A STUDY OF TWO-WAY BENDING IN UNREINFORCED MASONRY

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I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.
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ABSTRACT

Masonry walls will almost invariably be required to resist lateral out-of-plane loads due to the action of wind or earthquakes; less commonly walls may be subjected to water or earth pressure or blast loading. Of particular interest is the common case which arises when the walls are supported on two or more adjacent edges. Under these conditions the masonry is subjected to a complex state of biaxial (two-way) out-of-plane bending combined with vertical in-plane compression due to the self weight of the wall and any superimposed loads. Different approaches currently exist for the design of masonry wall panels subjected to out-of-plane loads. However, these approaches are all empirical and often yield widely varying design recommendations and there has been significant criticism by proponents of the different methods regarding the use of alternative approaches.

In this study an extensive program of laboratory testing in parallel with numerical analysis was conducted to examine the bending, biaxial bending in particular, behaviour of masonry walls. The aim was to provide a better understanding of the behaviour at the fundamental level towards ultimately developing a fully rational biaxial-bending failure model that can predict behaviour under any simultaneous combination of bending moments in the two principal directions, along with a superimposed compression force on the bed joints.

Experimentally, “single joint” four brick unit specimens were studied comprehensively, using a newly commissioned test rig, by subjecting them to various vertical and horizontal bending moments both separately and in combinations, along with a superimposed compression force on the bed joints. These tests provided important information about the flexural behaviour of mortar joints and the torsional behaviour of bed joints. In addition, a complete set of characterization tests was also performed to study the fundamental material properties of masonry, which were important input parameters in the numerical modelling.

Numerically, a 3D non-linear finite element micro-model with cohesive contact was proposed and implemented in the ABAQUS/Standard software package. Numerical
analyses were performed to provide rational explanations to the bending behaviours observed in the four brick unit specimen tests and evaluate a newly proposed torsion shear test method. A simplified 3D non-linear finite element micro-model was also proposed to simulate the bending behaviour of small walls. Its effectiveness was clearly demonstrated in its application to masonry walls, with or without openings, subjected to both in-plane and out-of-plane loads.


## List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>The area of brick surface (or bed joint area)</td>
</tr>
<tr>
<td>$c$</td>
<td>Cohesive shear strength</td>
</tr>
<tr>
<td>$c_0$</td>
<td>Initial cohesive shear strength</td>
</tr>
<tr>
<td>$E$</td>
<td>Elastic modulus of masonry</td>
</tr>
<tr>
<td>$E_b$</td>
<td>Elastic modulus of brick</td>
</tr>
<tr>
<td>$E_m$</td>
<td>Elastic modulus of mortar</td>
</tr>
<tr>
<td>$f_{mt}$</td>
<td>Flexural tensile strength of mortar joint</td>
</tr>
<tr>
<td>$f_t$</td>
<td>Tensile bond strength</td>
</tr>
<tr>
<td>$f_{ul}$</td>
<td>Brick’s modulus of rupture</td>
</tr>
<tr>
<td>$F_h$</td>
<td>Ultimate extreme fibre stresses in the masonry in the horizontal direction</td>
</tr>
<tr>
<td>$F_v$</td>
<td>Ultimate extreme fibre stresses in the masonry in the vertical direction</td>
</tr>
<tr>
<td>$F_f$</td>
<td>Slip tolerance in the contact model</td>
</tr>
<tr>
<td>$G$</td>
<td>Shear modulus of joint</td>
</tr>
<tr>
<td>$G'_I$</td>
<td>The mode I fracture energy</td>
</tr>
<tr>
<td>$G''_I$</td>
<td>The mode II fracture energy</td>
</tr>
<tr>
<td>$h_{max}$</td>
<td>Maximum overclosure distance in the contact</td>
</tr>
<tr>
<td>$I_p$</td>
<td>Polar moment of inertia of the circular cross section</td>
</tr>
<tr>
<td>$l_i$</td>
<td>Characteristic contact surface length</td>
</tr>
<tr>
<td>$M_h$</td>
<td>Bending moment around vertical axis</td>
</tr>
<tr>
<td>$M_{hp}$</td>
<td>Peak bending moment around vertical axis</td>
</tr>
<tr>
<td>$M_{hr}$</td>
<td>Residual moment around vertical axis</td>
</tr>
<tr>
<td>$M_v$</td>
<td>Bending moment around horizontal axis</td>
</tr>
<tr>
<td>$M_{vp}$</td>
<td>Peak bending moment around horizontal axis</td>
</tr>
<tr>
<td>$M_{vr}$</td>
<td>Residual bending moment around horizontal axis</td>
</tr>
<tr>
<td>$p_{max}$</td>
<td>Maximum allowable tensile stress across the contacted surfaces</td>
</tr>
<tr>
<td>$P_v$</td>
<td>Vertical pre-compressive force on the four brick unit specimens</td>
</tr>
<tr>
<td>$r_i$</td>
<td>Inner radius of the cylindrical specimen</td>
</tr>
<tr>
<td>$r_o$</td>
<td>Outer radius of the cylindrical specimen</td>
</tr>
<tr>
<td>$t$</td>
<td>The brick thickness</td>
</tr>
<tr>
<td>$T$</td>
<td>The measured torque</td>
</tr>
</tbody>
</table>
\( \nu_b \) Brick Poisson’s ratio
\( \nu_m \) Mortar Poisson’s ratio
\( w \) The crack width
\( W \) Weight of brick
\( Z \) Section modulus of the bed joint
\( \sigma, \sigma_n \) Compressive stress normal to the bed joint
\( \sigma_f \) Mean flexural strength of the bed joint of the four brick unit specimen
\( \tau \) Joint shear stress
\( \tau_1, \tau_2 \) Shear stress component in one of the two perpendicular directions
\( \tau_{\text{crit}} \) Critical shear stress in the contact model
\( \tau_{\text{residual}} \) Residual shear stress
\( \tau_u \) Peak torsional shear stress
\( \gamma_1, \gamma_2 \) Slip component in one of the two perpendicular directions
\( \gamma_{1}^{pr}, \gamma_{2}^{pr} \) Elastic predictor strain in one of two perpendicular directions
\( \gamma_{cr} \) The allowable elastic slip in the contact model
\( \gamma_{eq}^{sl} \) Resultant slip
\( \gamma_{i}^{el} \) Elastic tangential slip at the beginning of the increment
\( \gamma_{i}^{el} \) Elastic tangential slip at the end of the increment
\( \gamma_{i}^{pr} \) Elastic predictor strain
\( \mu \) Shear friction coefficient
\( \mu_i \) Internal shear friction coefficient
\( \mu_r \) Residual shear friction coefficient
\( \varphi \) Angle of linear softening of shear stress
\( \Delta \gamma_{i}^{sl} \) Slip increment