Seismic response of Roman concrete arches and vaults

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  - Alejandra Albuerne
  - Victoria Lawson
- Funding:
  - EPSRC
  - University of Oxford Bracken Fund
  - Yeotown Fund, New College Oxford

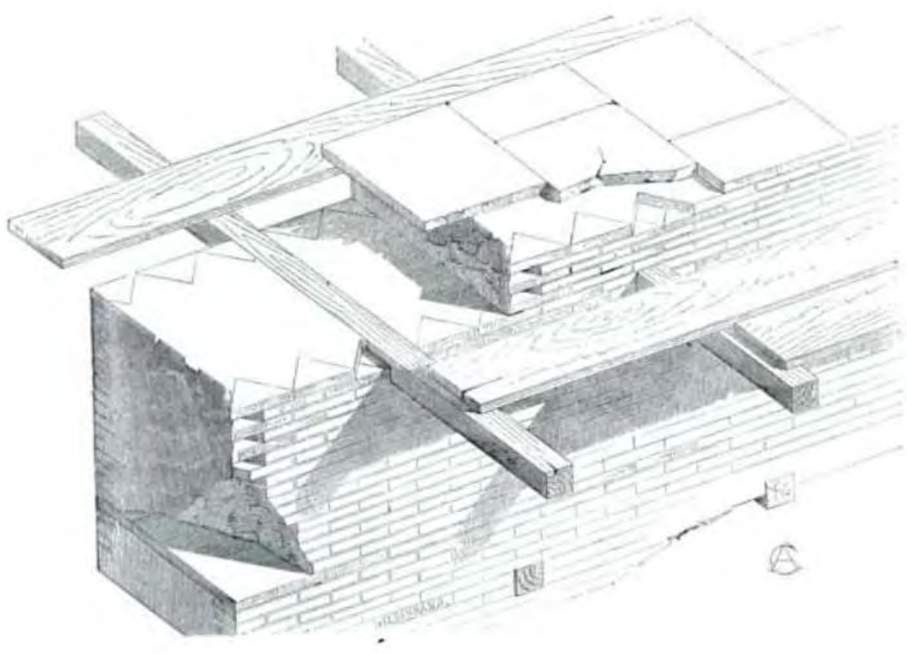
Structures and dynamics at Oxford

- Based within a unified Engineering Science department of about 100 academics
- Key personnel:
  - Martin Williams, Tony Blakeborough, Manolis Chatzis, Zhong You (Structures)
  - Byron Byrne, Ross McAdam (Geotechnics)
  - Tom Adcock (Fluids)
- Topics:
  - real-time hybrid test methods
  - passive energy dissipation systems in earthquake engineering
  - human-structure interaction in grandstands and footbridges
  - passive control of suspension bridge flutter
  - non-linear system identification
  - rocking mechanics
  - deployable and origami structures
  - dynamics of offshore renewable energy systems

Contents

Introduction – Roman concrete

- Alternating layers of pozzolanic mortar and layers of fist-sized aggregate (*caementa*: broken bricks, stones) – "mortared rubble"
- Often cast between brick facings, and with occasional layers of flat bricks (*bipedales*)
- Properties broadly similar to modern concretes



Lancaster (2009) Concrete vaulted construction in Imperial Rome

Introduction – vaulted Roman structures

- A structural form dating from 1st century BC
- Principal forms:
  - barrel vaults
  - cross vaults
  - domes

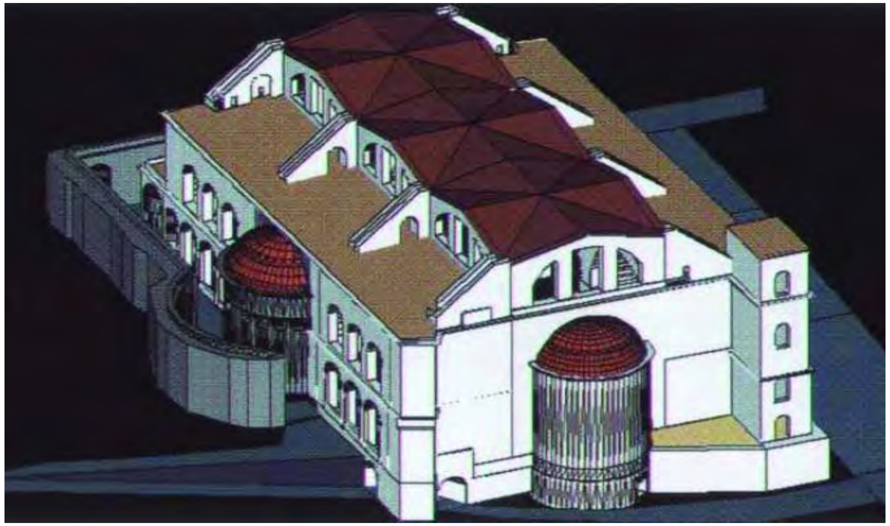
Herculaneum

Santa Maria degli Angeli, Rome

Pantheon, Rome

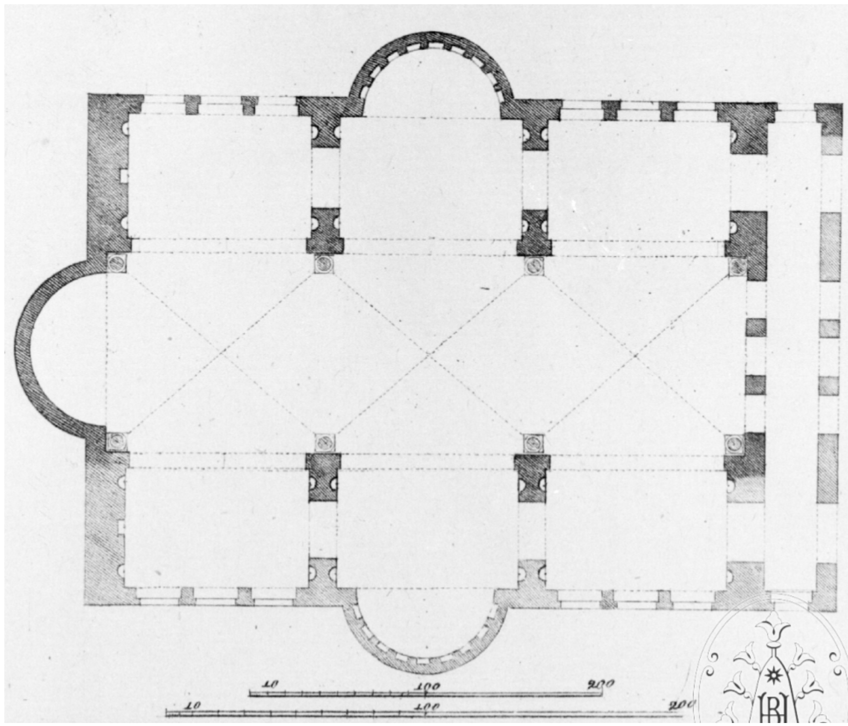
The Basilica of Maxentius

- Built 307-313 AD on the Via Sacra, just north of the Colosseum
- The largest vaulted space in antiquity – overall plan dimensions 100 x 80 m
- Central nave – three cross-vaults each 25 x 21 m in plan
- Side naves – barrel vaults of 23.5m diameter
- Built on sloping ground (9m height drop from NE to SW corner), and on remains of earlier structures



The Basilica of Maxentius

- Partial collapse at unknown date in early Middle Ages "widely believed to have been caused by an earthquake"
- Cross-vaults and one range of barrel vaults were lost, leaving only the barrel vaults of the northern nave
- Subsequently, many changes of ground level both within and outside the remaining structure
- Changes from 15th century onwards can be traced through contemporary engravings

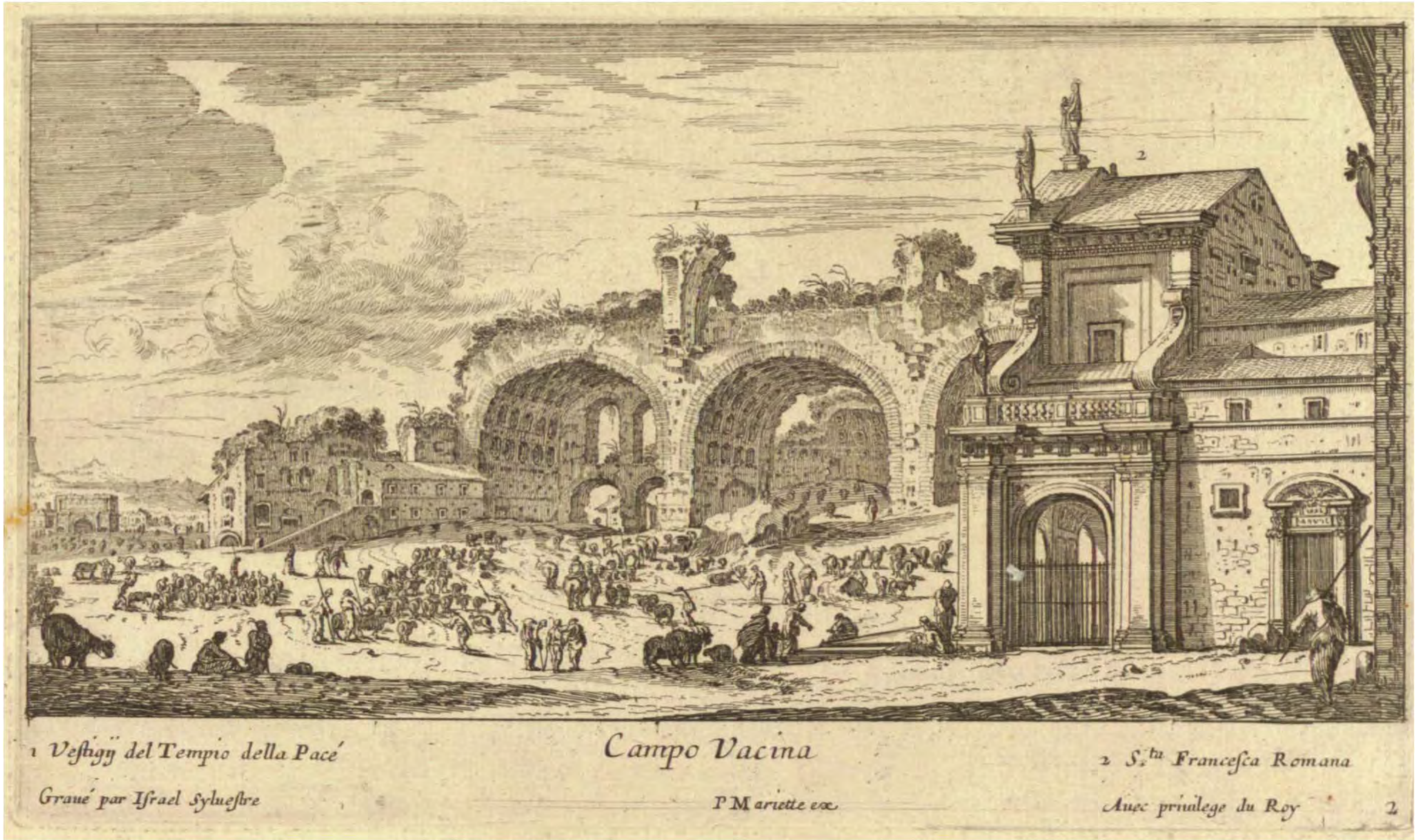


Images of the remains

- Duperac (1575)

Images of the remains

- Sylvestre (1650)

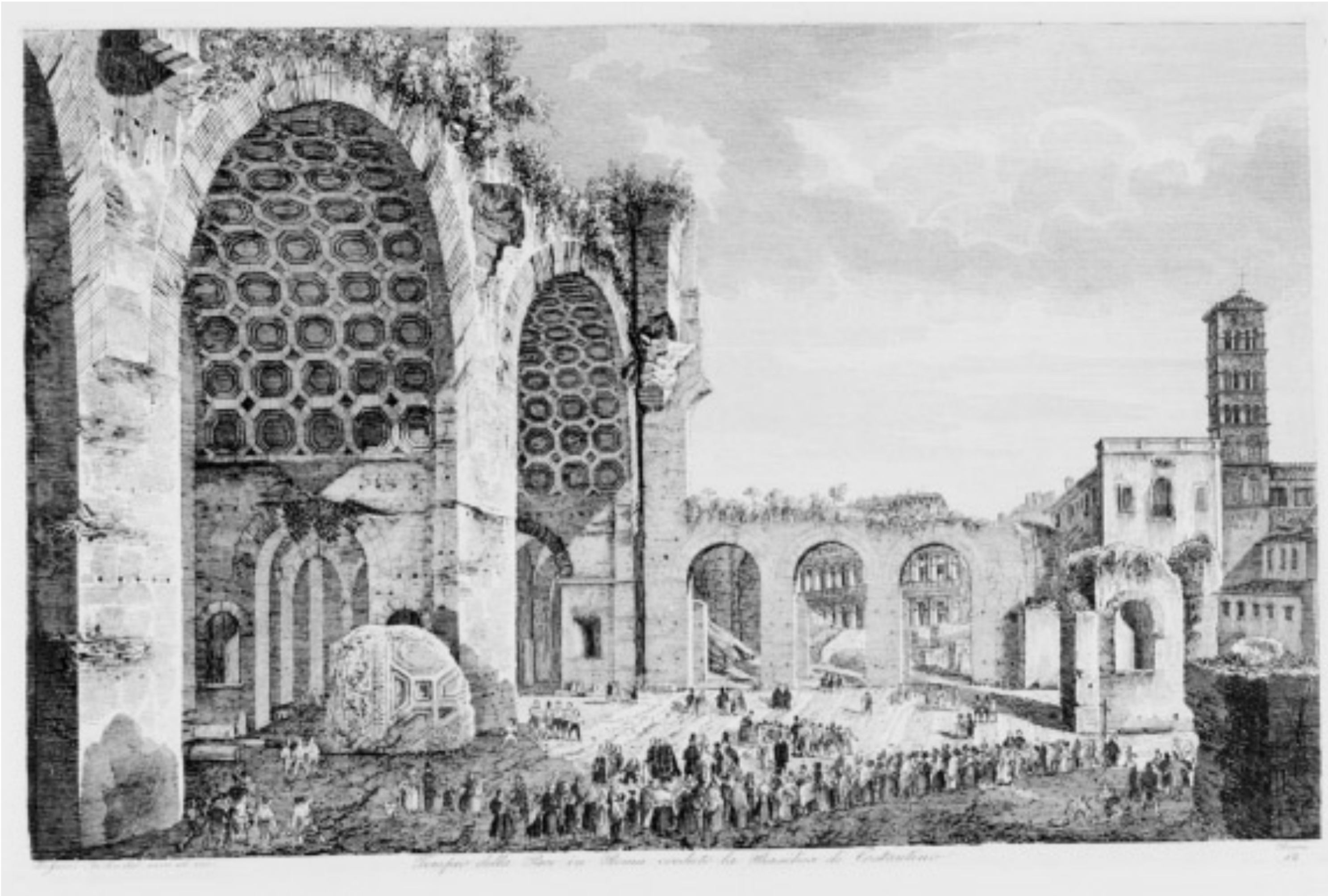


Images of the remains

- Vasi (1752)

Images of the remains

- Rosini (1839)



Images of the remains

- Present day:

Aims of surveys and analyses of remains

- Establish accurate geometry
- Quantify structural deformations
- Reconstruct geometry of the lost cross vaults
- Establish state of foundations

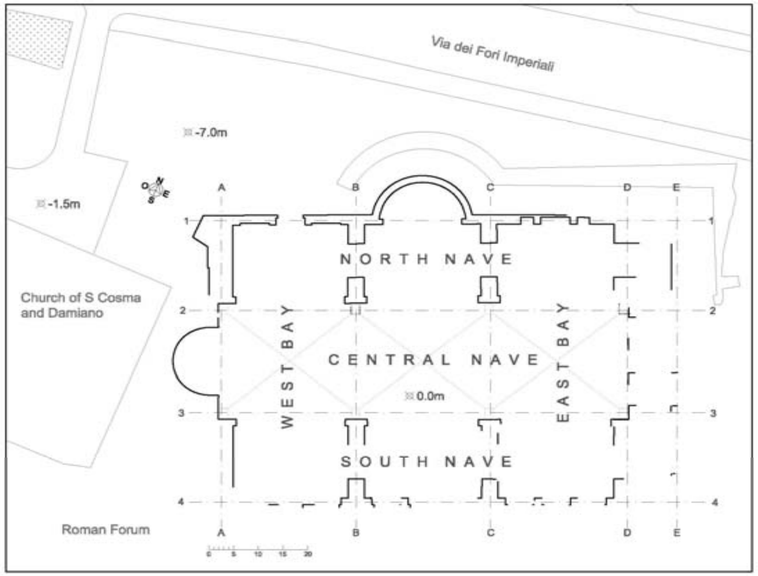
and hence…

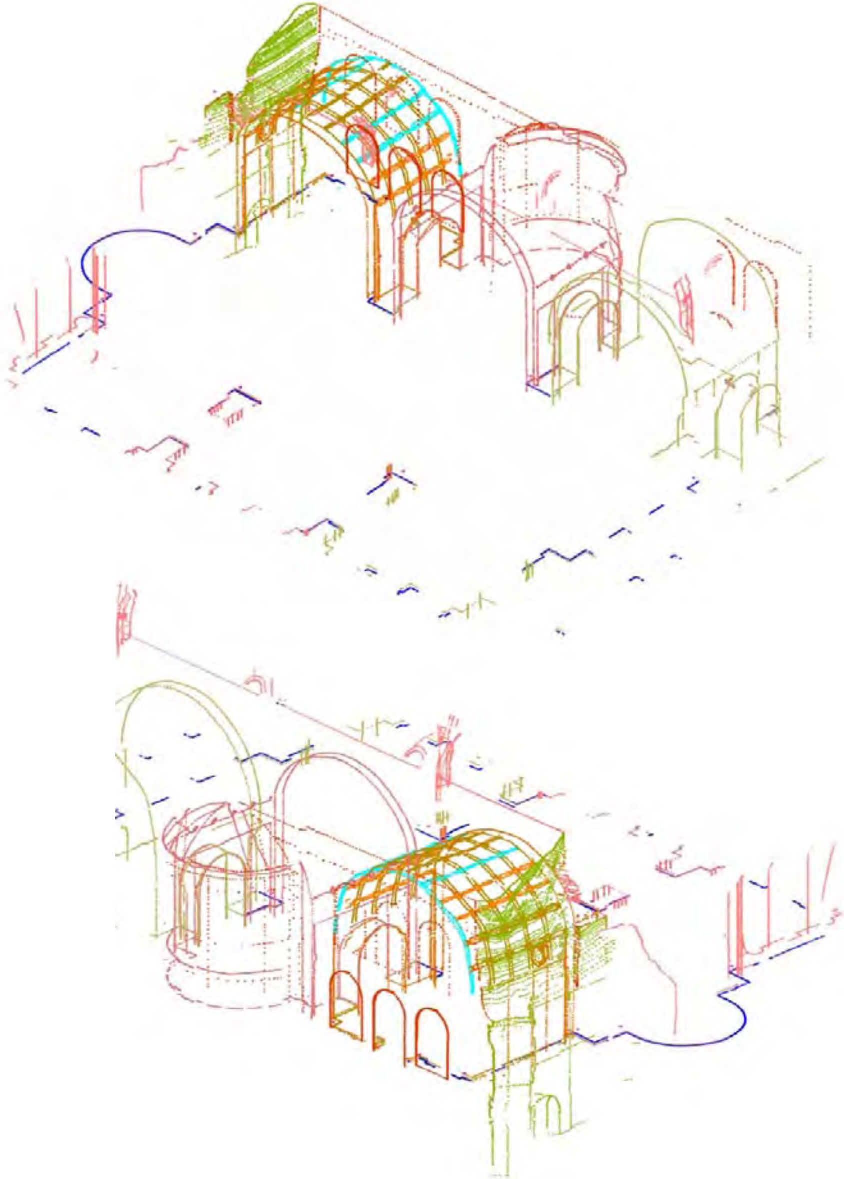
- Assess stability of original structure, and likelihood of collapse due to earthquake
- Assess stability of remains

Foundation survey

- Shows signs of significant lateral loads in the past
  - diagonal cracking of walls
  - leaning of walls
  - horizontal slip at bonding courses

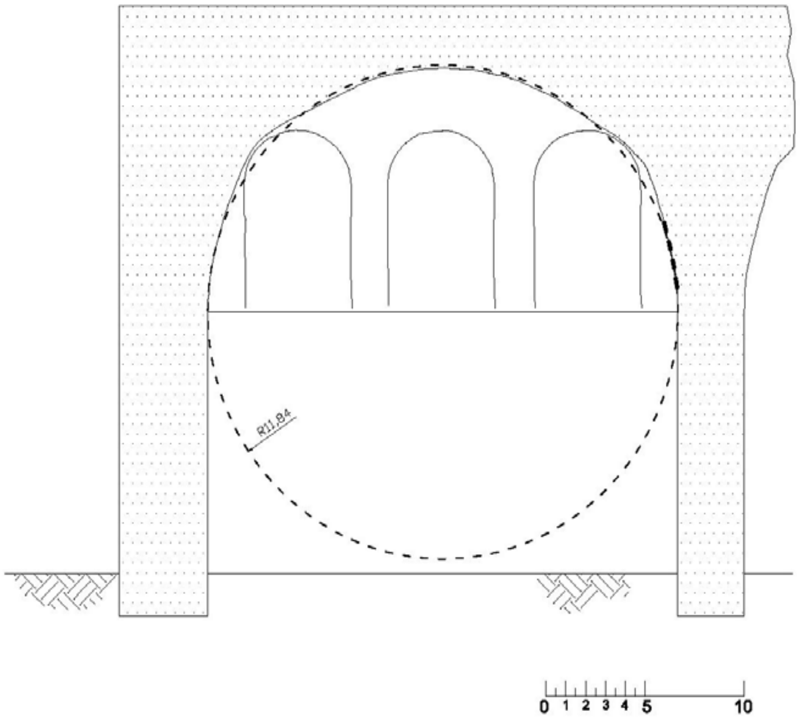
Point cloud survey





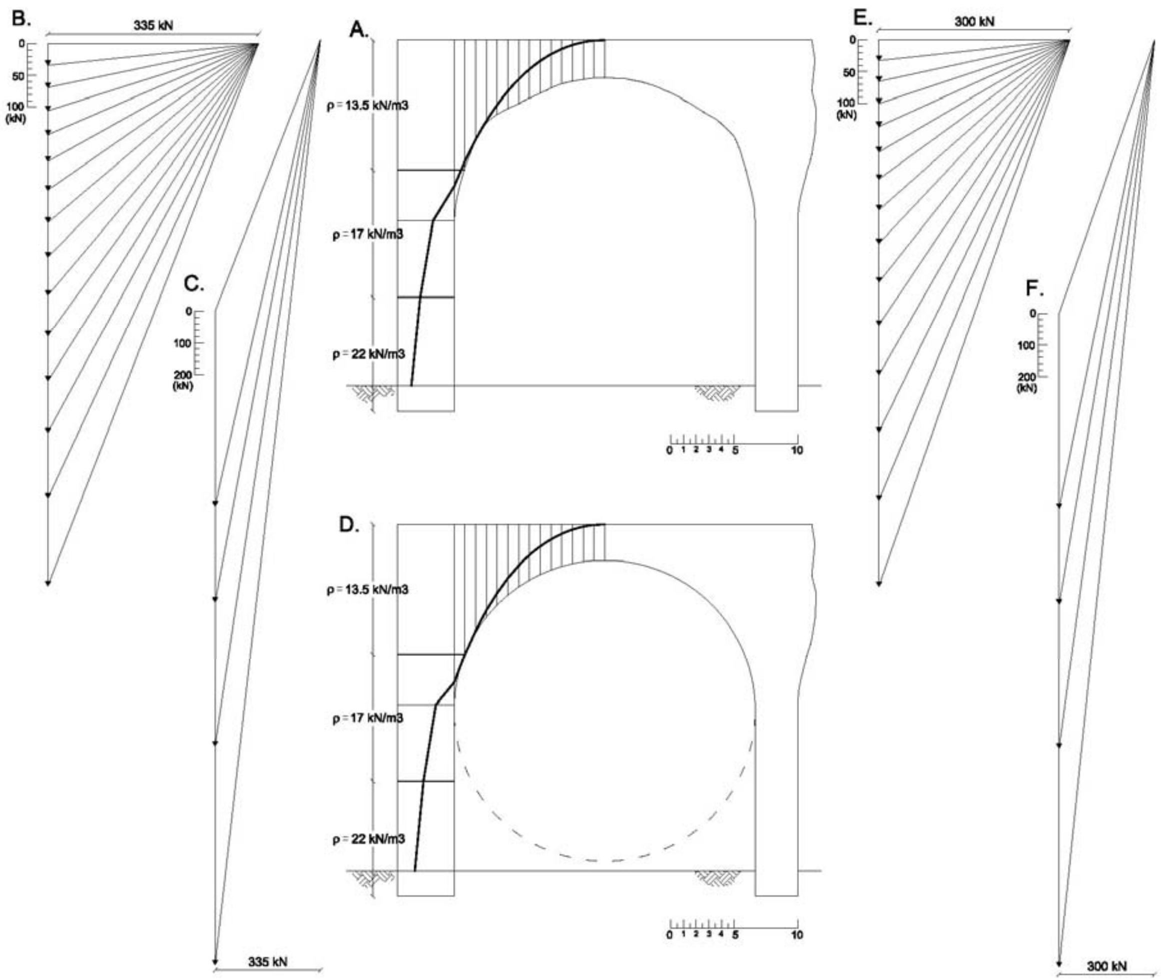
Stability of the remaining barrel vaults

- Distortion of barrel vaults close to outside wall
- Diagnosed as a construction modification to avoid overlapping with windows in the wall



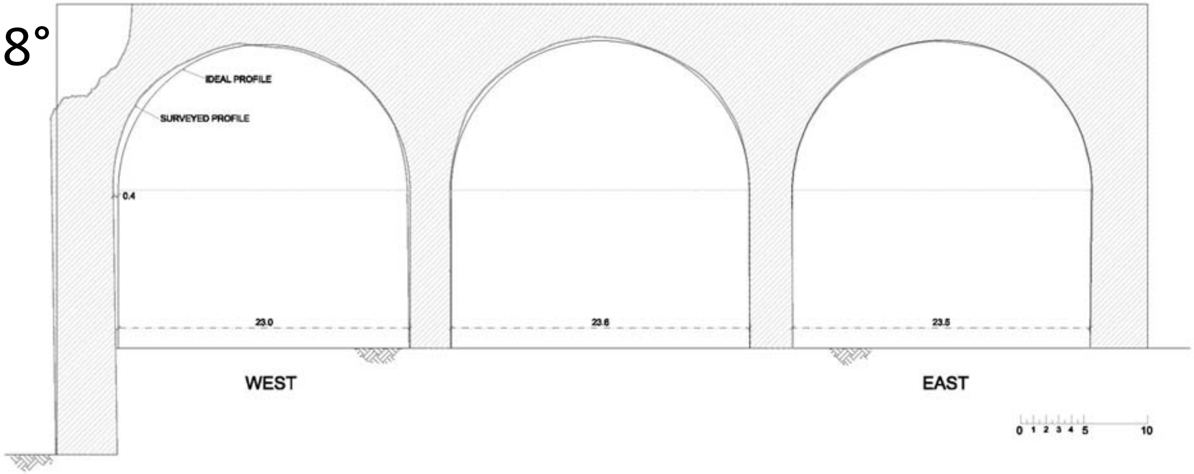
Thrust line analysis

- Concrete density varied from 13.5 kN/m^3 at top to 22 kN/m^3 near base
- Plots show thrust line corresponding to minimum horizontal reaction
- Variation from circular intrados shape increases minimum thrust from 300 to 335 kN
- …but structure remains stable

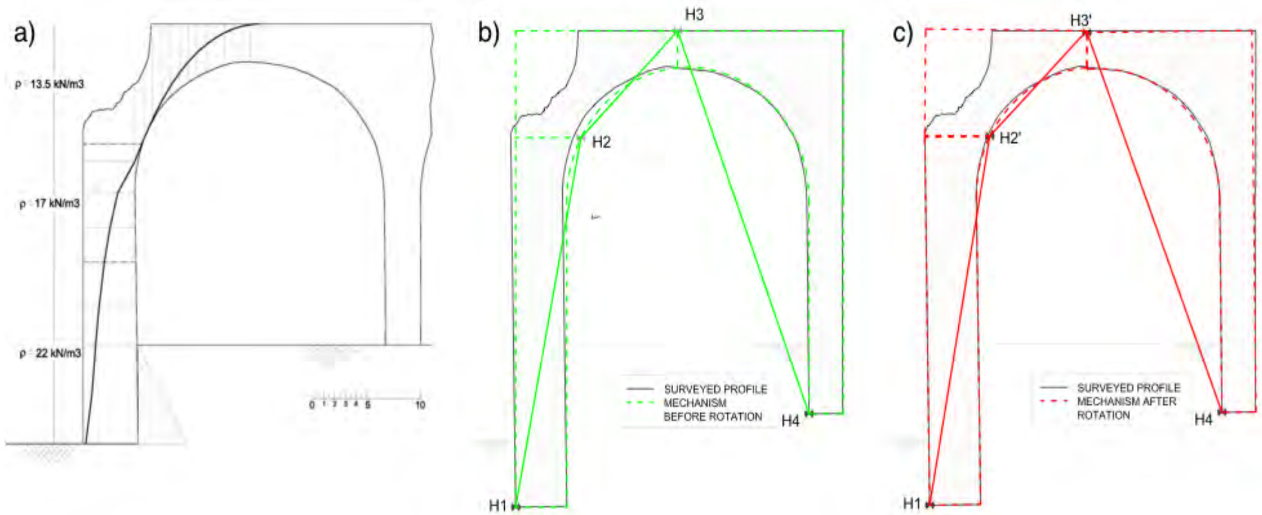


Deformation of west wall

- Outward lean of 0.8° at west end, and distortion of end barrel vault

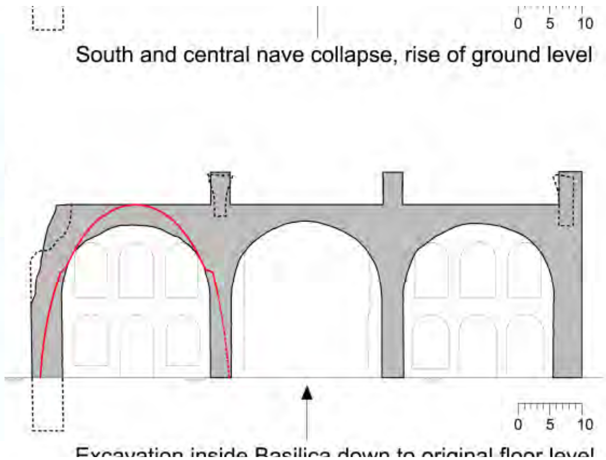


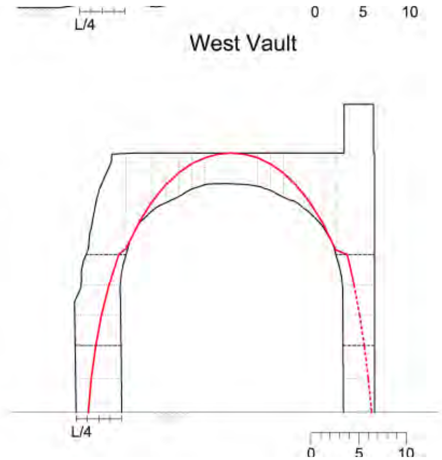
- Consistent with 4-hinge mechanism
- Close to stability limit at most damaged cross-section



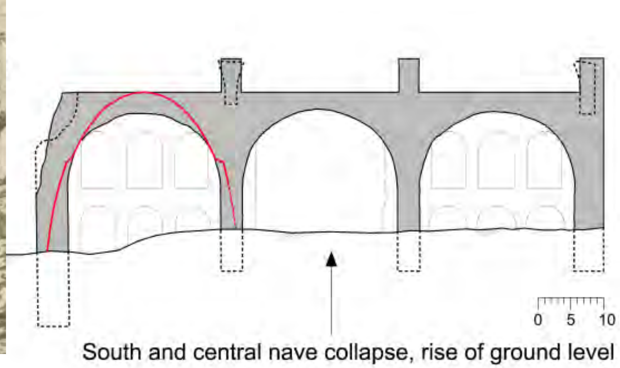
Stability through the ages

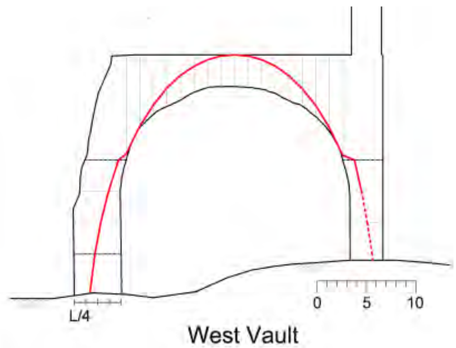
- Original structure: 313 AD





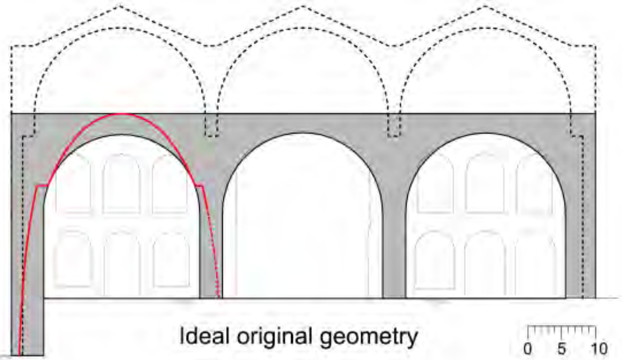
- After collapse of central nave, raised ground levels: pre-1500

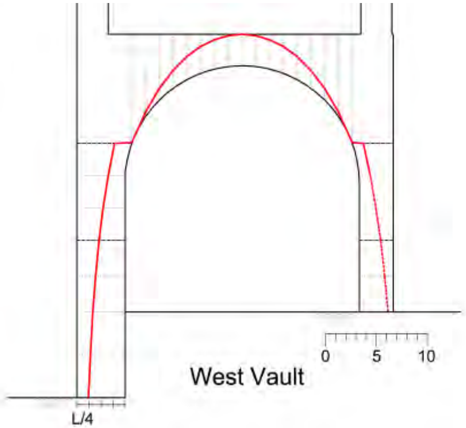




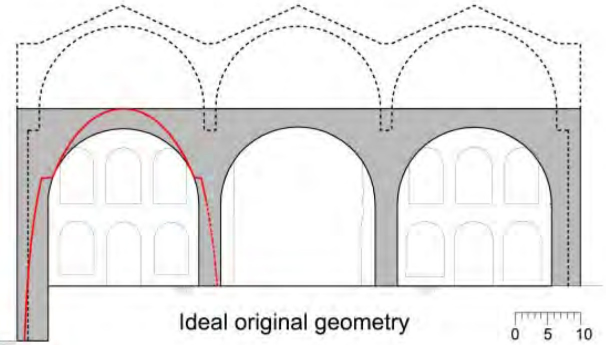
Stability through the ages

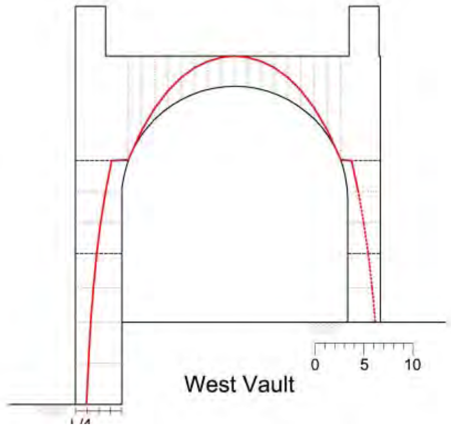
- First excavation: c. 1820





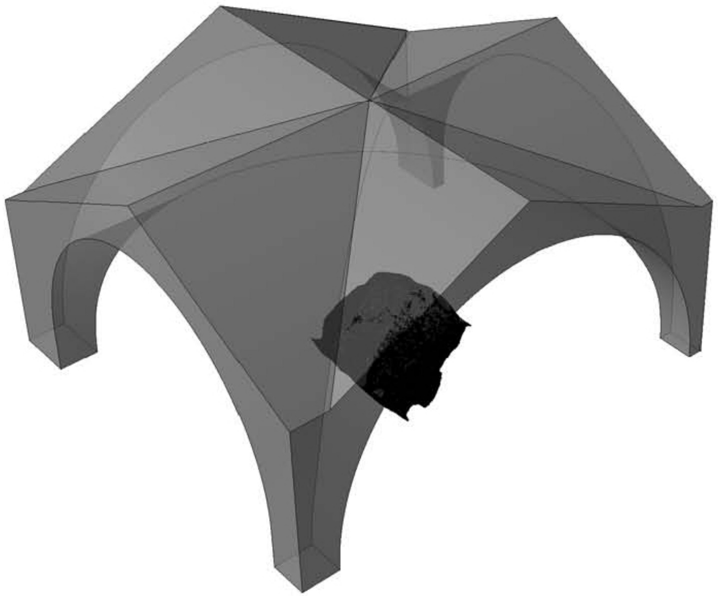
- Second excavation: c. 2000





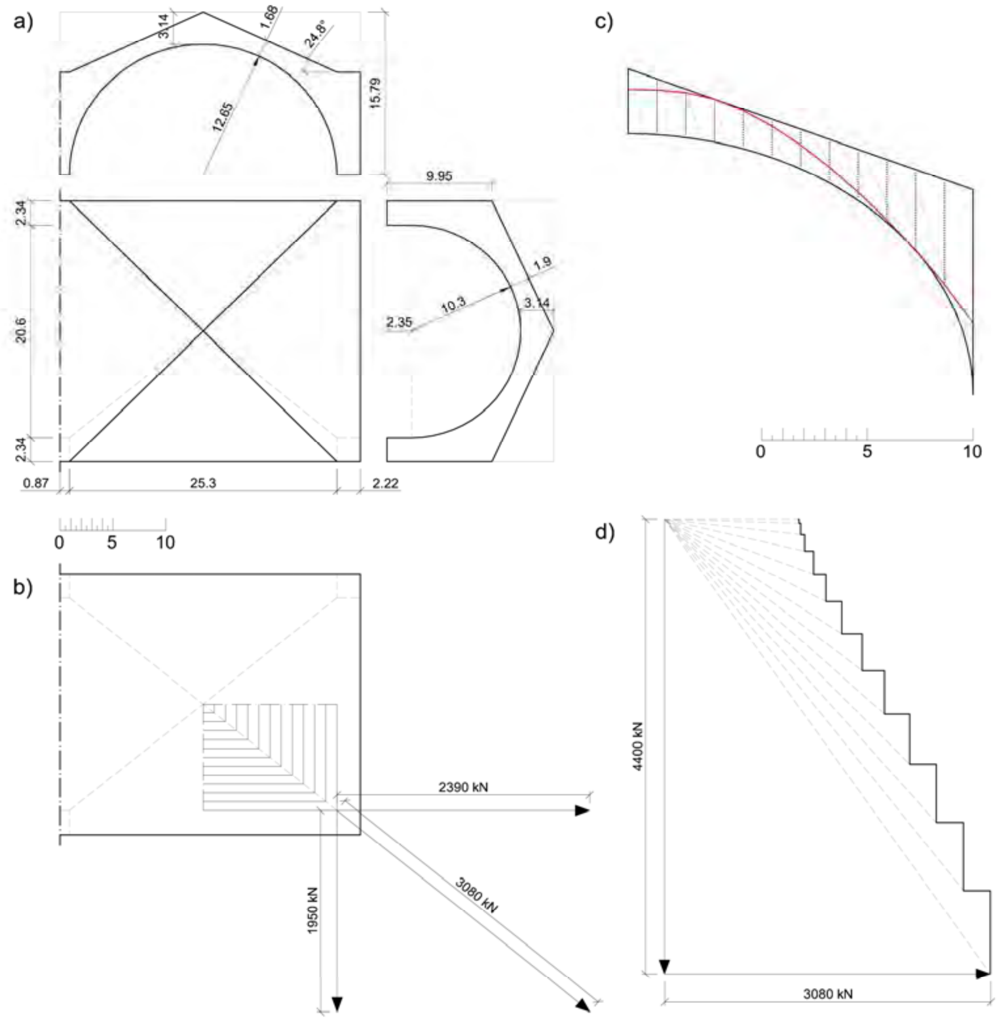
Reconstruction of cross-vault geometry

- Accurate scaled reconstructions of elements (springings, buttresses, fragments) achieved using digital photogrammetry
- These can then be used to infer overall vault geometry



Stability analysis by slicing technique

- Analysis by slicing technique shows the vault to be stable under self-weight loads
- Imposes lateral thrust of 2.4 MN on the vulnerable west wall
- But this is only one of many possible equilibrium solutions



Conclusion (1)

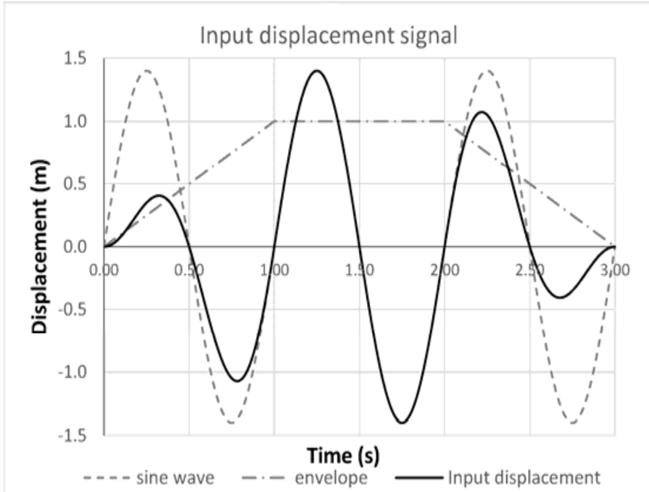
- Survey has provided most accurate available data on:
  - the current geometry and condition of the remaining structure
  - the likely dimensions of the collapsed part
- Evidence of significant lateral loading in the past
- But still no compelling evidence of cause of collapse
- Original structure shown to be stable under gravity loads
- Remaining structure has only small factor of safety against collapse, due to changes in ground level

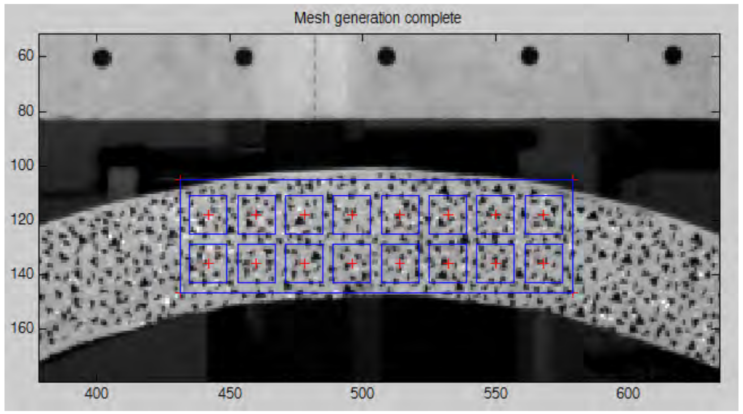
Laboratory testing of mortar arches

- Loosely inspired by the Basilica of Maxentius
- Shaking table tests of semi-circular mortar arches
- Aims:
  - understand differences in behaviour between continuous and voussoir arches
  - estimate lateral load capacity of continuous arches
  - investigate significance of pre-cracking of continuous arches under gravity loads

Experiment set-up

- Tests on small-scale arches with thickness:radius ratios of 0.13, 0.14, 0.15
- Pulse-type base motions
- Arch motion measured by PIV



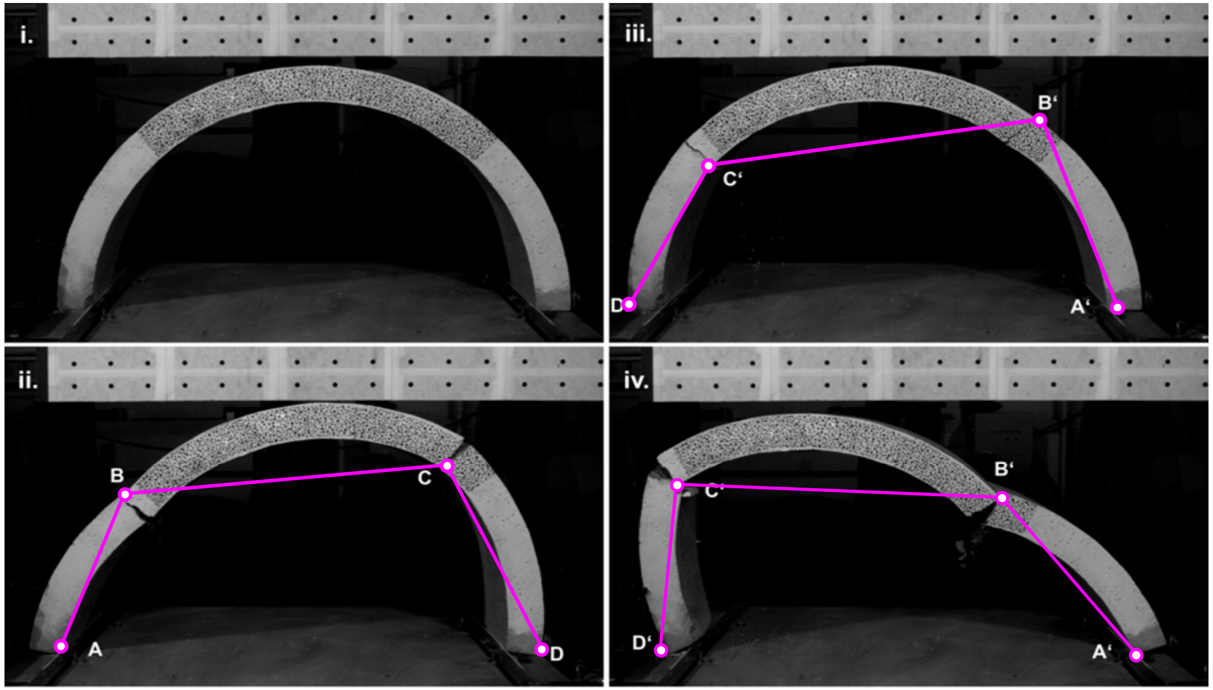


Typical four-hinge collapse

- Cracks have formed in a previous load cycle
- Mechanism rocks and then collapses
- Once formed, hinge locations are fixed

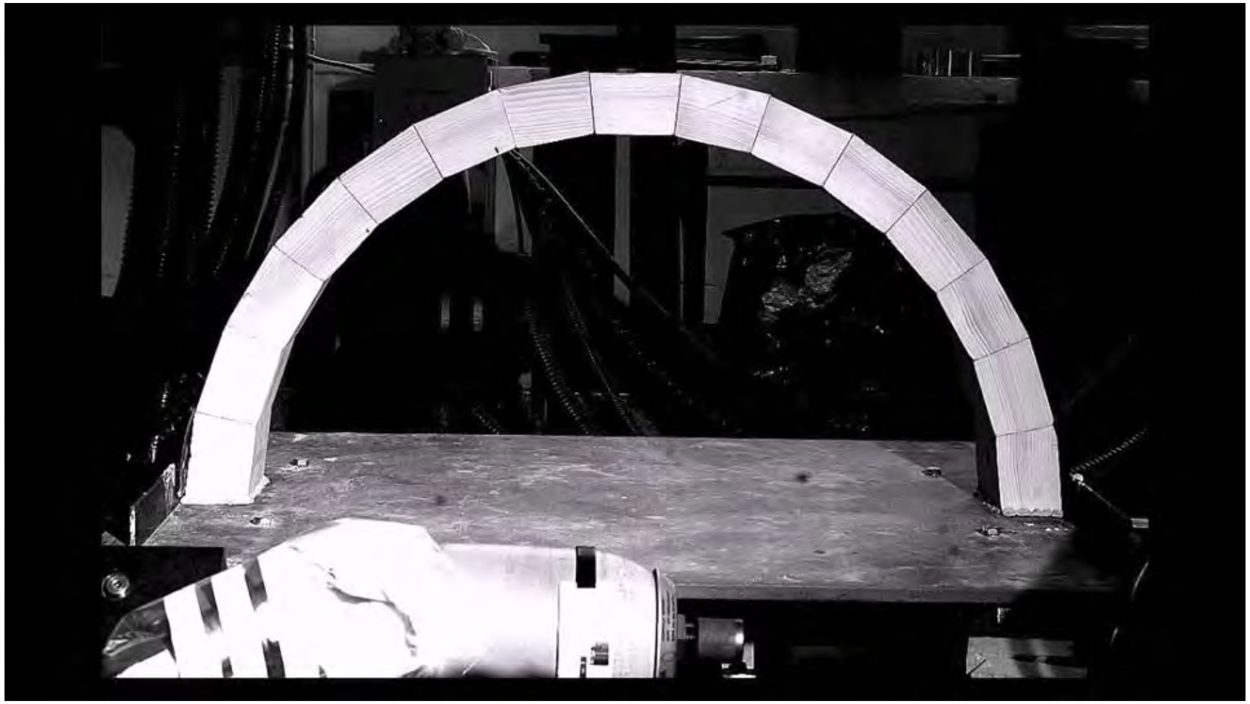
Four-link chain analogy

- Arch is free to rotate at feet (two hinges)
- Two further hinges required to form mechanism
- Arch then free to rotate as a four-bar chain



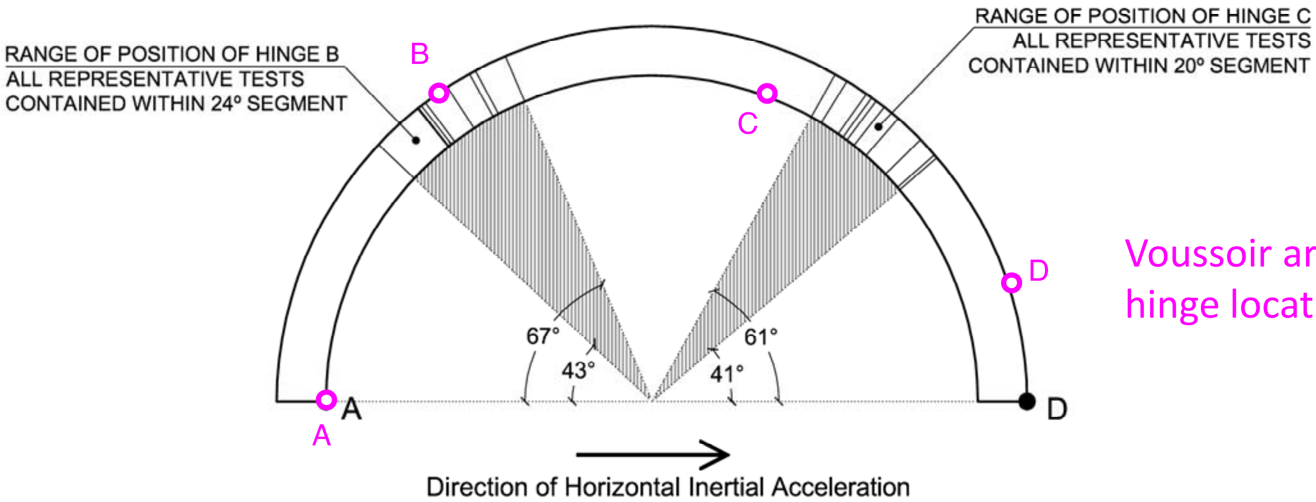
Comparison with voussoir arch

- Hinges can form at many possible locations
- Travelling hinges possible
- When motion reverses direction, mirror-image hinges form



Hinge locations

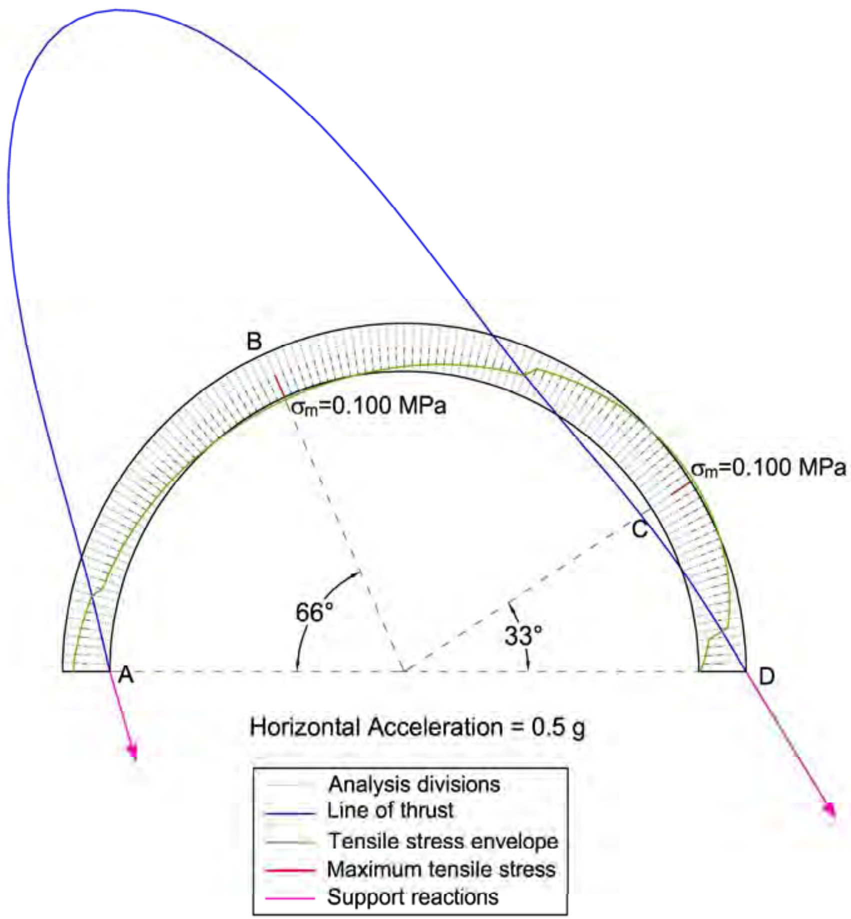
- For continuous arch, hinge locations are far more symmetrical than for the voussoir arch
- Two hinges always form at feet – only points of zero tensile strength
- Others at about one-third span points



Voussoir arch typical hinge locations

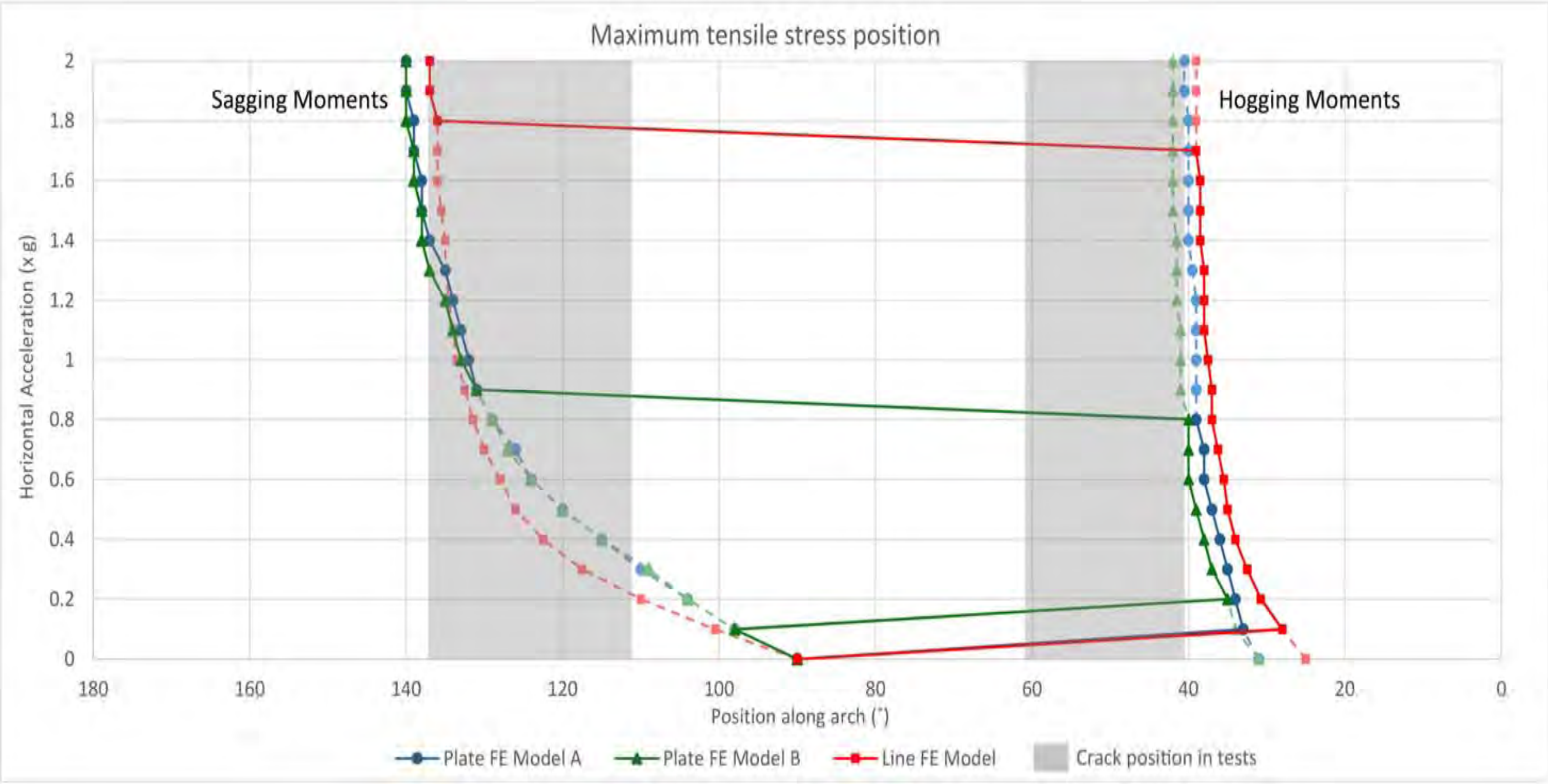
Can we predict hinge locations?

- Using thrust line analysis…
- With self-weight and lateral acceleration of 0.5g, thrust line and tensile stress envelope are as shown
- Implies highly asymmetric hinge locations
- But thrust line was found based on an assumption that hinges B and C form simultaneously – in reality they don't
- Without this (or some similar) assumption, problem is indeterminate



Can we predict hinge locations?

- Using elastic FE analysis…
- Again not a good prediction

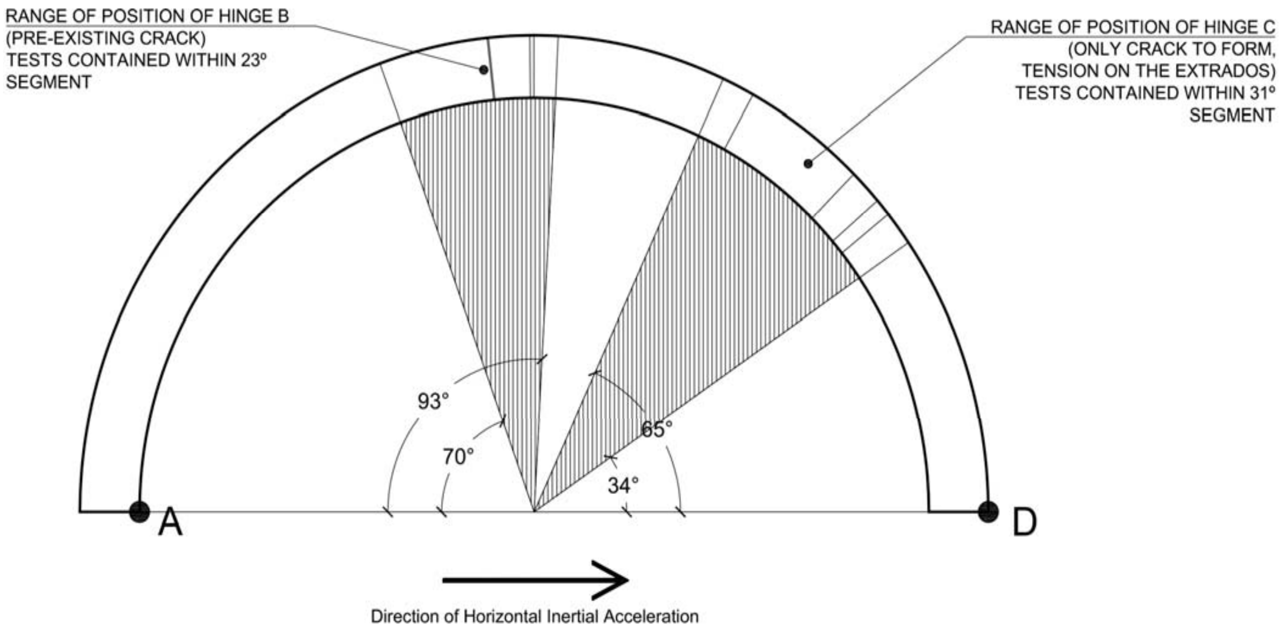


Failure of a pre-cracked arch

- Single crack at crown generated by lateral spreading of footings

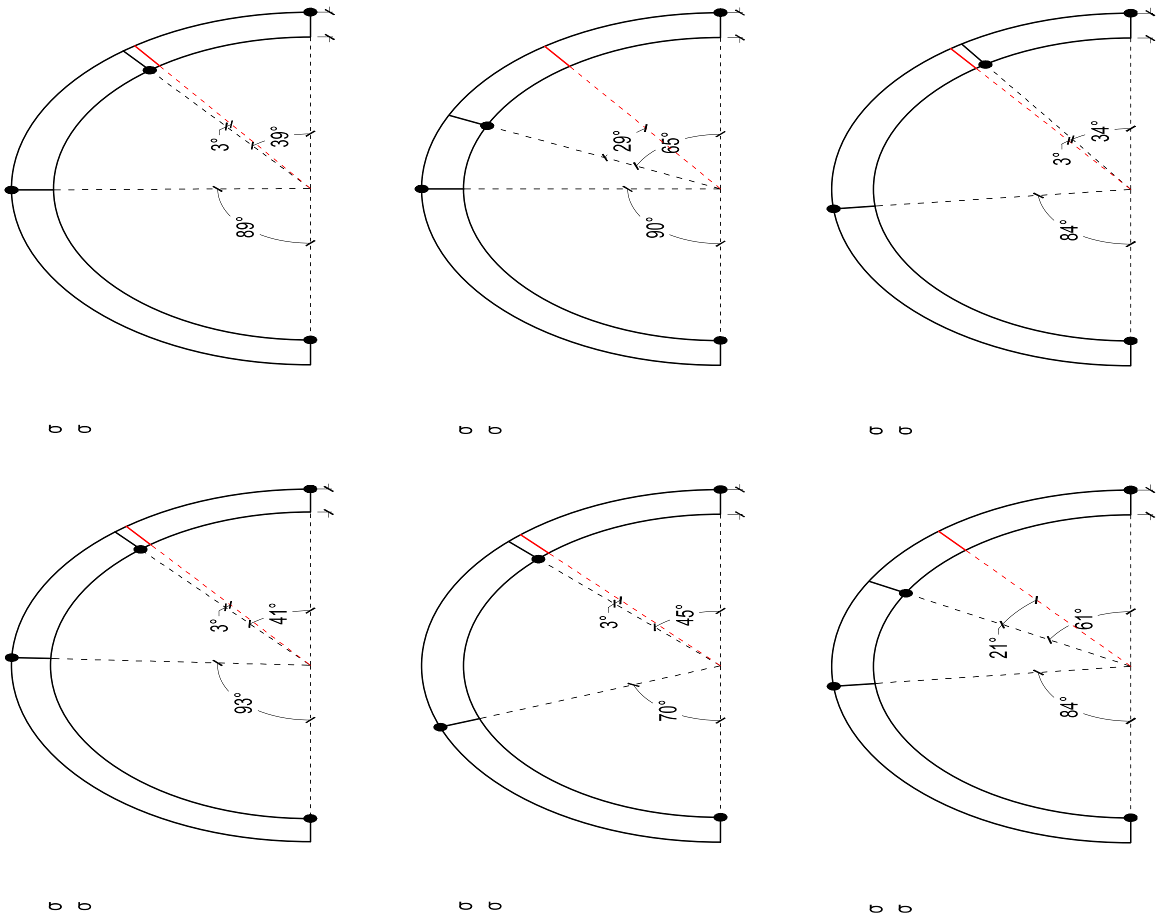
Hinge locations

- Hinge forms approximately midway between crown crack and support
- Lateral acceleration to cause failure is not significantly reduced by pre-cracking



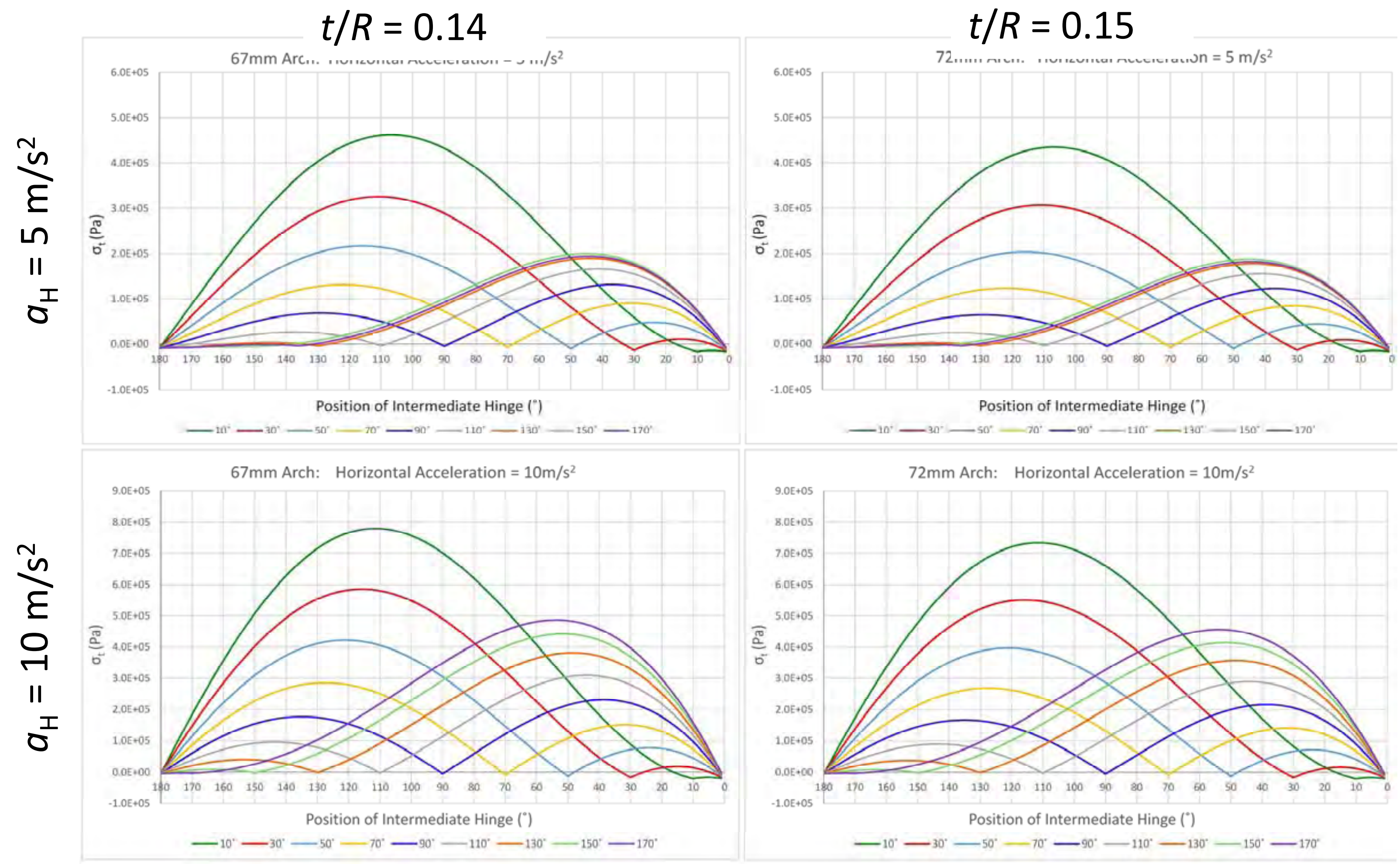
Can we predict final hinge location?

- Yes, using simple quasi-static elastic analysis



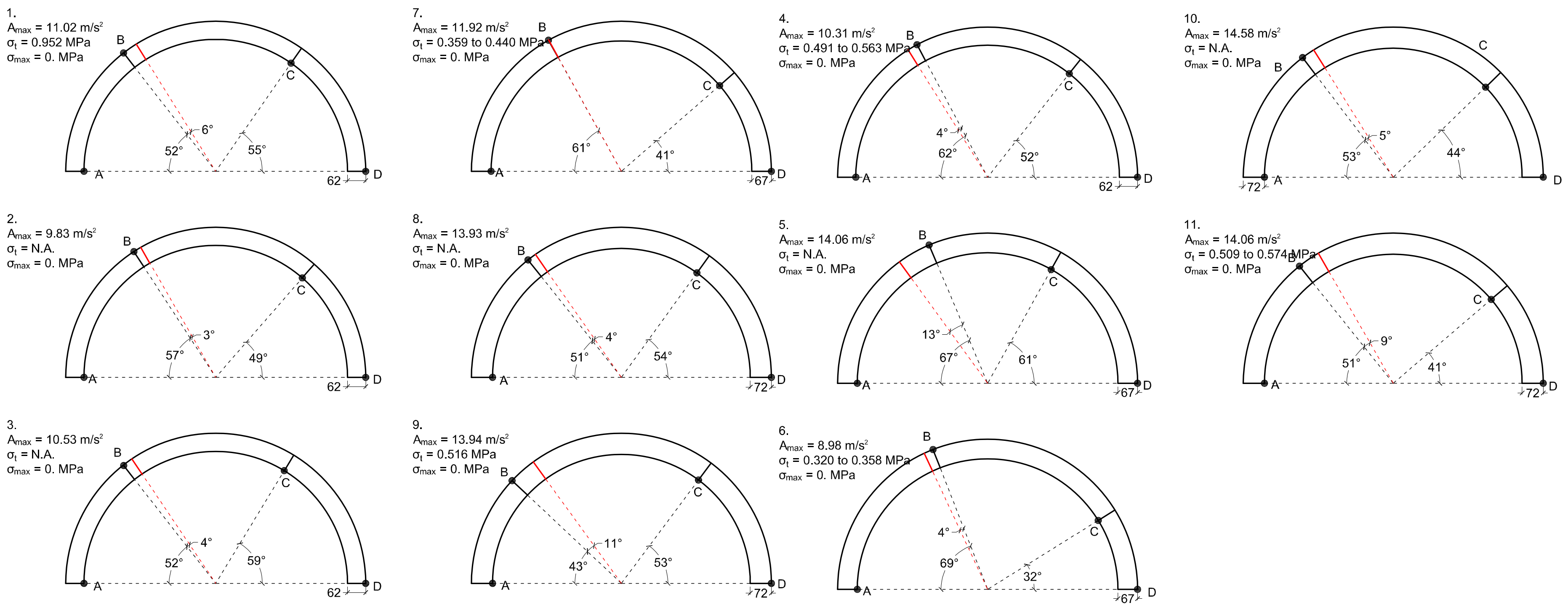
Expanding analysis to consider any hinge position

- Tensile stress distributions for different locations of the third hinge:



Returning to initially uncracked arches

- Applying same analysis to formation of final crack:



Conclusion (2)

- Continuous arches/vaults with modest tensile strength develop different hinge patterns to voussoir arches
- Near-simultaneous formation of two hinges – location of first hinge cannot be predicted by quasi-static methods
- Location of final hinge can be predicted using elastic analysis
- Pre-existing cracks have dramatic effect on collapse mechanism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Thank you!