure 2), the change in lengths starting from the original configuration produce

\[ \Delta l_{a22} > \Delta l_{b22} > \Delta l_{c22} > \Delta l_{d22} \]  \hspace{1cm} (1)

for bottom rotations,

\[ \Delta l_{a22} < \Delta l_{b22} < \Delta l_{c22} < \Delta l_{d22} \]  \hspace{1cm} (2)

for top rotations and

\[ \Delta l_{a22} \approx \Delta l_{b22} \approx \Delta l_{c22} \approx \Delta l_{d22} > 0 \]  \hspace{1cm} (3)

for a slip, where

\[ \Delta l_{a22} = l'_{a22} - l_{a22} \]  \hspace{1cm} (4)

for each row. Similarly, the slip-rotation combinations produce

\[ \Delta l'_{a22} > \Delta l'_{b22} > \Delta l'_{c22} > \Delta l'_{d22} \]  \hspace{1cm} (5)

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**Figure 1** – Defined mechanical behaviours between two rigid blocks in an arch.
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And

\[
\Delta l'_{12} < \Delta l''_{23} < \Delta l'''_{32} < \Delta l''''_{43}
\]  

for bottom and top rotations respectively with

\[
\Delta l_{ij} = l''_{ij} - l'_{ij}
\]  

for each row. Equations (1) through (8) thus produce a simple method of motion identification for measurement selection.

Rotations

Rotations are measured by calculating the rotation angle, \( \alpha \), and then the distances from grid points to the rotation point. Assuming the point grid is parallel, normal and symmetric with the joint line in the original configuration, the rotation angle can be determined by

\[
\alpha = \cos^{-1}\left(\frac{l_{jk}l_{kl} - l_{kl}l_{jk}}{|l_{jk}||l_{kl}|}\right)
\]  

where the subscript \( j \) represents the column number and \( k \) and \( l \) are the two points in the
column. The hinge location is located through triangulation. The geometry defined in figure 3 results in normal, \( L_n \), and parallel, \( L_p \), lengths

\[
L_n = \frac{L_{c2}}{2} \\
L_p = \frac{L_{c2}}{2\tan(\alpha)} - \frac{L_{c2}}{2\sin(\alpha)}
\]

for each symmetric point pair evaluation.

Figure 3 – Triangulation geometry used to calculate hinge rotation point.

Slip Displacements
Slip displacements, \( \delta \), can be measured by considering the right triangle established from the original and slip configuration lengths for symmetric point pairs

\[
\delta = \sqrt{(L'_{c2})^2 - (L_{c2})^2}
\]

Slip + Rotation
The combination of slip and then rotation can be measured by calculating the rotation angle (equation (9)), translating the slip-displaced points along the fixed block boundary, applying equation (10) with the translated points, and finally adjusting the fixed block point-hinge lengths by the slip-translation lengths.
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**Results**

In the process of analysing the results of experimental measurements, angle calculations are very sensitive to the precision of the measurements. Redundancy however, provides a way to mitigate this loss of precision. The 4x4 point grid produces six length measurements per column. Comparing the rotated and original systems produces 24 calculations of the rotation angle. The comparison of the left and right column length vectors of the rotated system alone produces another 24 angle calculations. Therefore, the application of the point grid allows for 48 calculations of the rotation angle. If the precision of the point locations is uniform, then averaging the 48 measurement calculations increases the precision by a factor of 6.9.

The length measurement calculations are less sensitive than those of rotations, but they are still benefited by redundancy. Using the joint symmetric pairs produces 16 measurements of the hinge position for the rotation condition. This relates to an increase in precision by a factor of four with uniform measurement error. For the slip condition, the symmetric pairs produce 8 measurements, or a precision increase factor of 2.8.

For the slip to rotate conditions, the rotation calculation maintains its precision since the dot product has no sensitivity to the associated vector positions. The hinge position however requires a translation from the original slip. Precision is lost, but the ability to capture the transformation holds.

**Conclusions and Contributions**

The purpose of this work is to establish a simplified measurement technique for rigid-body displacements between two blocks of an arch in contact. By applying a 4x4 point grid parallel, normal and symmetric to the joint line and decomposing the identification and measurement strategies a simple measurement technique is developed. The identification of motion compares length changes in normal point pairs. The displacements, or rotations and hinge point can then be determined by simple triangulations. These measurements are constructed in the reference frame of the joint line and rotation point. The identified behaviour then allows the measurements to be oriented in the frame of the arch itself. Furthermore, the 4x4 grid produces an appreciable redundancy, increasing the precision of the calculated motions.

The next step in this work is to incorporate these measurements with imaged based point tracking techniques to create an automated measurement system.

**References**

