# Structural Behaviour of Lime-Mortared Masonry

- **Triaxial compression…**

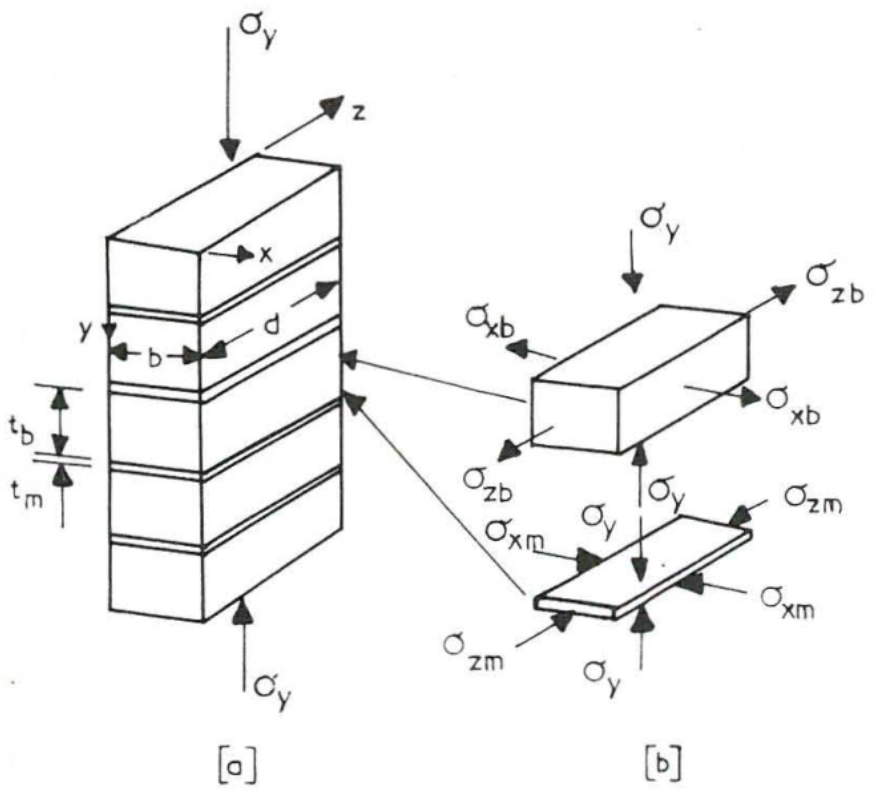



FIGURE 1—Brick and mortar stresses due to applied axial compressive load ($\sigma_y$).

*Extract from: Francis, A.J., Horman, C.B. and Jerrems, L.E., 'The effect of joint thickness and other factors on the compressive strength of brickwork', Proc. of the 2nd Int. Brick Masonry Conf., 1971*

# Structural Behaviour of Lime-Mortared Masonry

- **Strength of masonry composite is a function of masonry unit strength, mortar strength, joint thickness, and cross-sectional bond detailing.**

- **EC6 formula:**

$$f_{ck} = K \cdot f_{b,c}^{\alpha} \cdot f_{m,c}^{\beta}$$

*where K would be 0.45 for stone, α is 0.7 and β is 0.3 (UK NA, 2012).*

- **This is A) a <u>DESIGN</u> code, and B) for <u>CEMENT</u> mortared masonry, and C) for "standard" joint thicknesses**

# Structural Behaviour of Lime-Mortared Masonry

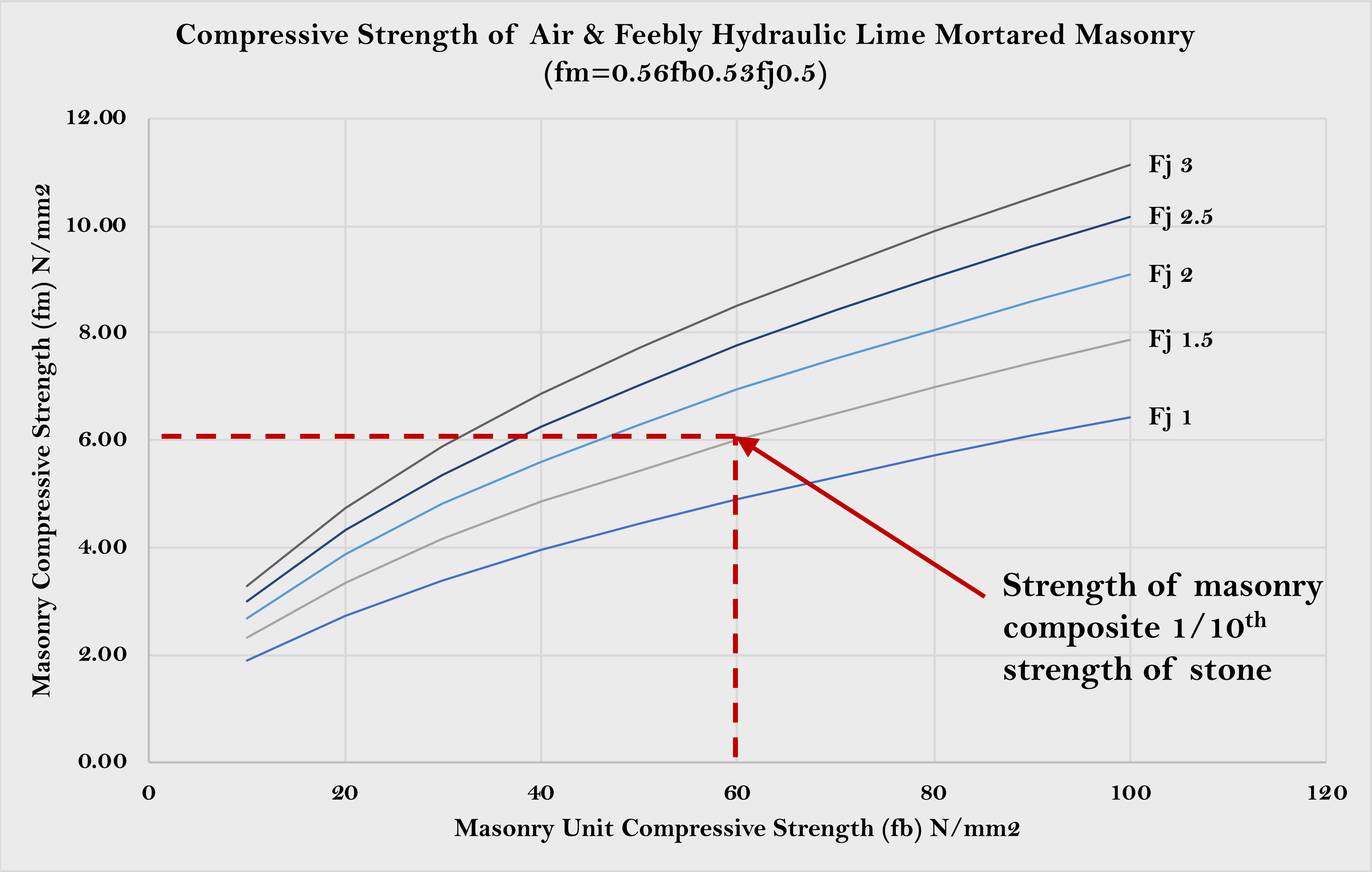
- Strength of masonry composite is a function of masonry unit strength, mortar strength, joint thickness, and cross-sectional bond detailing.

- Costigan et al (2015) corrected formula:

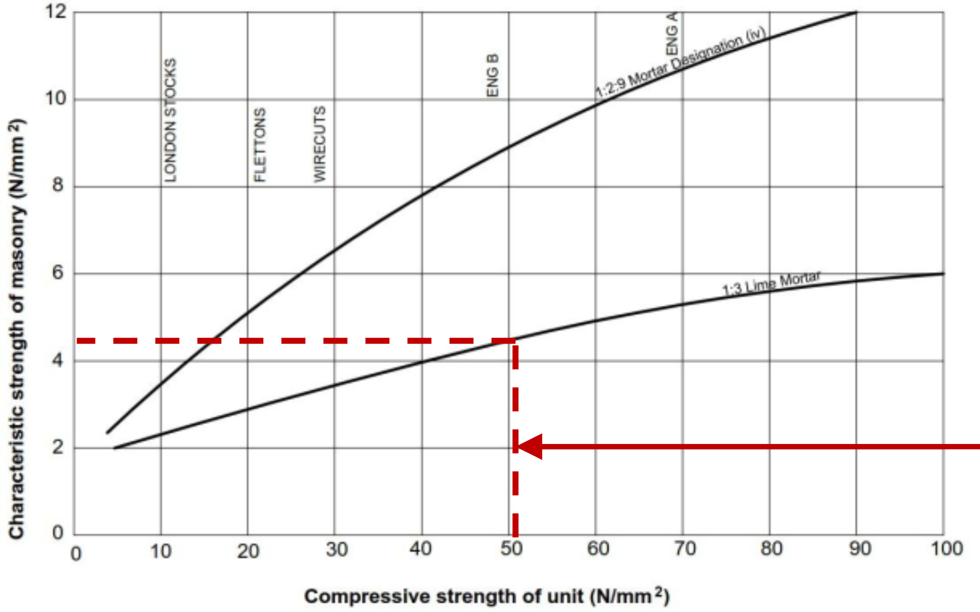
$$f_m = 0.56 \cdot f_b^{0.56} \cdot f_j^{0.5}$$

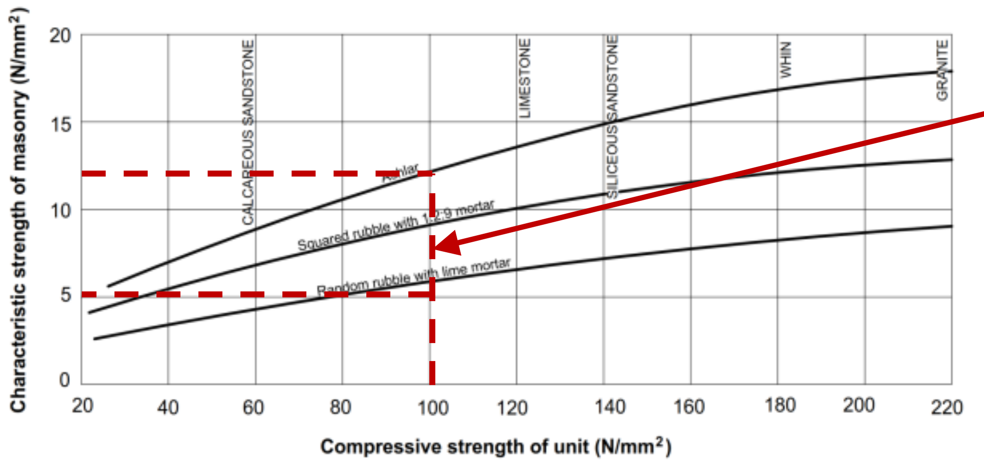
- For air and feebly hydraulic lime mortared masonry
- For ~12mm "standard" joint thicknesses…
- For 1:3 mix ratios

# Structural Behaviour of Lime-Mortared Masonry



# Structural Behaviour of Lime-Mortared Masonry




- <u>Assessment</u> code a bit more instructive than <u>design</u> code

$\theta \leq 0.6 \cdot f_k / (\gamma_m = 1.5)$

(CD 376 cl. 4.7)

**Strength of masonry composite about 1/10th strength of the brick for median values**

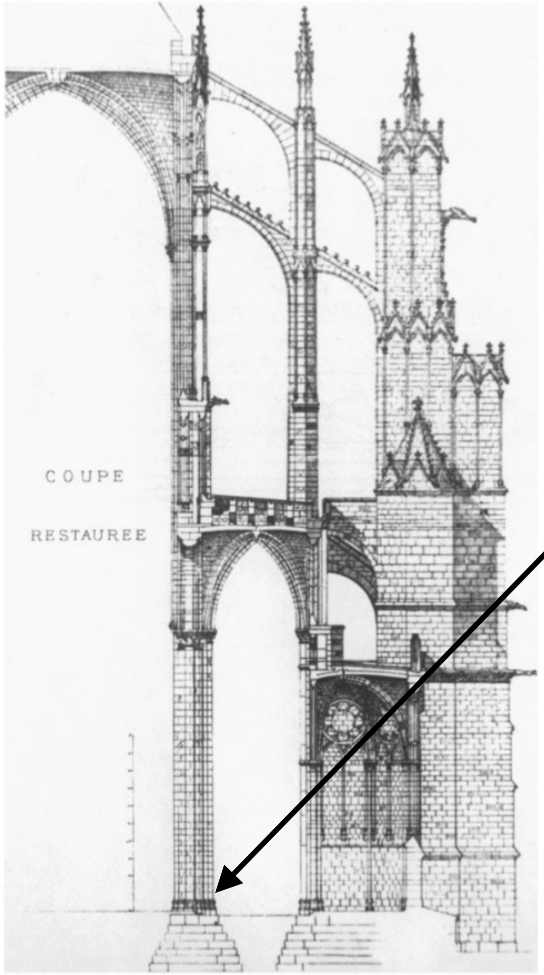
**Random rubble ca. 1/20th strength of the stone, significantly less strong than ashlar for the same stone type***

**(*mortar for ashlar work not recorded)**

*Extracts from: CS 454 – Assessment of Highway Bridges and Structures (DMRB, 2019)*

# Structural Behaviour of Lime-Mortared Masonry

- **Gothic cathedrals…**




- Historically stresses were consciously limited to 1/10th the crushing strength of the stone
- Beauvais: compressive stress in base of crossing pier around **1.3 N/mm²**
- (see Jacques Heyman – The Stone Skeleton)

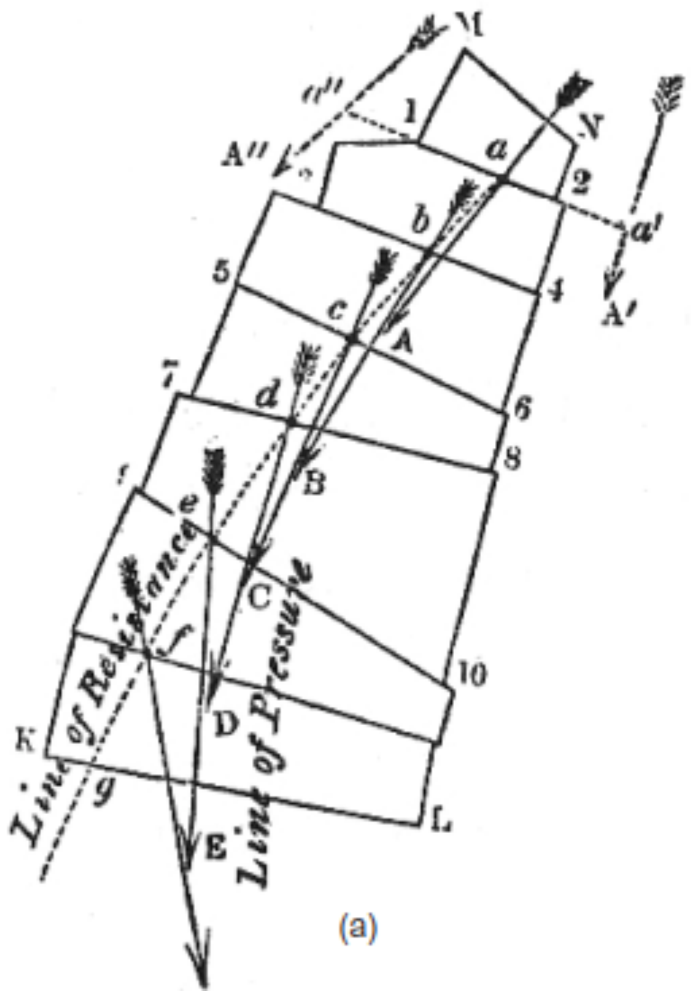
- **High load, low stress**

# Structural Behaviour of Lime-Mortared Masonry

## 'Safe Theorem':

- **<u>Unlimited compressive strength</u>**
- Sliding does not occur
- Zero tensile strength

*[The Safe Theorem – J. Heyman, 1995]*



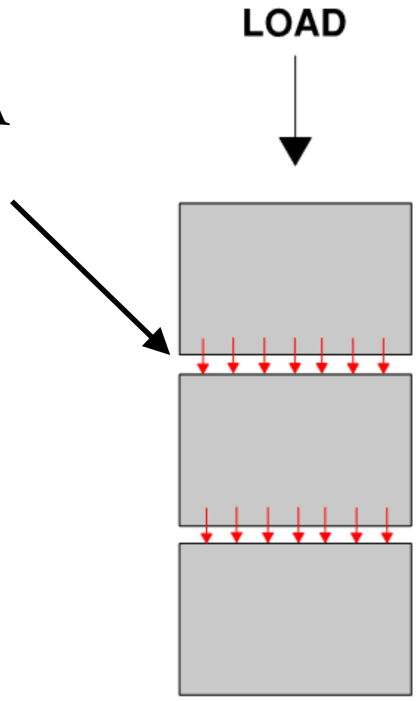

(a)

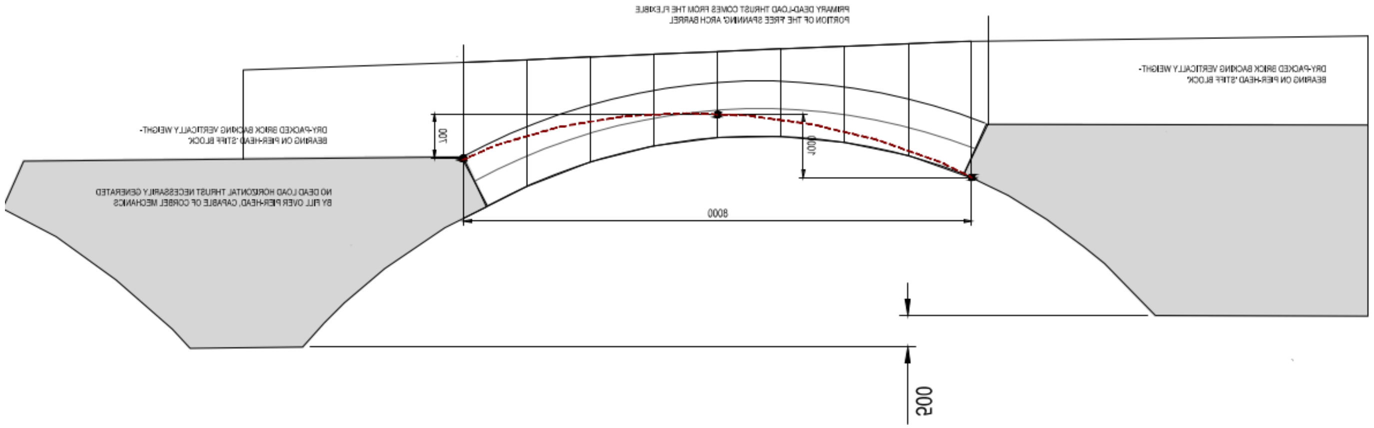
**The Stone Skeleton (Heyman, 1995) has got to be on any self-respecting conservation engineer's bookshelf…*

# Structural Behaviour of Lime-Mortared Masonry

- The role of the mortar joint…

**IT'S JUST A SPACER!!**



➔ A deformable spacer nevertheless…

# Structural Behaviour of Lime-Mortared Masonry

**Deformability:**

- Described by Young's Modulus
- Varies significantly according to joint thickness and binder type
- An expression for approximating the elastic modulus of masonry is given in EN 1996-1-1:2005(+A1: 2012):

$$\mathbf{E = K_E \cdot f_k}$$ *where $K_E$ would be 1,000 (UK NA).*

- Formula relates compressive strength of the masonry composite with stiffness by a constant
- Intended application of the code is **CEMENT**-mortared masonry

- **Grossly over-estimates the modulus of lime-mortared masonry**

# Structural Behaviour of Lime-Mortared Masonry

**Deformability:**

- Costigan et al. (2015) corrected formula (non/feebly hyd'c):

$$\mathbf{E = 85 \cdot f_m}$$

- Ditto for NHL 3.5/5 eminently hydraulic:

$$\mathbf{E = 130 \cdot f_m}$$

- (EC6 for cement mortared masonry):

$$\mathbf{E = 1{,}000 \cdot f_m}$$

**MASONRY BUILT WITH TRADITIONAL LIME MORTAR IS <u>AN ORDER OF MAGNITUDE MORE DEFORMABLE</u> THAN CEMENT MORTARED MASONRY**

# Structural Behaviour of Lime-Mortared Masonry

- **Oft-neglected mechanical role…**

- Real buildings creak, groan and wobble around
- Heavy structures on rubbish foundations
- Lego bricks, jointed in plasticine, bearing on play-dough

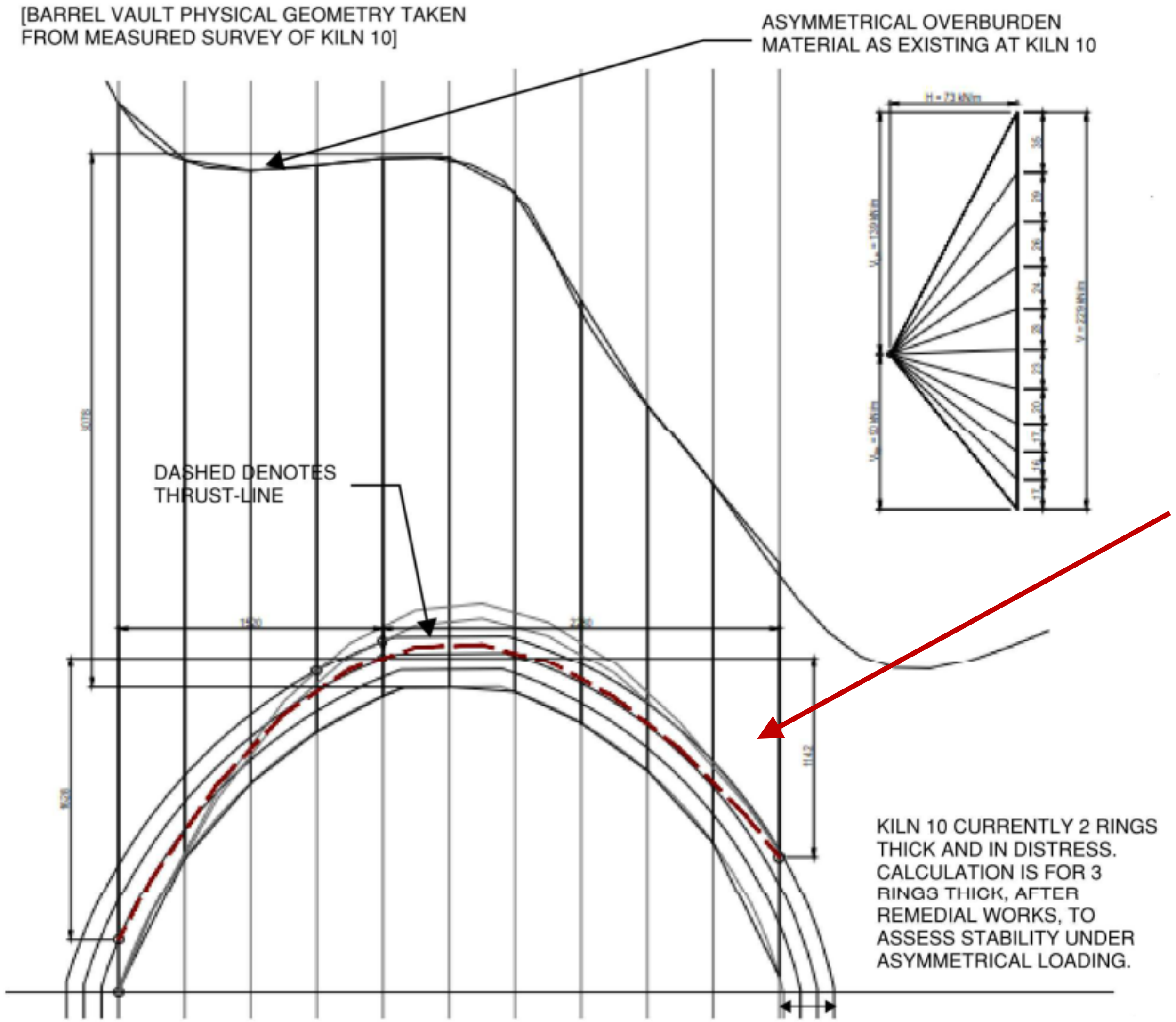
- **Deformable cushion**

# Structural Behaviour of Lime-Mortared Masonry

**This one's dangerous…** 

See the 3D model of the kiln here: https://sketchfab.com/3d-models/rosedale-east-stone-kilns-frontage-7c28dc01d8e84bdc9dbfac0a7dca9ff2

# Structural Behaviour of Lime-Mortared Masonry




**Rosedale Kilns**

This barrel vault is clinging to life, having lost 3 out of 5 rings.

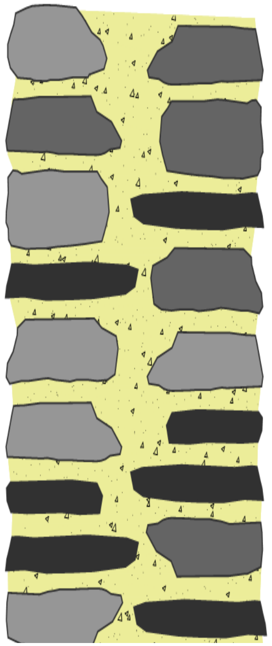
Mean comp. stress 0.6-0.8N/mm$^2$; peak comp. stress ~1.5-2.1N/mm$^2$

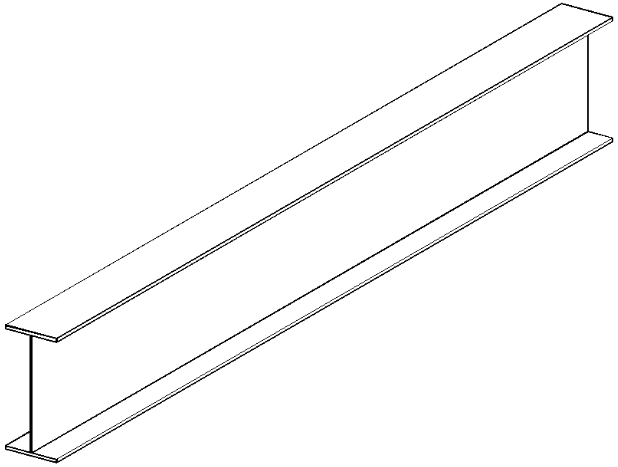
*(genuinely – had to go back and work it out, as it just didn't feature in the assessment calcs…!)*

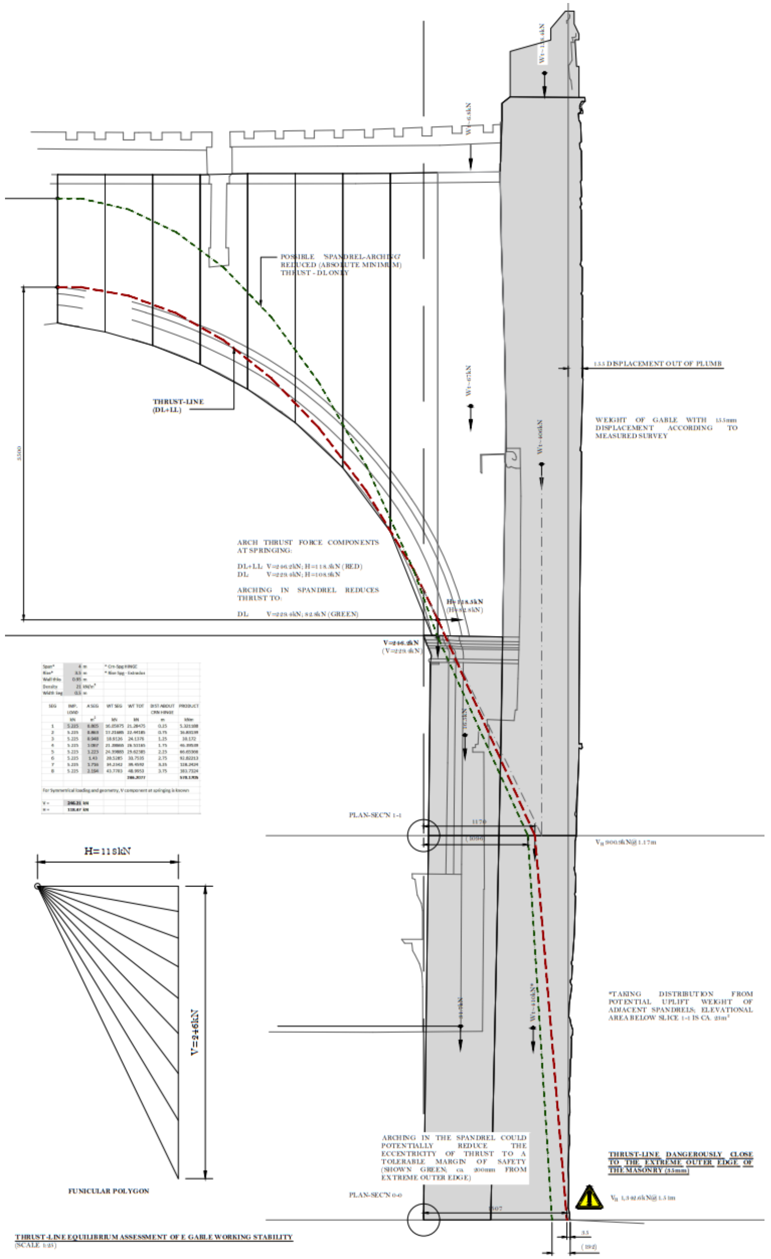
Load **POSITION** not magnitude is important

# Structural Behaviour of Lime-Mortared Masonry

## Walls are like deep, slender beams...



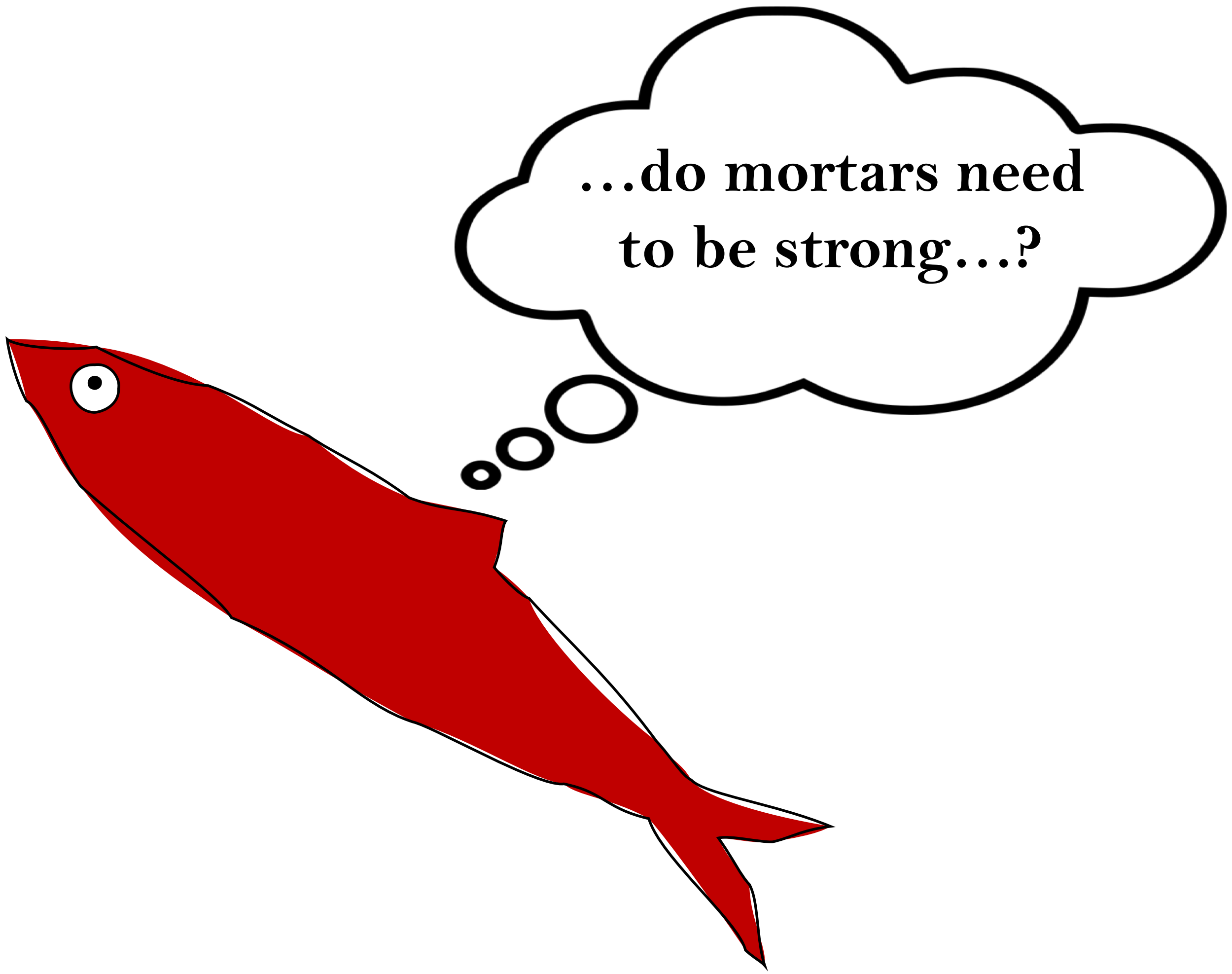





- Masonry buildings don’t fall down. They fall over...

# Structural Behaviour of Lime-Mortared Masonry

- **Daft question #1…**

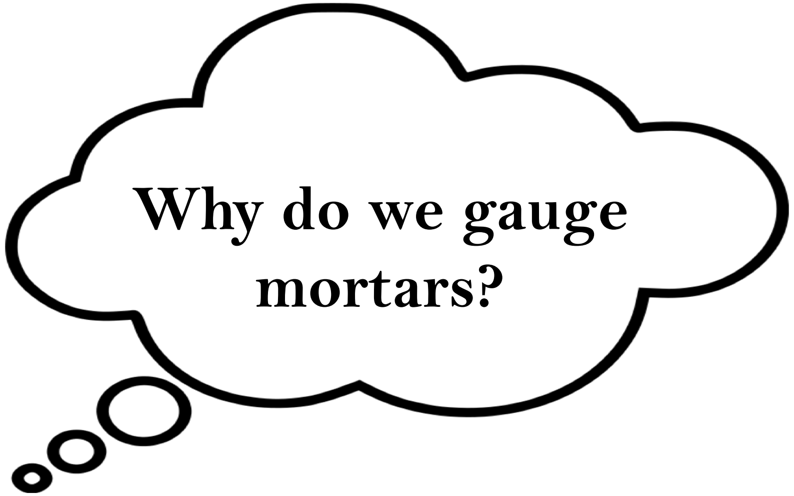



**Lime mortar is simply a low-stress deformable packer between masonry units.**

# II. Hardening Kinetics of Traditional Mortars

# Hardening Kinetics of Traditional Mortars

- **Daft question #2…**



# Hardening Kinetics of Traditional Mortars

**Carbonation:**

1. Carbon dioxide diffuses into pore space of mortar;
2. $CO_2$ dissolves in pore water to form carbonic acid $H_2CO_3$;
3. Free lime $CaOH_2$ dissolves in pore water (reduced ph);
4. Carbonic acid carbonate ions react with calcium ions from the lime, to form calcium carbonate $CaCO_3$.

**Word to the wise: moisture is essential to carbonation process. BUT!**

- Carbonation 'impossible' below 20% RH…
- Carbonation impossible at 100% RH…
- Optimum RH ~60%
- Lab environment?
- Meanwhile in Scotland

**AIR WITHIN PORES OF DAMP MATERIALS PRACTICALLY 100% RH…**

# Hardening Kinetics of Traditional Mortars

**Hydraulic mortars:**

1. Hydraulic limestone source or pozzolanic mortar;
2. Calcium silicates and aluminates react with water molecules to form calcium silicate & aluminate hydrates
3. i.e. "Hydration". $2CaOSiO_2$ (Belite), $3CaOSi0_2$ (Alite), $3CaOAl_2O_3$ (Tricalcium aluminate)…
4. This chemical set gives initial hardening and early strength;
5. Thereafter, carbonation takes place

**Or so the story goes…**

# Hardening Kinetics of Traditional Mortars

**Gauged lime mortars:**

- To make them strong
- To make them harden in damp/wet
- To resist frost

**To get the best of both worlds?**

- So we use a mortar that needs to stay wet to hydrate, but needs to be dry to carbonate…

1. The early set lulls us into a sense of false security
2. We think it's 'went off', it's exposed to the elements, probably wet to begin with…
3. But the mortar's still overwhelmingly air lime and this means no carbonation
4. The more hydraulic the mix, the slower the carbonation rate…
5. The wetter the substrate is, and the more water we add to it by 'aftercare', the longer the delay in carbonation will be…