Imperial College London

Engineering and Physical Sciences Research Council

Exploiting the Resilience of Masonry Arch Bridge Infrastructure
Workshop, London 5-6 Sept. 2023

Multi-level assessment of masonry arch bridges

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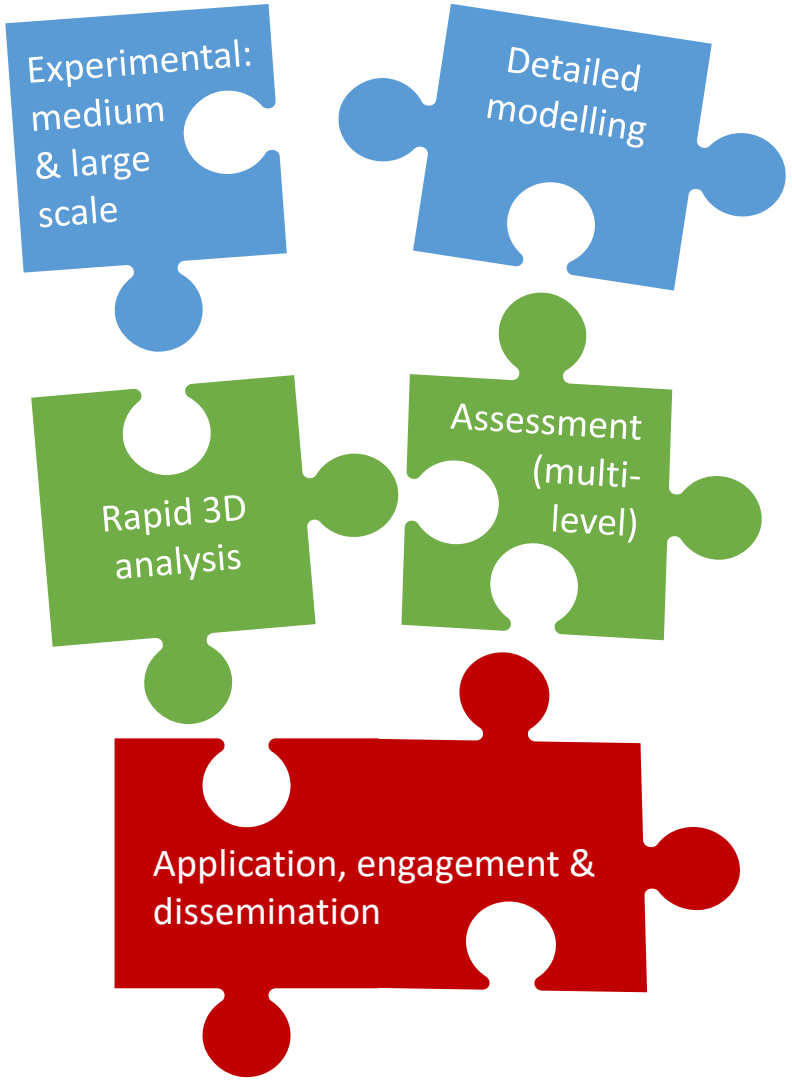
ERMABI: project context

UKRI Engineering and Physical Sciences Research Council

Understanding:

Practical tools:

Impact:



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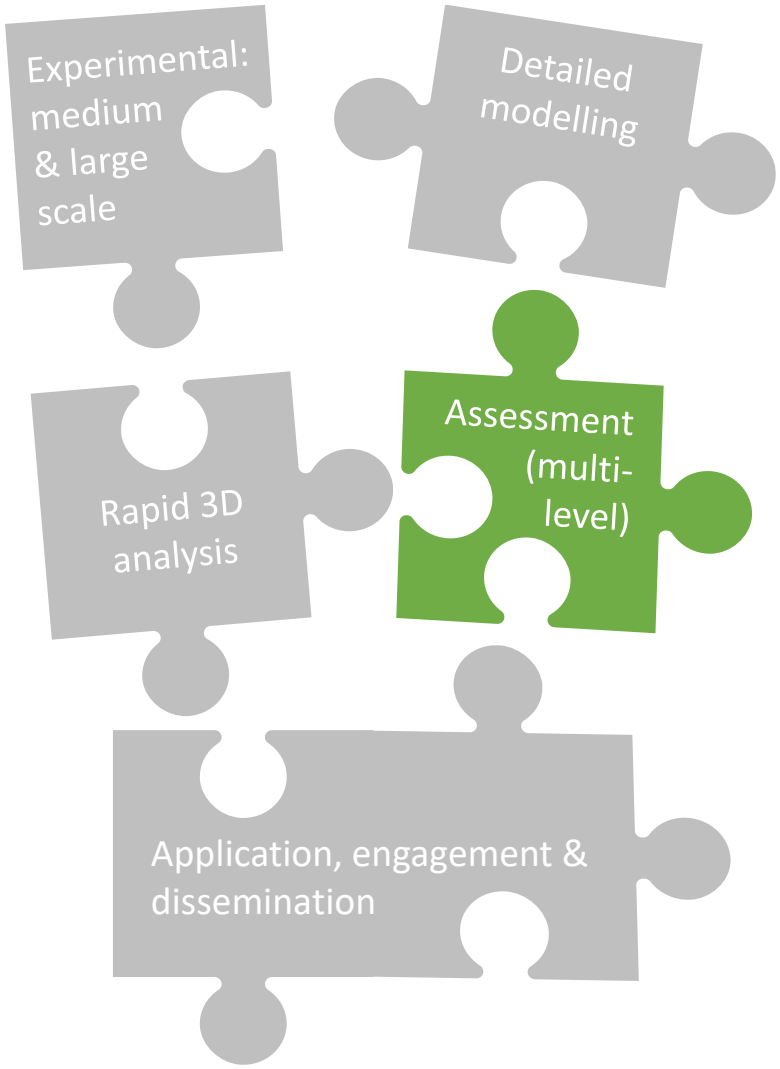


Outline

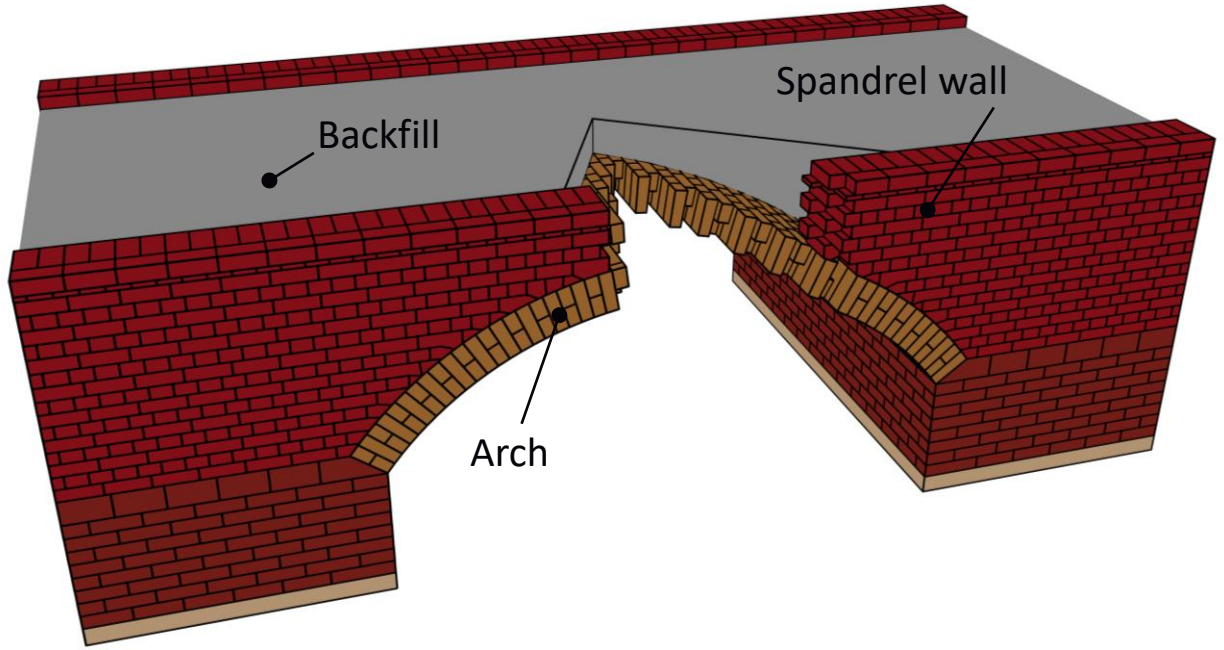
- Background
- Computational strategies for masonry arch bridges
- Parametric study details
- Numerical results
- Conclusions

Background

Real bridge behaviour

Masonry arch bridges are inherently three-dimensional, and their response depends upon the interaction between different components, e.g:

- Masonry arch(es)
- Masonry spandrel walls
- Backfill



Accurate 3D models can explicitly represent the different structural and non-structural parts, their nonlinear response and mutual interactions

Multi-level assessment

Increasing sophistication

Table 4.2 Multi-level assessment levels and recommended idealisations

Level	Description	Geometry	Materials	Loading	Calculation tools
0[1]	Highly simplified	Approximated	Assumed representative	Assumed representative	N/A
1	Simple, where possible based on demonstrably conservative assumptions	Measured (longitudinal slice)	Assumed representative	Assumed representative, taking due account of foreseeable loading patterns	Usually 2D analysis, to model likely global response
2	Escalated	Measured (several longitudinal slices)	Assumed representative and/or measured mechanical properties[2]	Current and planned actual	Usually 2D or simplified 3D analysis, both capable of taking account of local details
3	Advanced	Measured	Measured mechanical properties[2]	Current and planned actual	Full 3D analysis, capable of capturing key aspects of behaviour

Notes

1 Used by some organisations as a sift to identify bridges to be prioritised for more in-depth assessment. However, it may not offer much time saving compared with a Level 1 assessment.

2 If necessary derived from a population of similar bridges.

(CIRIA C800, 2022)

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Approach: start with level 3 & then reduce complexity (for levels 2, 1)

Multi-level assessment

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Main focus of this presentation

(CIRIA C800, 2022)

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Ultimate aim is to cover Levels 1-3

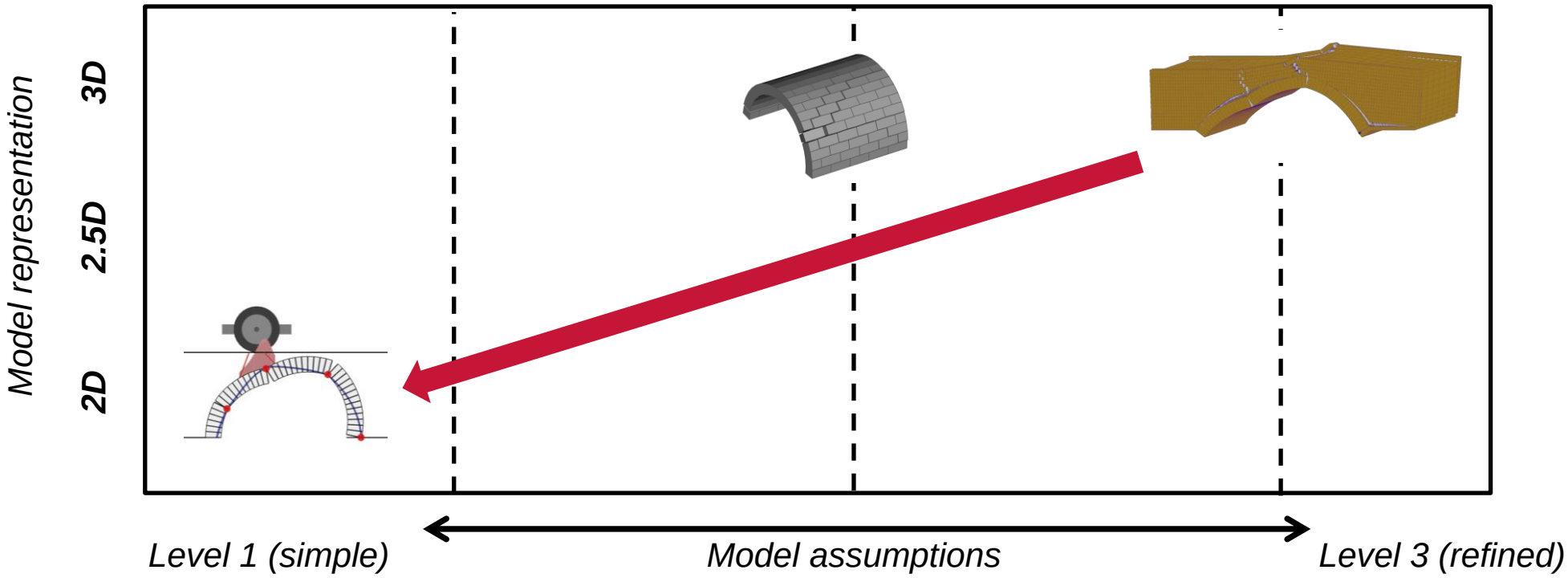
(CIRIA C800, 2022)

Simplified models

Current Level 1 tools incorporate 2D arch-backfill models, used in conjunction with an assumed effective width.

Aim of Level 1 tools is generally not to model the actual response, but to obtain a reasonable prediction of capacity.

However, currently some assumptions used in Level 1 tools are non-conservative.



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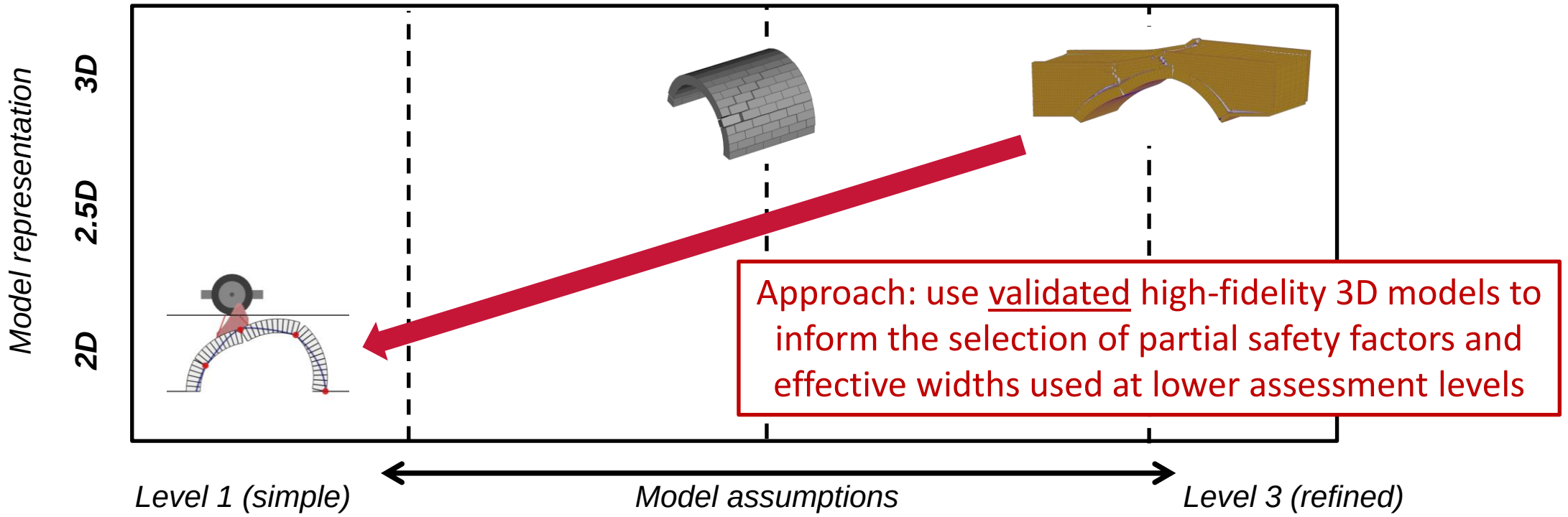


Computational strategies for masonry arch bridges

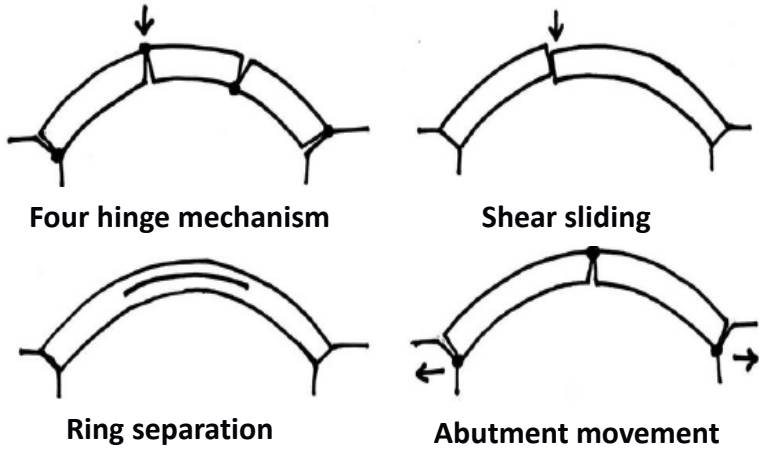
Computational strategies: masonry

Masonry material

Anisotropic response which depends upon

- characteristics of the individual components (bricks/blocks and mortar joints)
- masonry bond

Failure modes for masonry arches



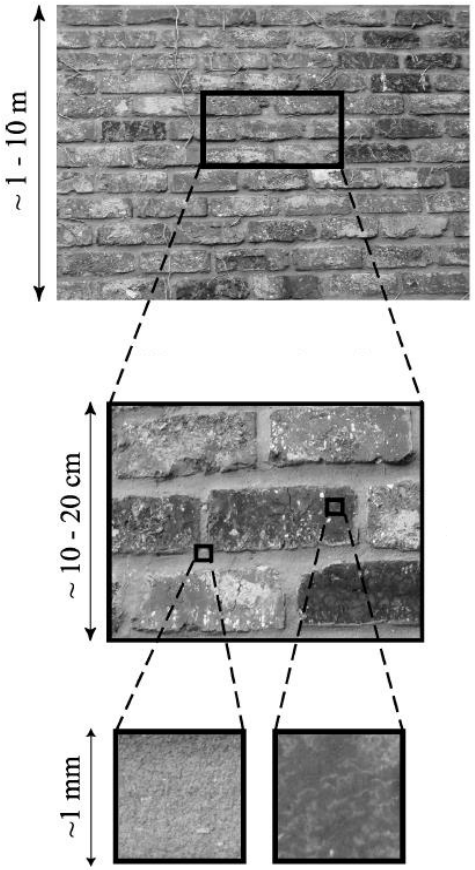
Single ring arch

Multi-ring (stretcher bond)

Multi-ring (header bond)

Computational strategies: masonry

Scale of representation



Massart (2003)

Structural scale

Mesoscale scale

Microscale scale

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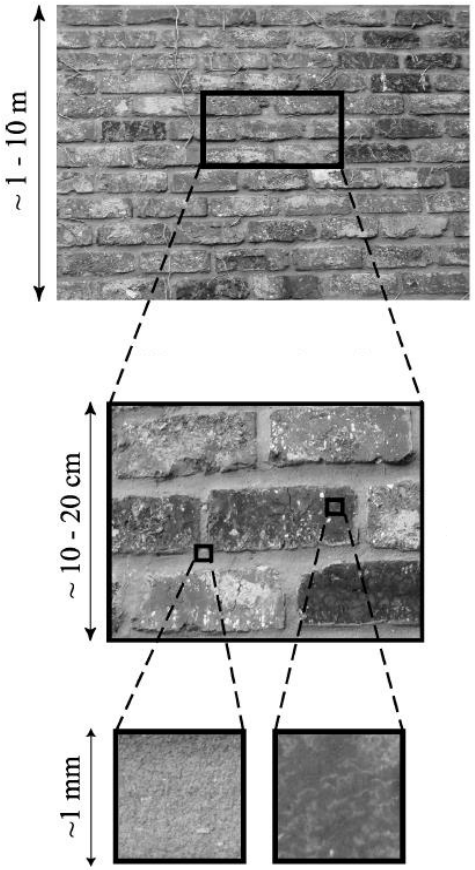
Computational strategies: masonry

Scale of representation



Massart (2003)

Structural scale

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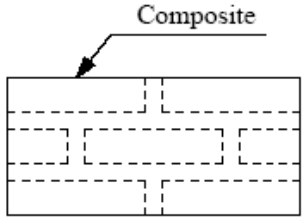
Microscale scale

Macroscale model

Equivalent material approach



Advantages

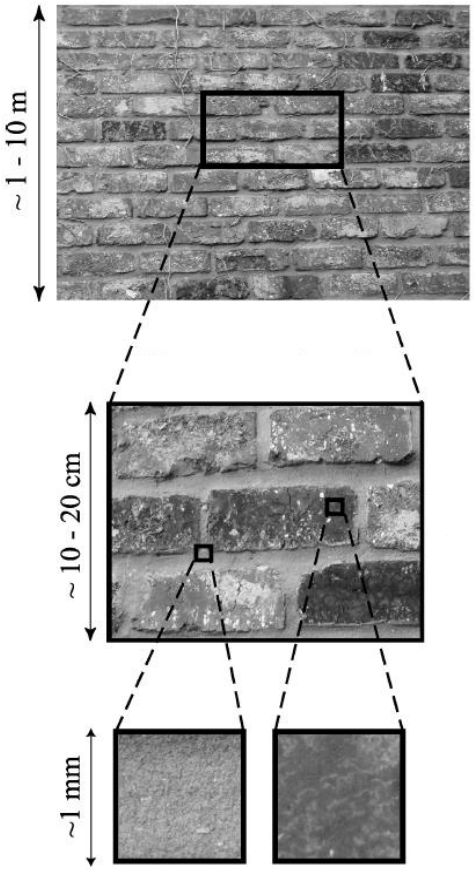
- Computational efficiency - analysis of large structures

Disadvantages

- Material model parameters must be obtained from tests on large components

Computational strategies: masonry

Scale of representation



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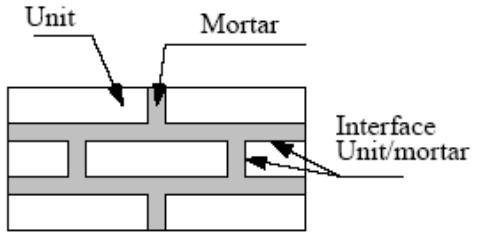
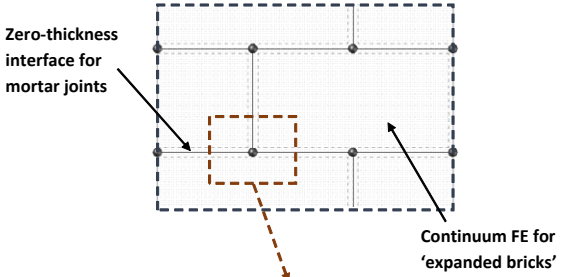
Microscale scale

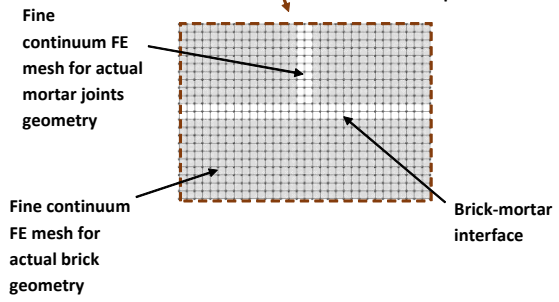
Two-material approach



Mesoscale model

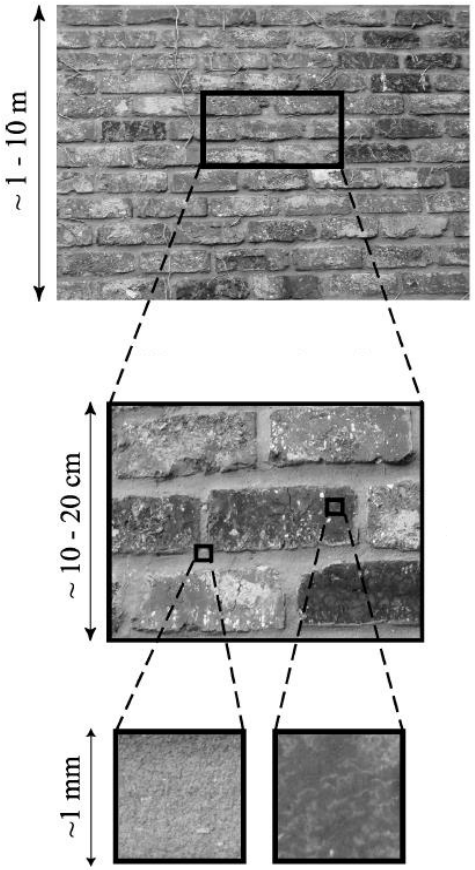


Microscale model



Computational strategies: masonry

Scale of representation



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Structural scale

Mesoscale scale

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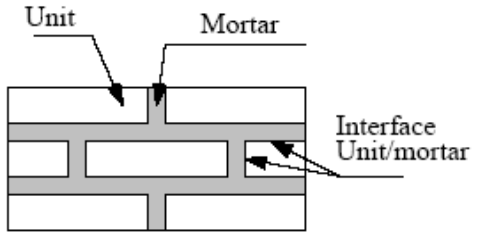
Micro- Mesoscale models

Two-material approach

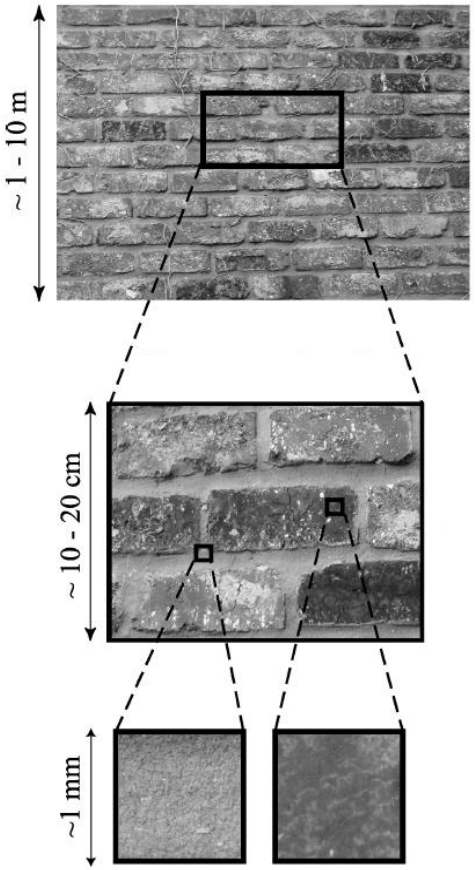


Advantages

- Material parameters can be obtained by tests on constituents or small specimens

Computational strategies: masonry

Scale of representation



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Structural scale

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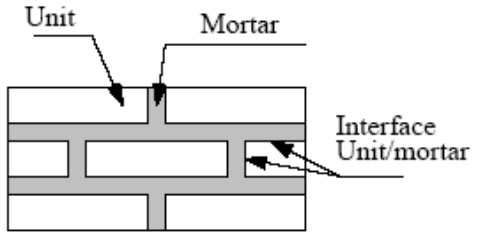
Microscale scale

Micro- Mesoscale models

Two-material approach



Advantages

- Material parameters can be obtained by tests on constituents or small specimens

Disadvantages

- High computational cost - analysis of small components

Computational strategies: bridges

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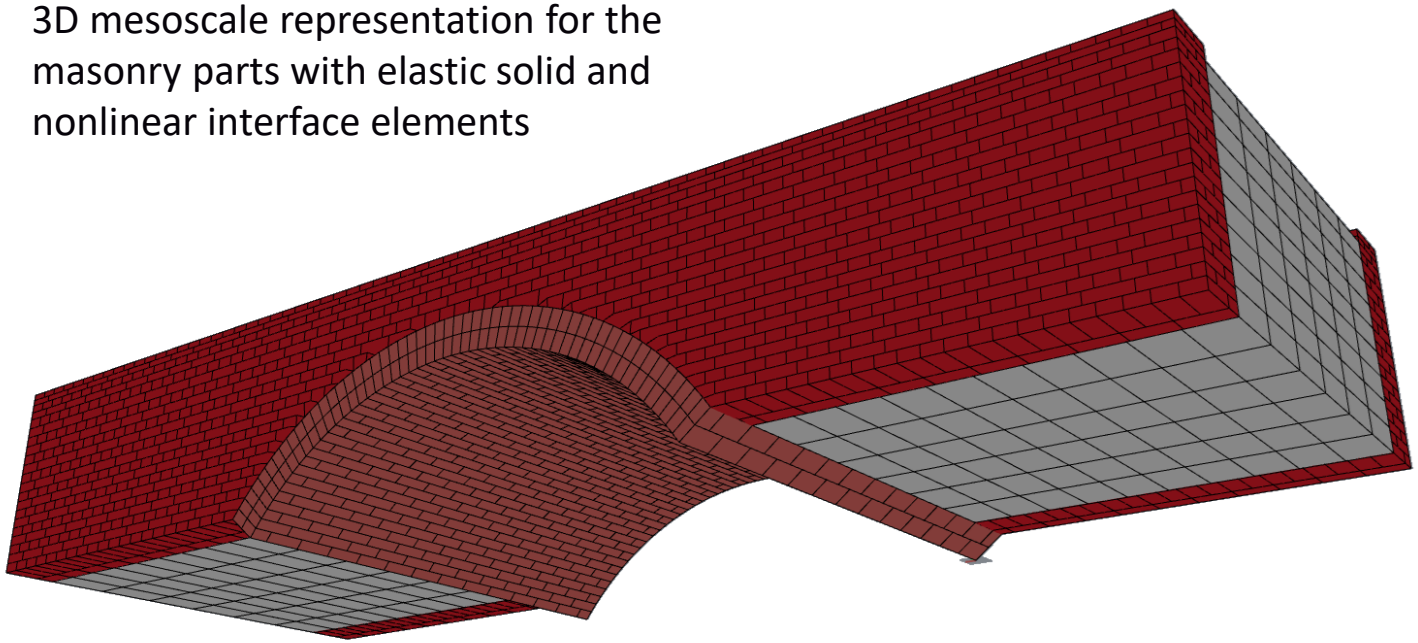
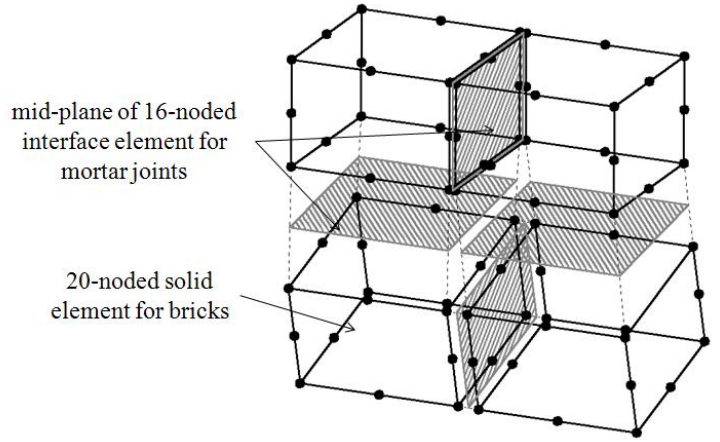
Developments - CSM Group

3D mesoscale high-fidelity models (Grosman et al. 2021)

- 3D mesoscale representation for the masonry parts with elastic solid and nonlinear interface elements



Detailed description of masonry bond for arch and spandrel walls



- Elastoplastic material model for the backfill allowing for cohesion and friction
- Frictional cohesive nonlinear interface elements to represent the physical interfaces between the difference bridge components

Computational strategies: bridges

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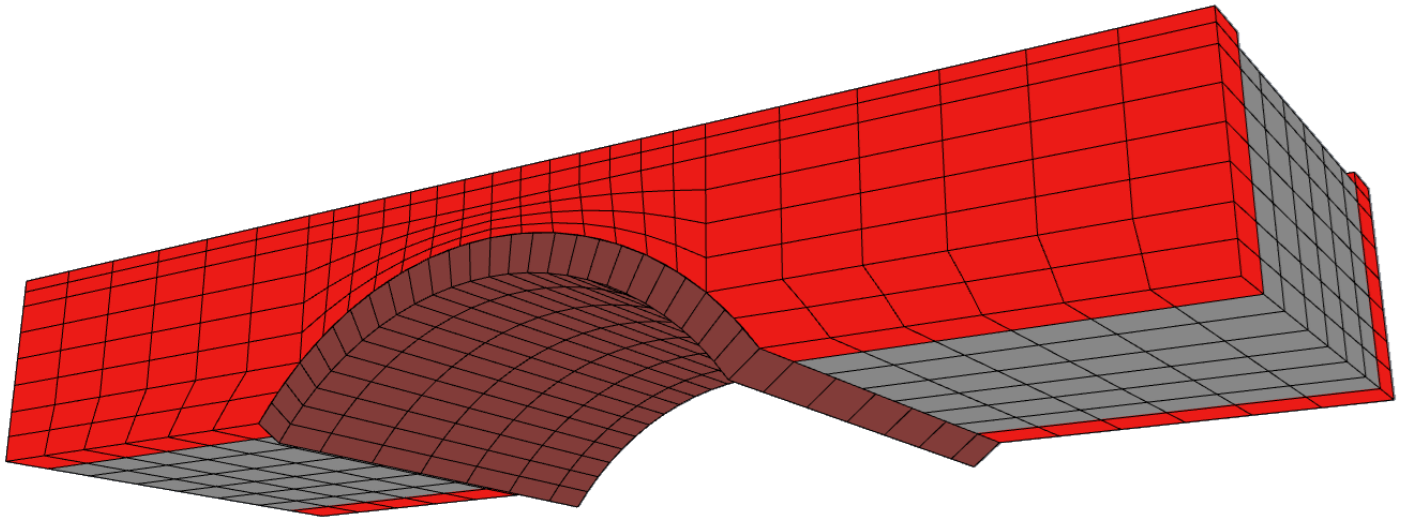
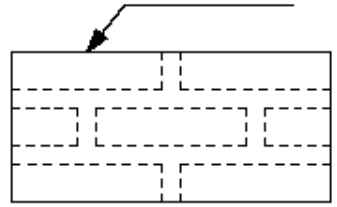
Developments - CSM Group

3D macroscale models

- Masonry components are modelled by an isotropic elasto-plastic material model allowing for damage (Lee & Fenves, 1998)



Masonry as a continuum material



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Computational strategies: bridges

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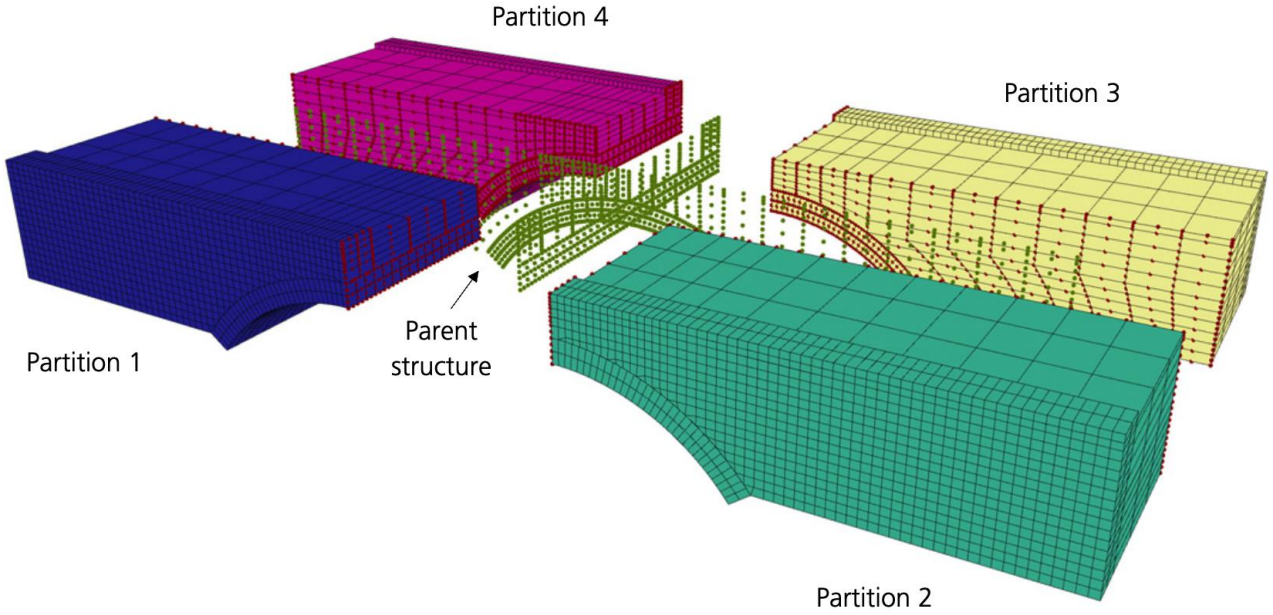
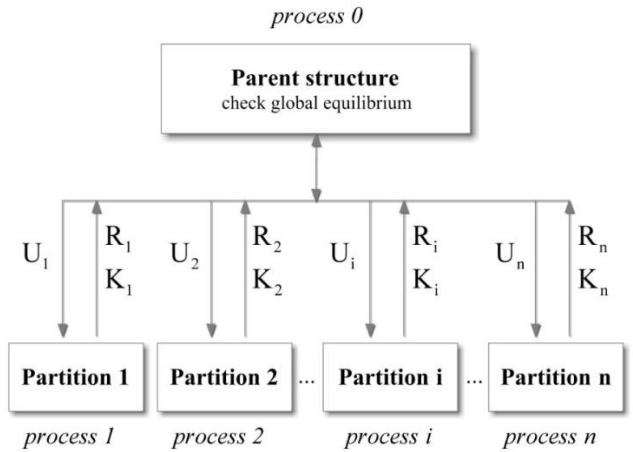
Developments - CSM Group

Domain partitioning approach



- Parallel computation
- Improved computational efficiency

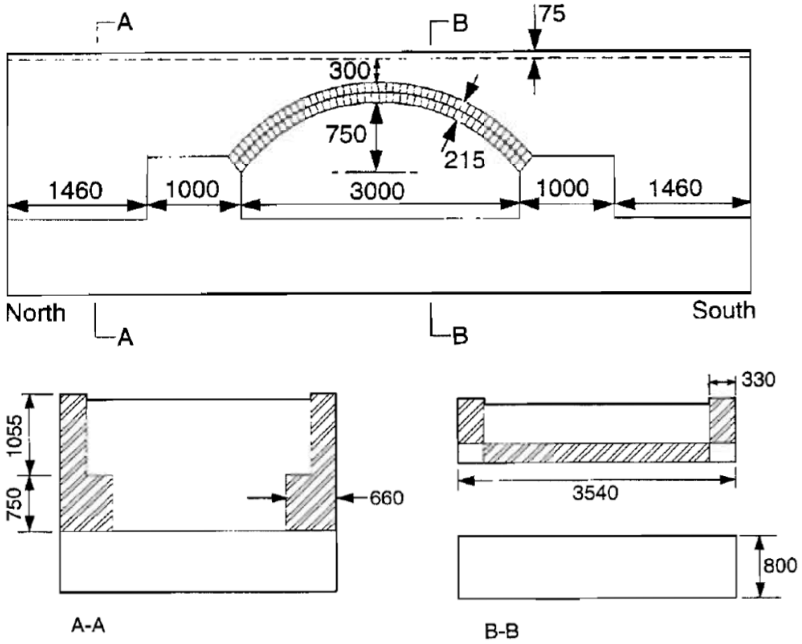


(Jokhio & Izzuddin 2015)

Parametric study details

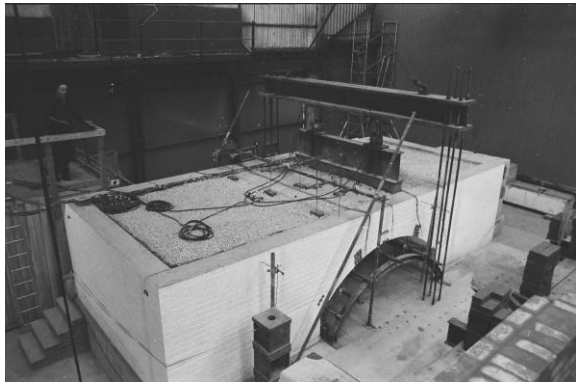
Parametric study details

Starting point: validated 3D mesoscale bridge models



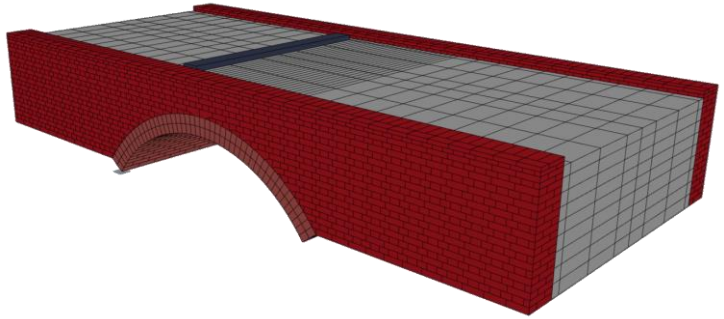
Bridge 3-3 Characteristics:

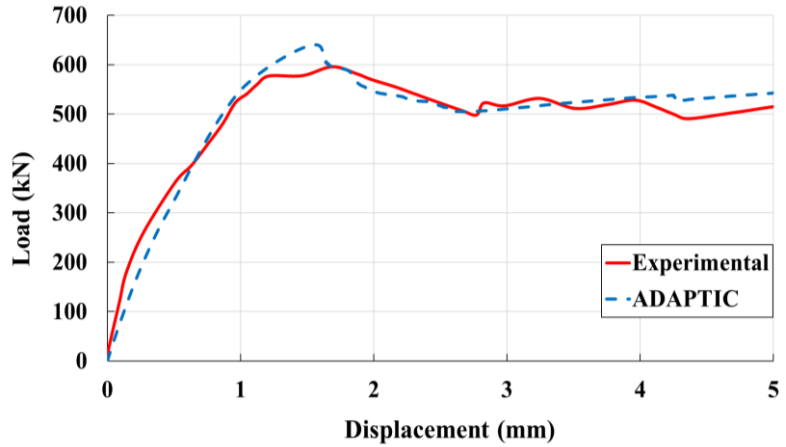
- Span = 3m
- Width = 3.54m
- Rise = 0.75m
- 2 Rings



Melbourne & Gilbert, 1995

- Line load at quarter span increased up to collapse

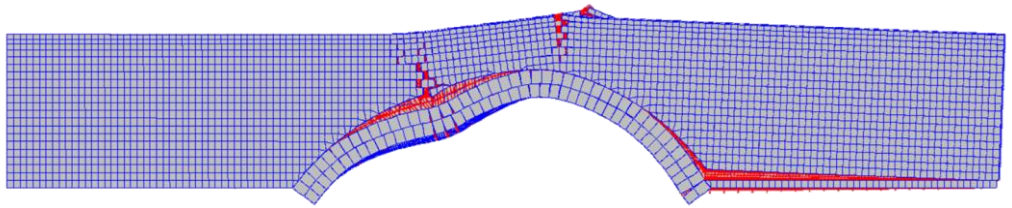




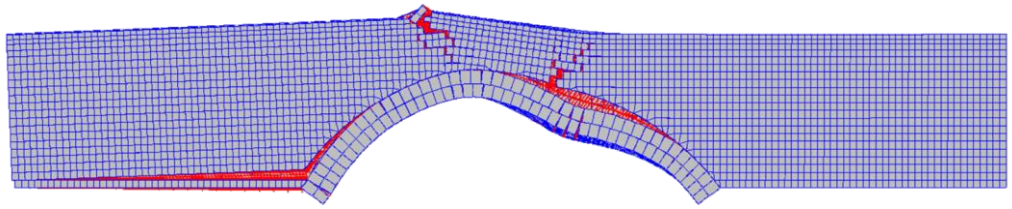
Parametric study details

Starting point: validated 3D mesoscale bridge models

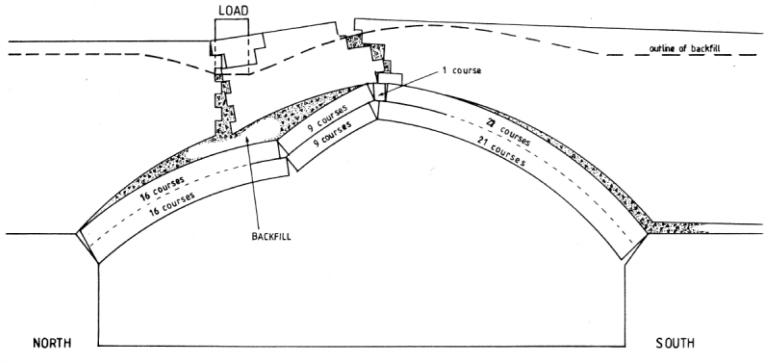
Deformed Shape at Failure



West Elevation



East Elevation



Melbourne & Gilbert, 1995

Parametric study details

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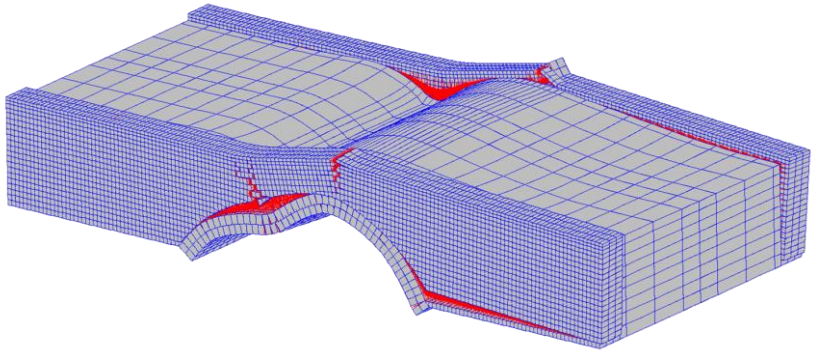
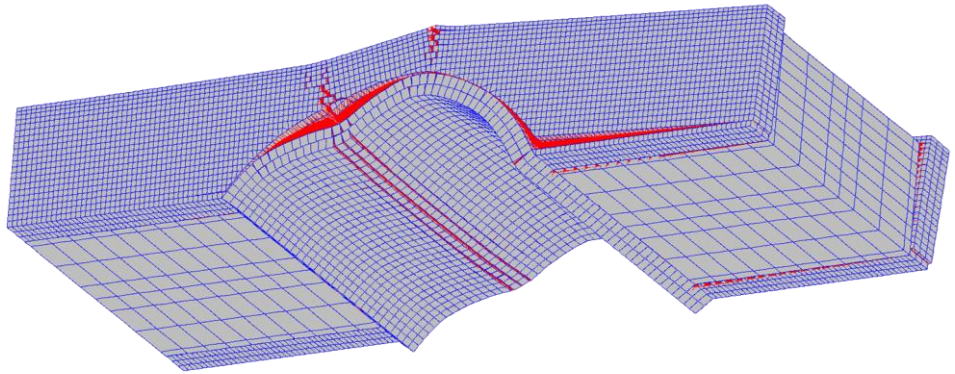
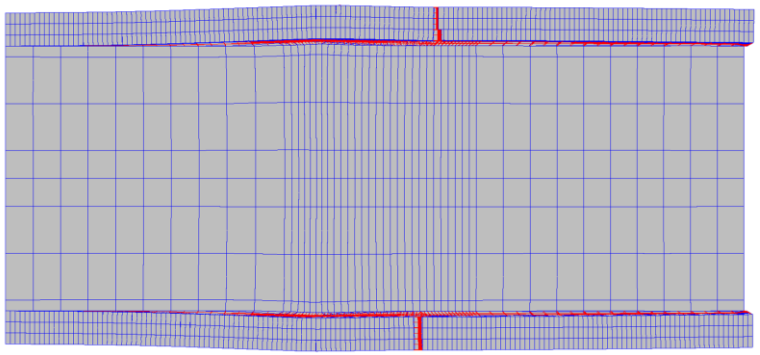




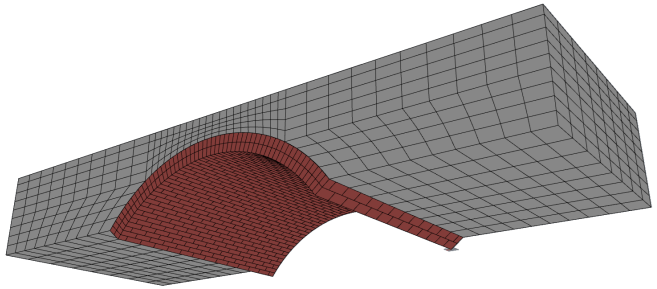


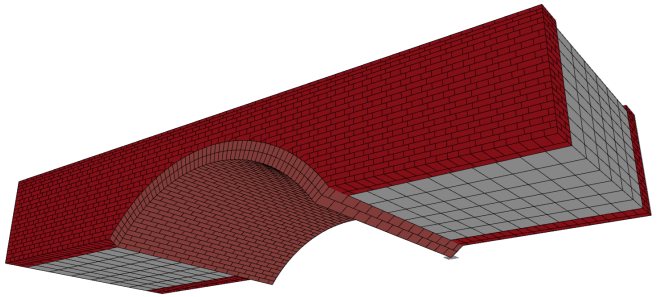
Melbourne & Gilbert, 1995

Parametric study details

Validated high-fidelity models are used to:

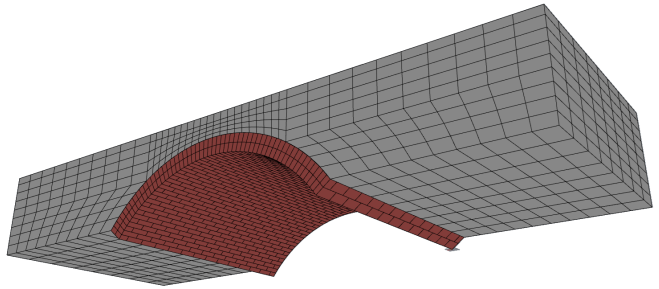
- investigate 3D behaviour and interaction among different components

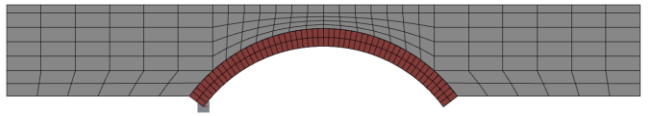




Comparing models with attached and detached spandrel walls

- establish realistic effective width values for 2D simulation



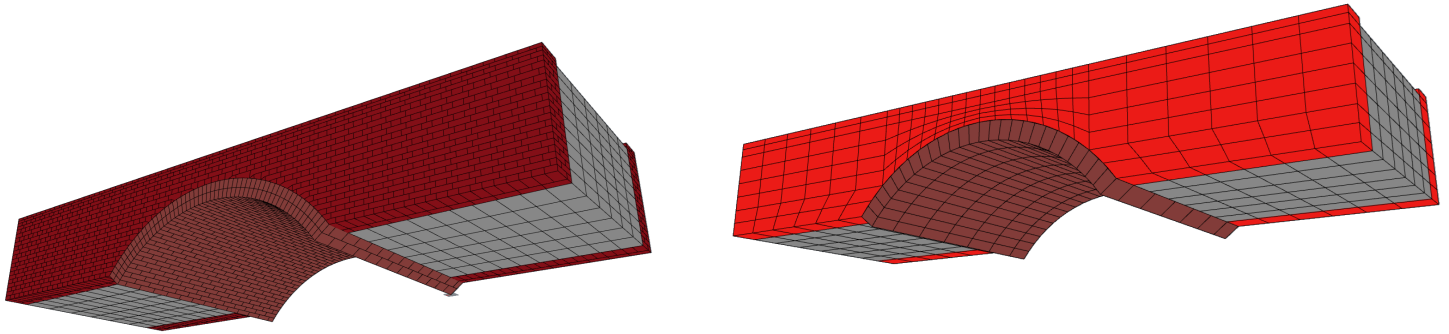


Comparing predictions from 2D and 3D models

Parametric study details

Validated high-fidelity models are used to

- assess accuracy of reduced FE models



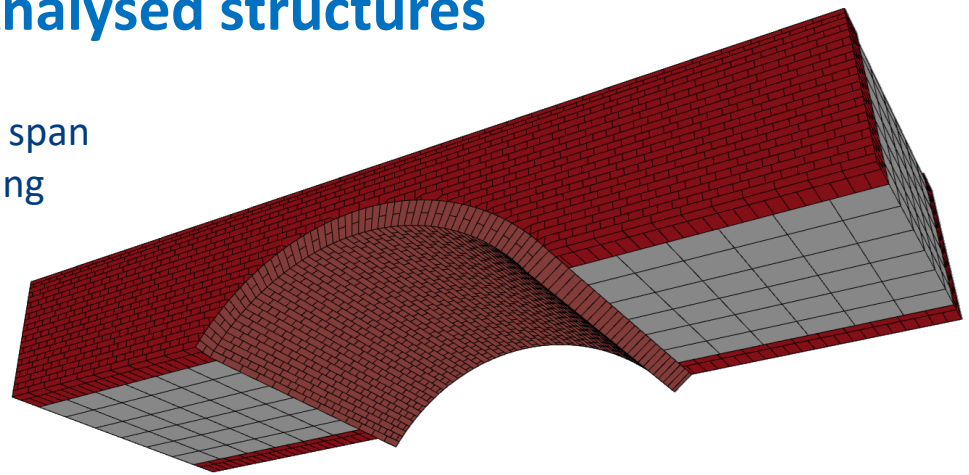
Compare meso against macroscale models

- <u>obtain baseline response data for multi-level assessment</u>

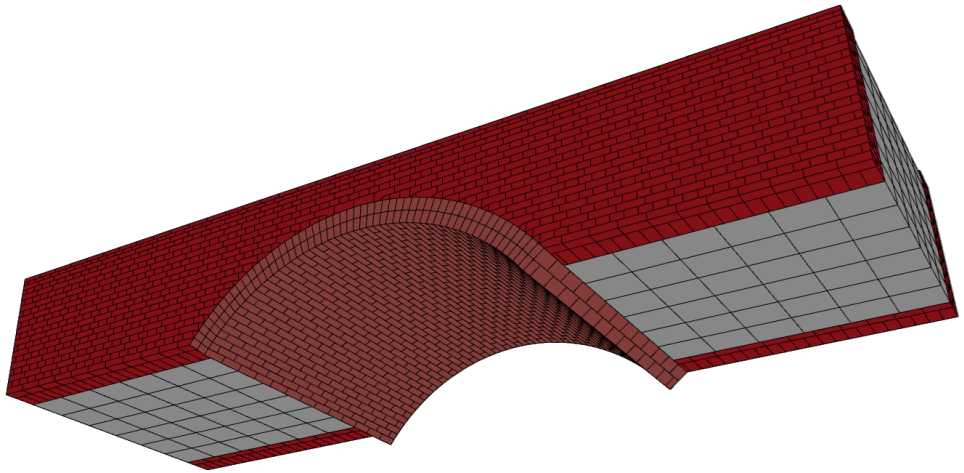
Parametric study details

Analysed structures

3m span
2-ring



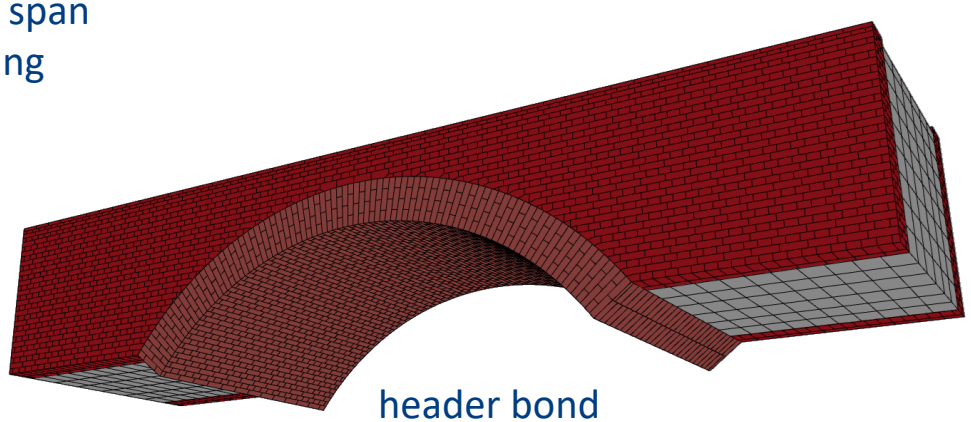
header bond



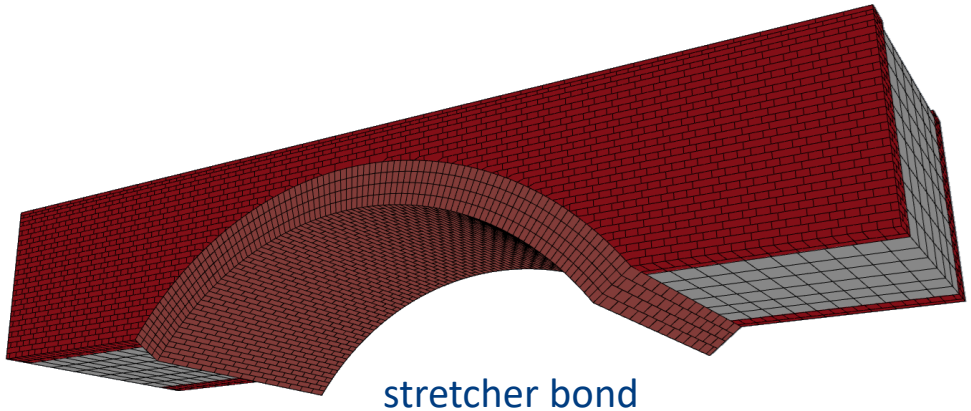
stretcher bond

Width 3m, 6m, 9m
Rise-to-span 1:4

5m span
4-ring



header bond



stretcher bond

Parametric study details

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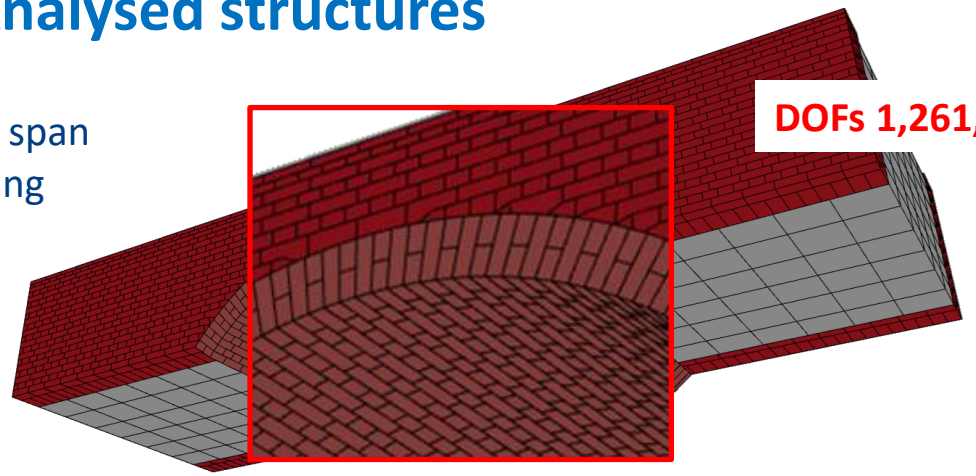
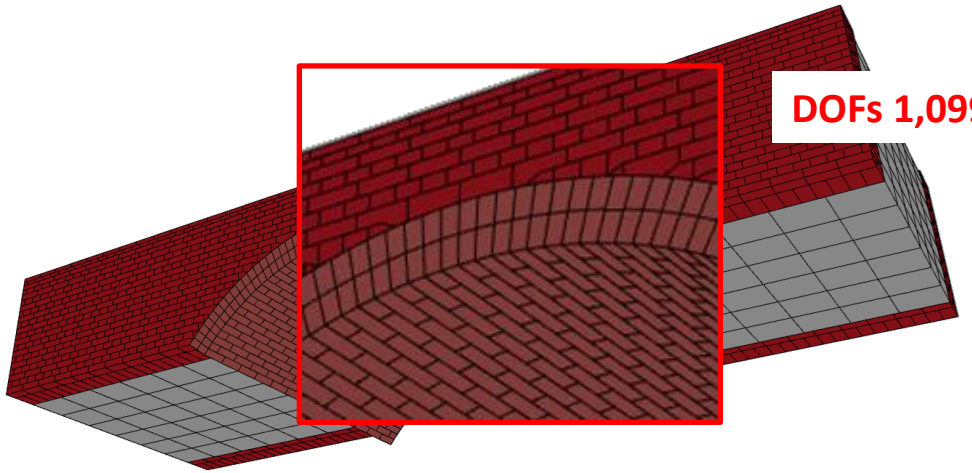
3m span
2-ring



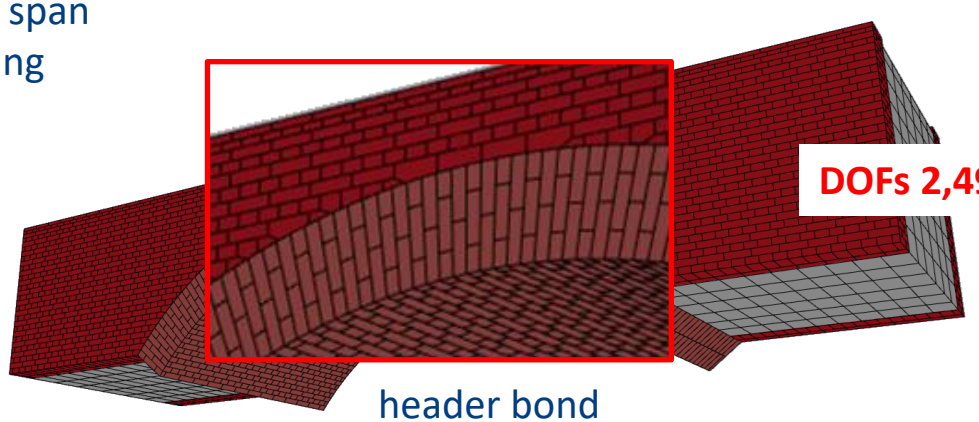
header bond



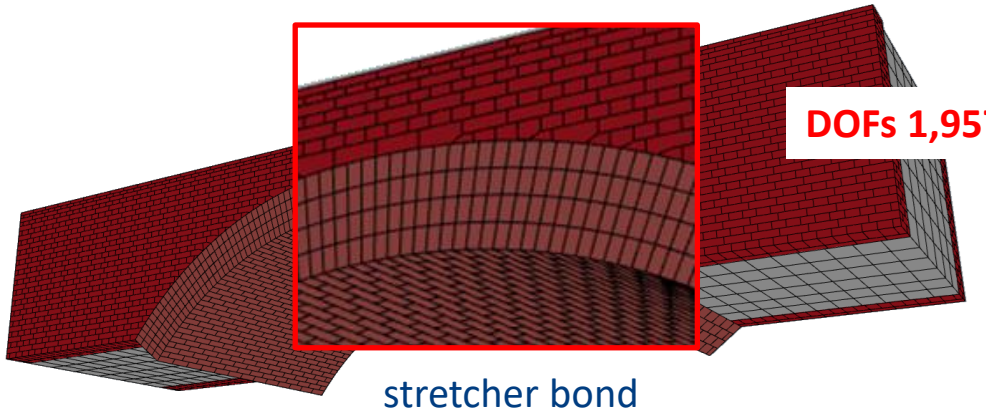
stretcher bond

Width **3m**, 6m, 9m
Rise-to-span 1:4

5m span
4-ring



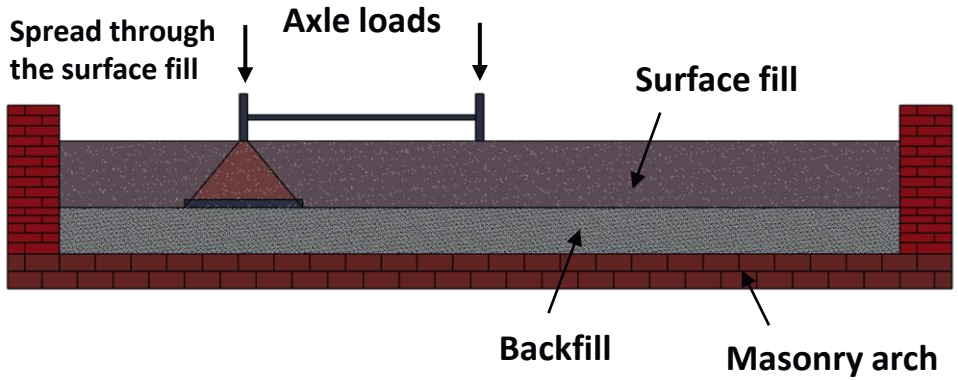
header bond

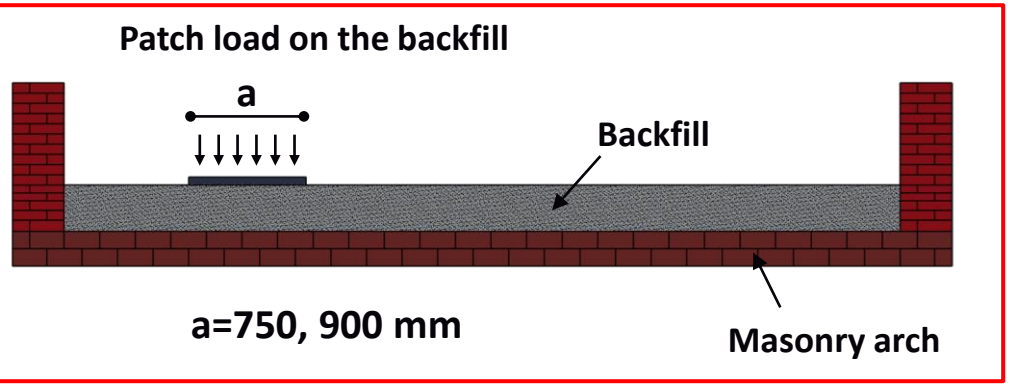


stretcher bond

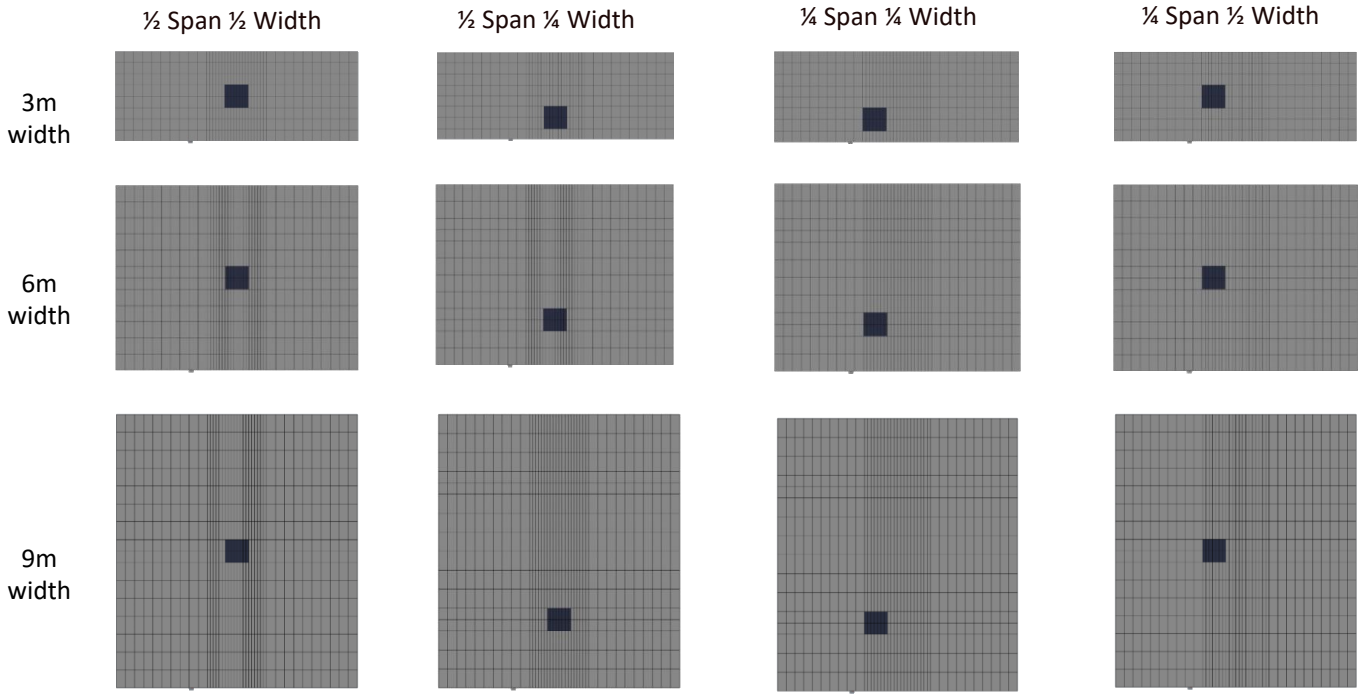
Parametric study details

Loading





Patch load positions



patch area: a×a

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Parametric study details

Material parameters for units and mortar joints*

Brick units		
E (Young's modulus)	N/mm^2	69000
ν (Poison's ratio)		0.15
Mortar Interfaces		
K_n (normal stiffness)	N/mm^3	295
K_t (tangent stiffness)	N/mm^3	118
F_t (tensile strength)	N/mm^2	0.21
tan(φ)(friction angle)	rad	0.64
c (cohesion)	N/mm^2	0.29
F_c (compressive strength)	N/mm^2	23.8
Gf_t (Fracture energy in tension)	Nmm/mm^2	0.01
Gf_s (Fracture energy shear)	Nmm/mm^2	0.029

*from material tests (Melbourne & Gilbert 1995) used for model validation

Material parameters for backfill*

Backfill		
Ef (Young's modulus)	N/mm^2	200
ν (Poison's ratio)		0.2
c (cohesion)	N/mm^2	0.001
φf (friction angle)	rad	1.047
Ψf (dilatancy angle)	rad	0.5236

Numerical results

Spandrel wall study

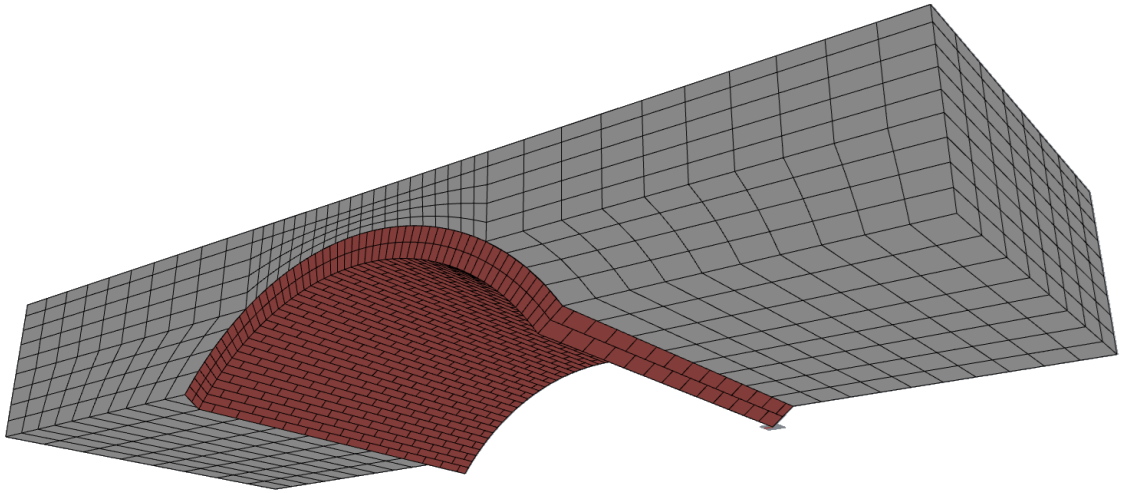
Numerical results

Influence of spandrel walls

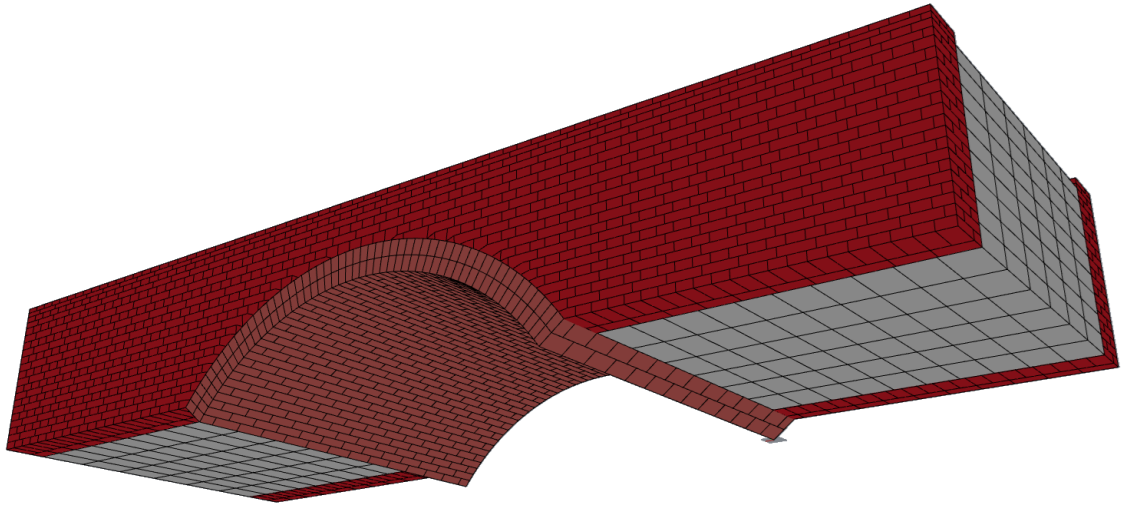
Engineering and Physical Sciences Research Council

Detached vs Attached Spandrel Wall models

- 3m Span
- 3m Width
- 0.75m Rise
- 2 Rings
- SW thickness 330mm
- Stretcher Bond



Detached SW



Attached SW

Numerical results

Influence of spandrel walls

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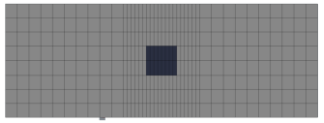
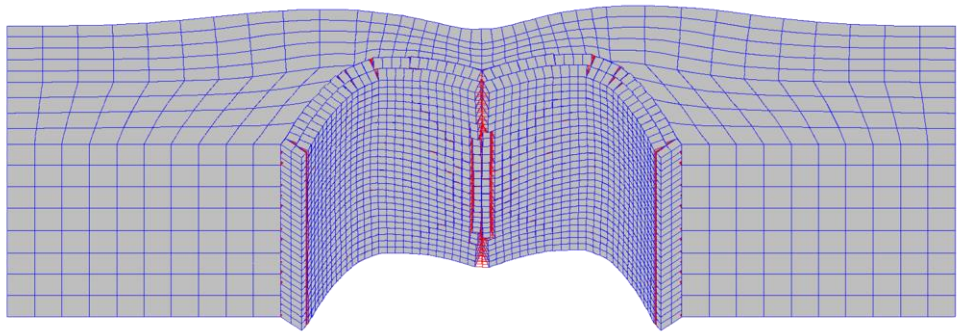
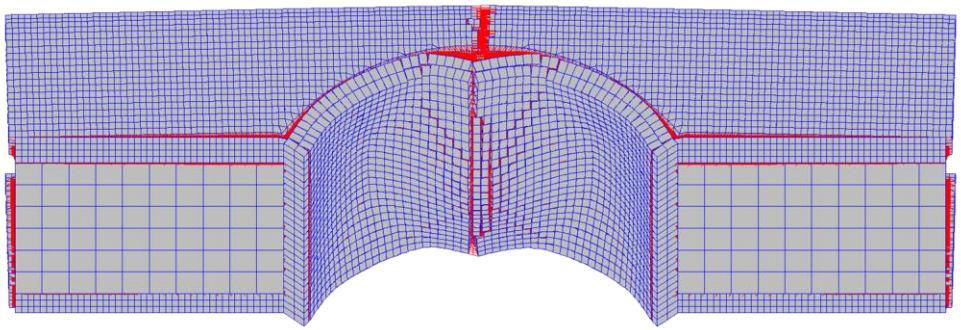
Patch 750mm×750mm at ½ Span ½ Width

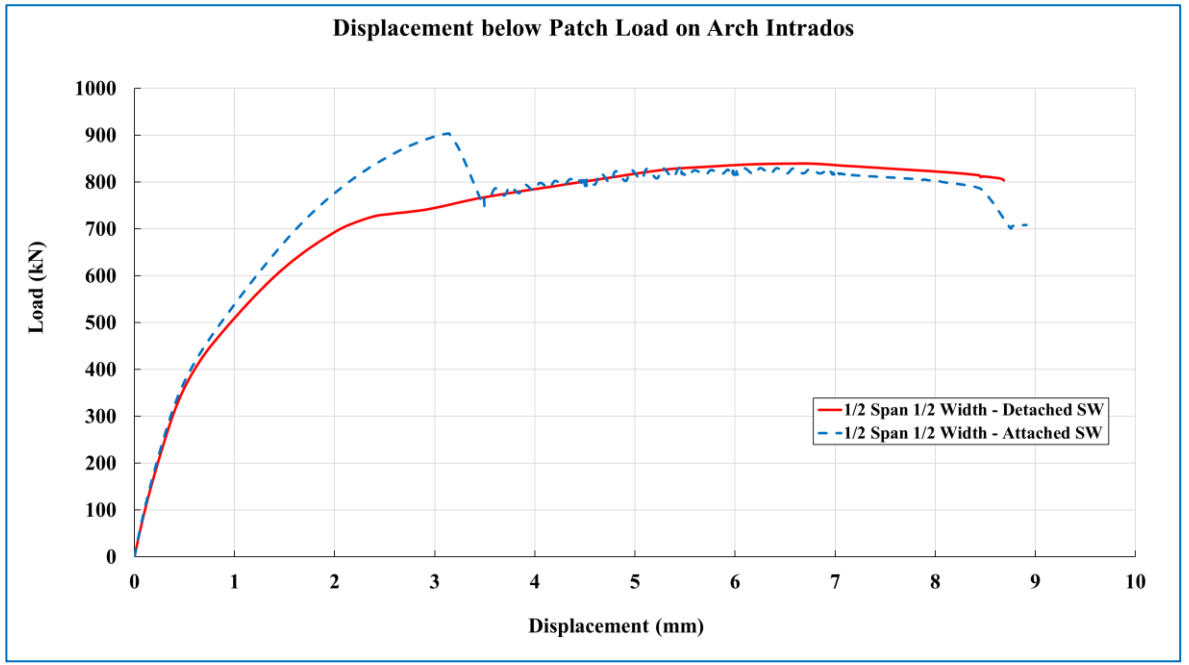




Detached SW



Attached SW – West Elevation

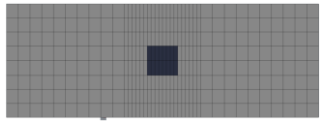


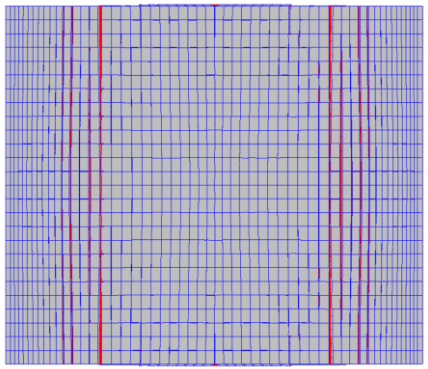
Numerical results

Influence of spandrel walls

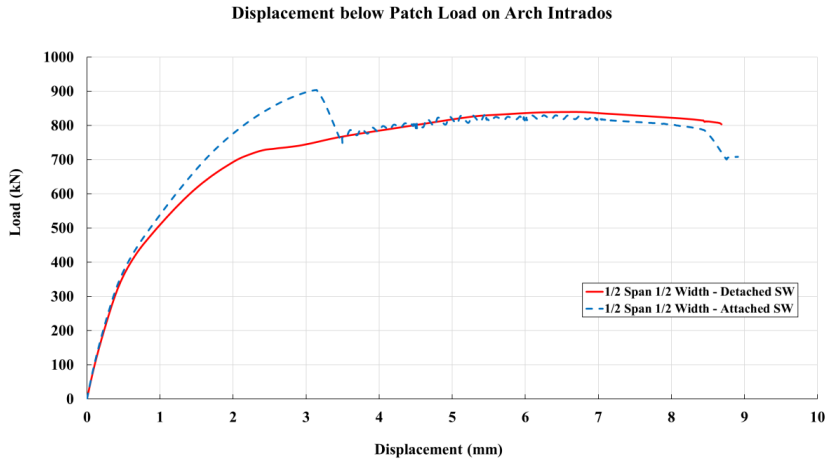
Engineering and Physical Sciences Research Council

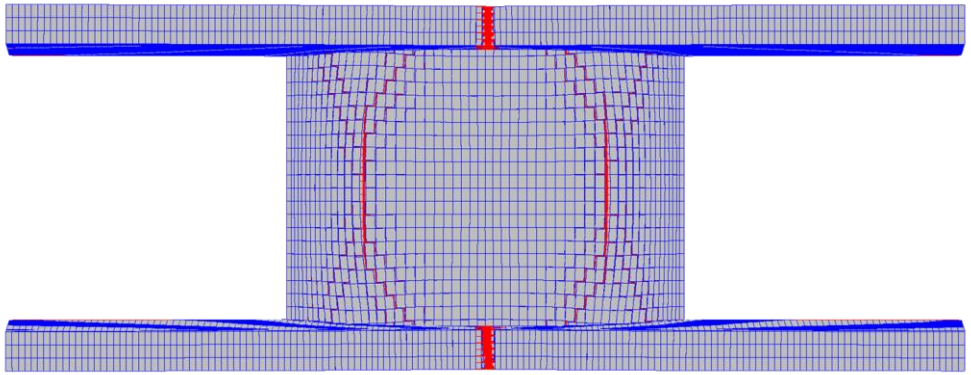
Patch 750mm×750mm at ½ Span ½ Width



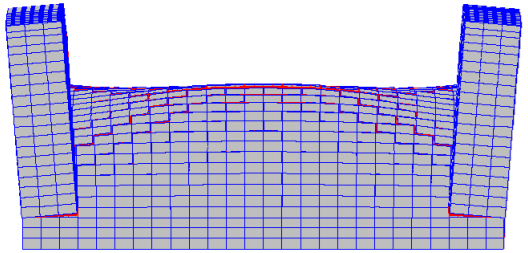


Detached SW – Top View

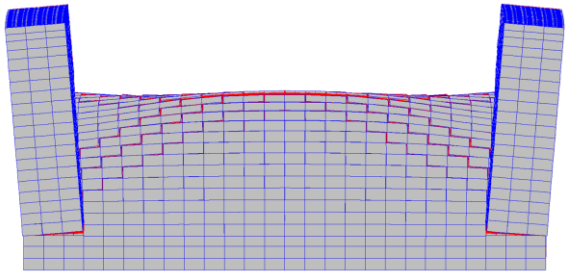




Attached SW – Top View



Attached SW – Right Side View



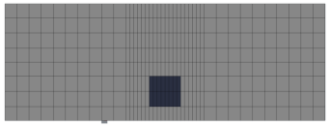
Attached SW – Left Side View

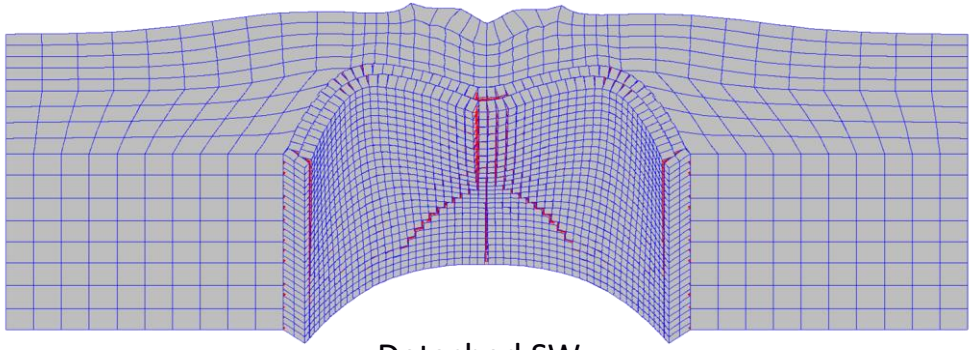
Numerical results

Influence of spandrel walls

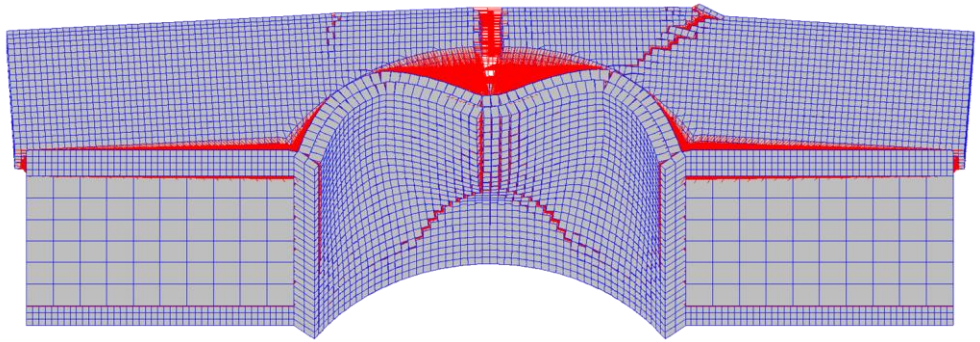
Engineering and Physical Sciences Research Council

Patch 750mm×750mm at ½ Span ¼ Width

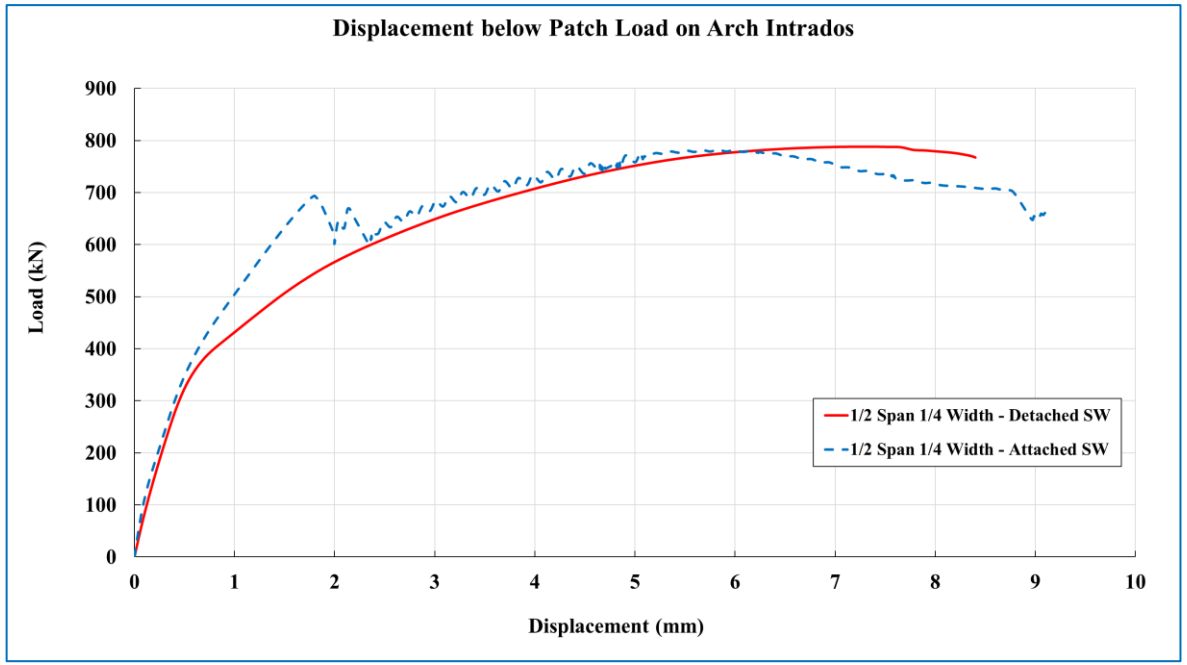




Detached SW



Attached SW – West Elevation

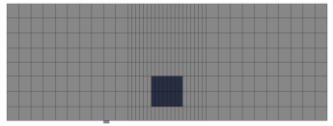


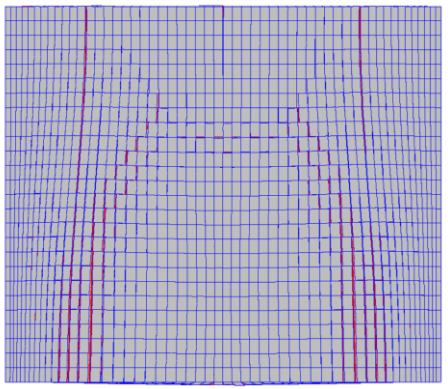
Numerical results

Influence of spandrel walls

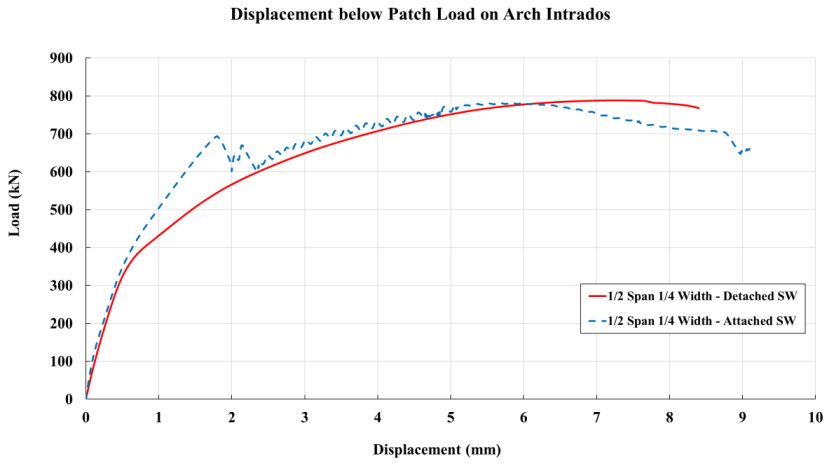
Engineering and Physical Sciences Research Council

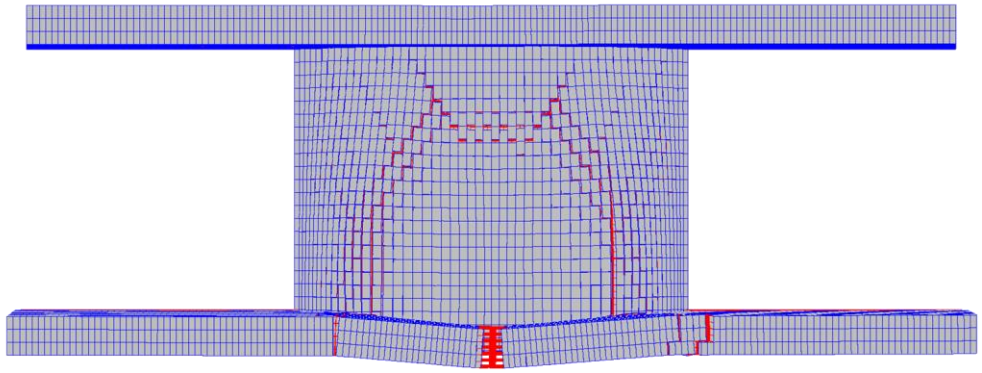
Patch 750mm×750mm at ½ Span ¼ Width



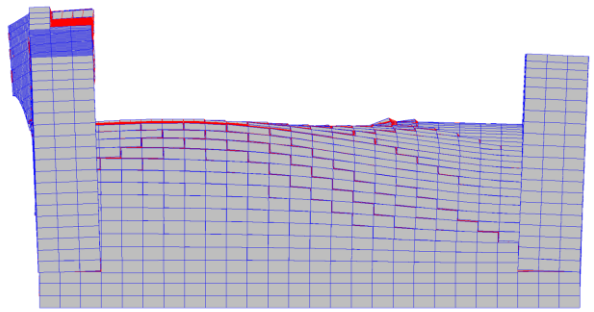


Detached SW – Top View

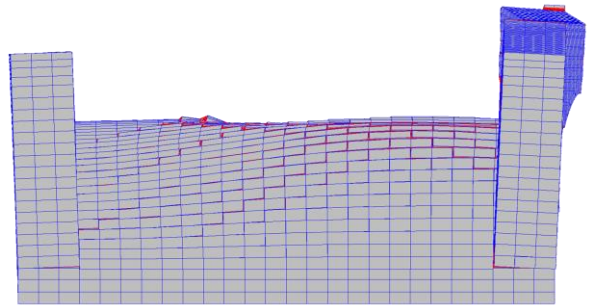




Attached SW – Top View



Attached SW – Right Side View



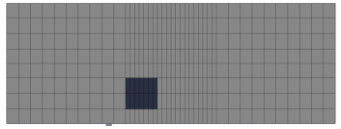
Attached SW – Left Side View

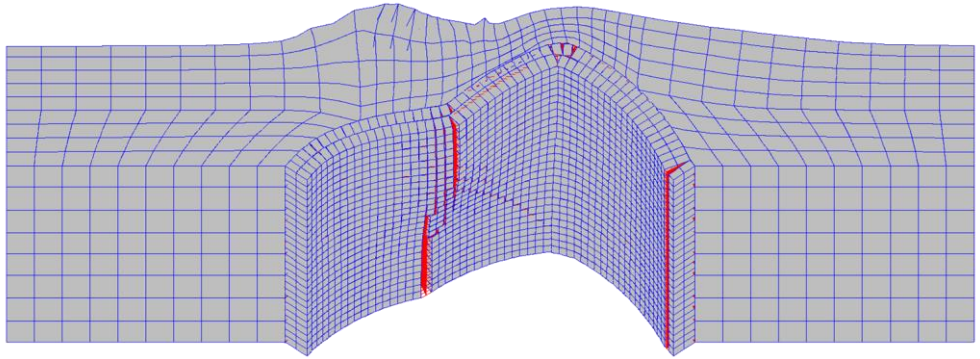
Numerical results

Influence of spandrel walls

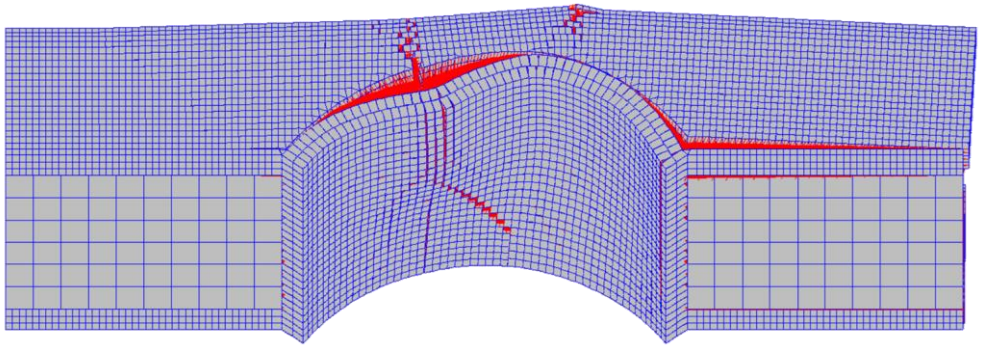
Engineering and Physical Sciences Research Council

Patch 750mm×750mm at ¼ Span ¼ Width

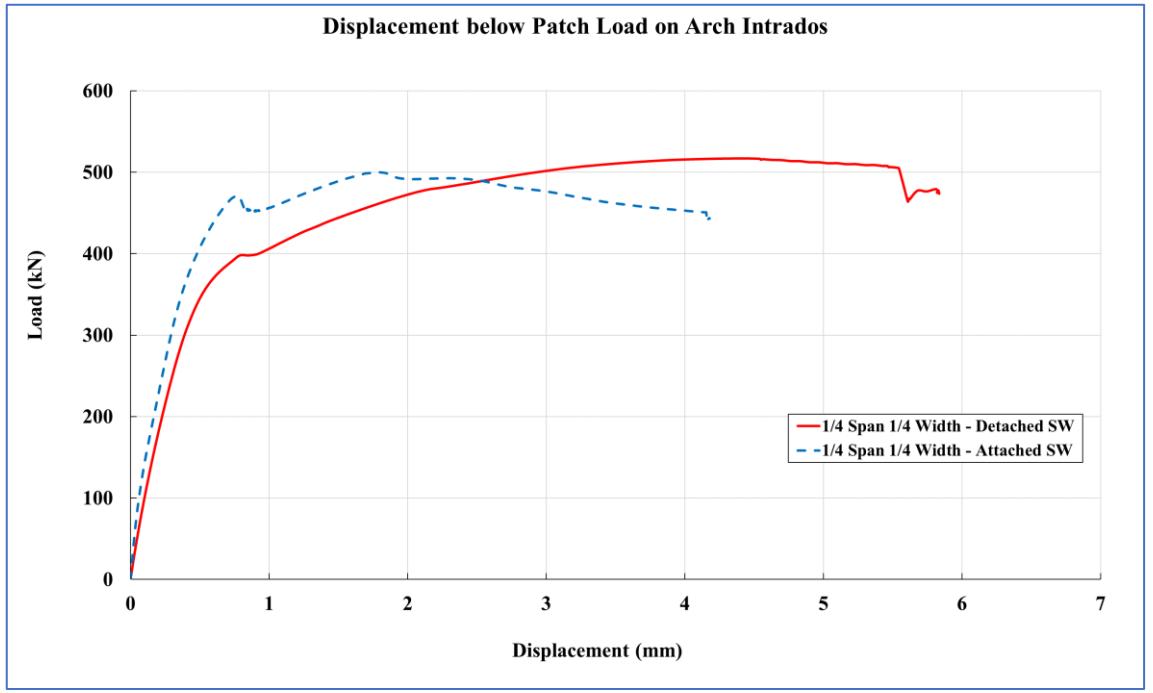




Detached SW



Attached SW – West Elevation



Numerical results

Influence of spandrel walls

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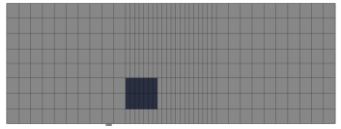
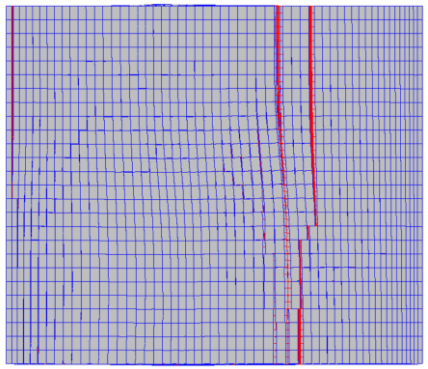
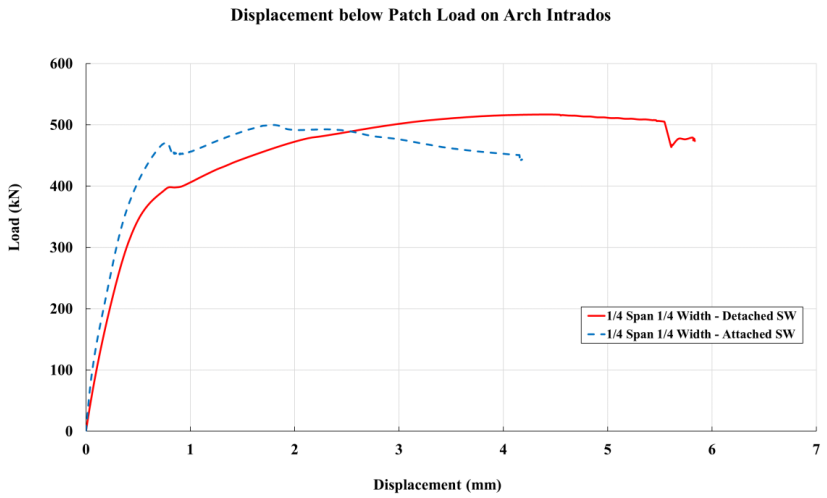
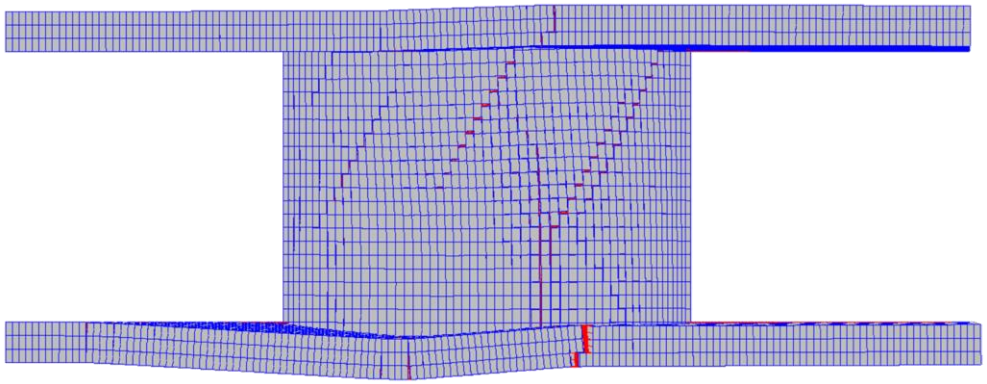
Patch 750mm×750mm at ¼ Span ¼ Width



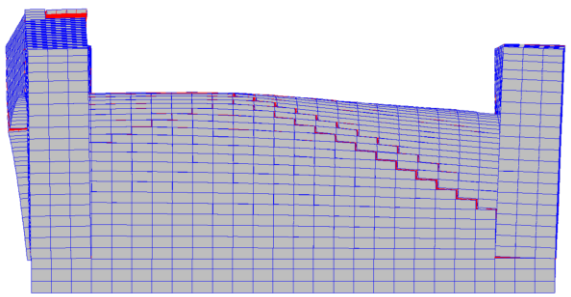


Detached SW – Top View

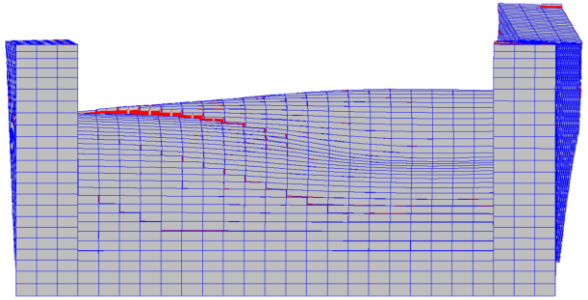




Attached SW – Top View



Attached SW – Right Side View



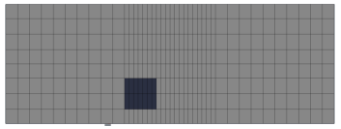
Attached SW – Left Side View

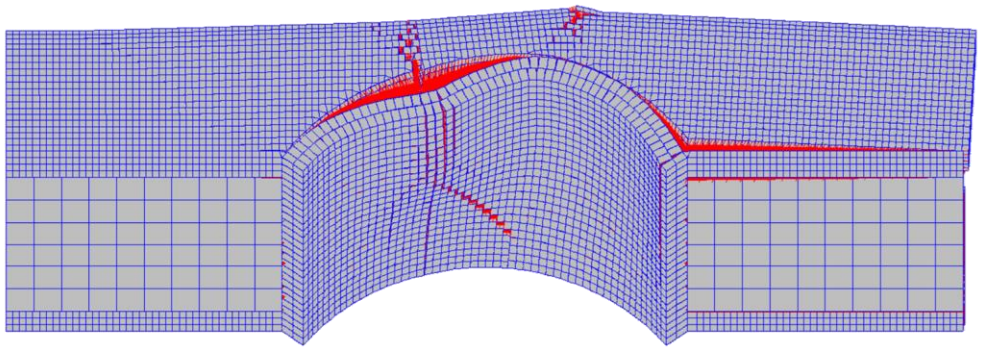
Numerical results

Influence of spandrel walls

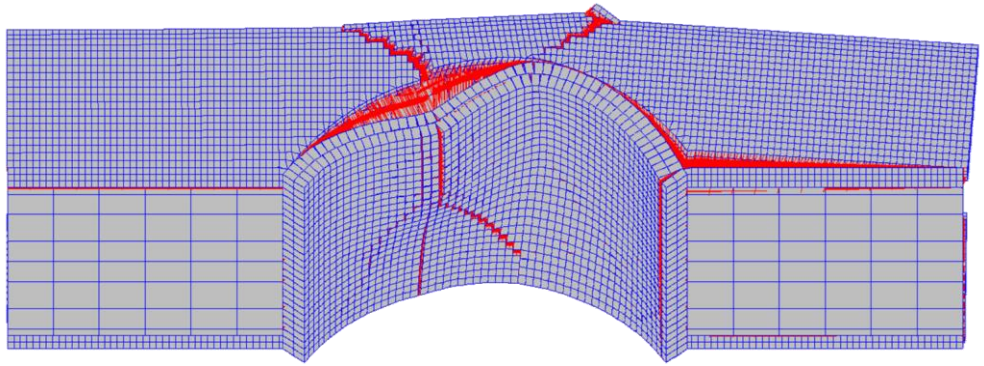
SW thickness

Patch 750mm×750mm at ¼ Span ¼ Width

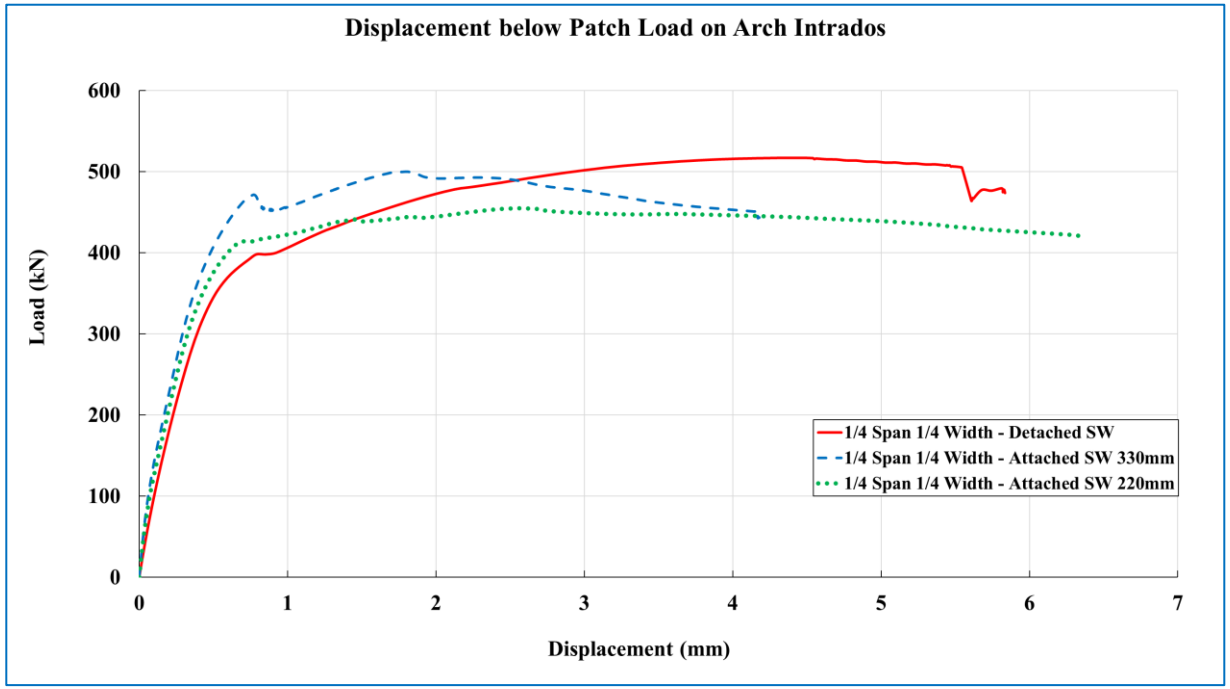




SW 330mm – West Elevation



SW 220mm – West Elevation

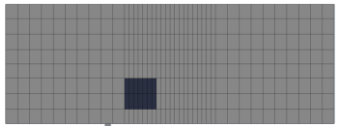


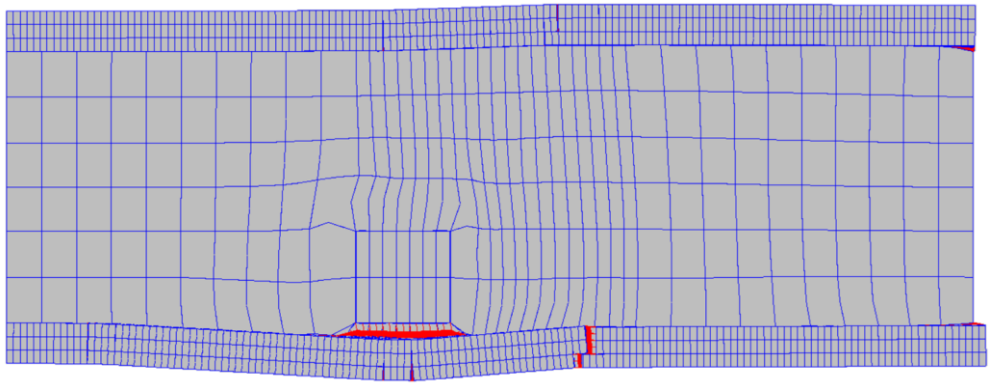
Numerical results

Influence of spandrel walls

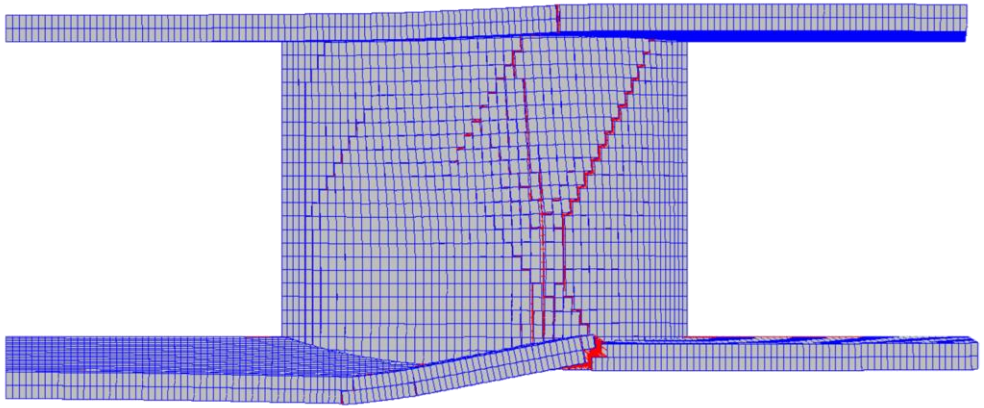
SW thickness

Patch 750mm×750mm at ¼ Span ¼ Width

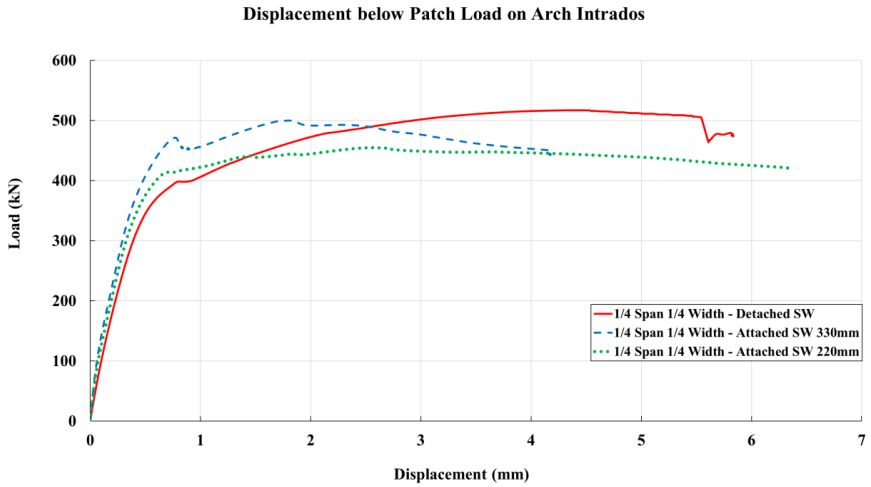


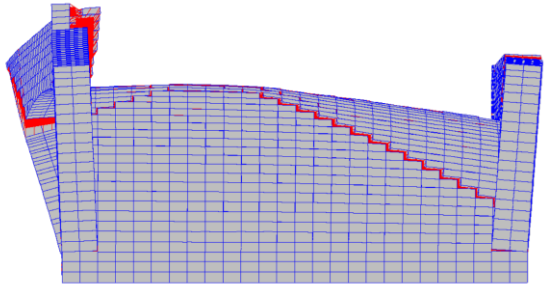


SW 330mm – Top View

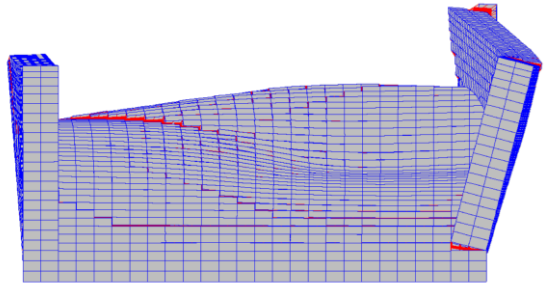


SW 220mm – Top View





SW 220mm – Right Side View



SW 220mm – Left Side View

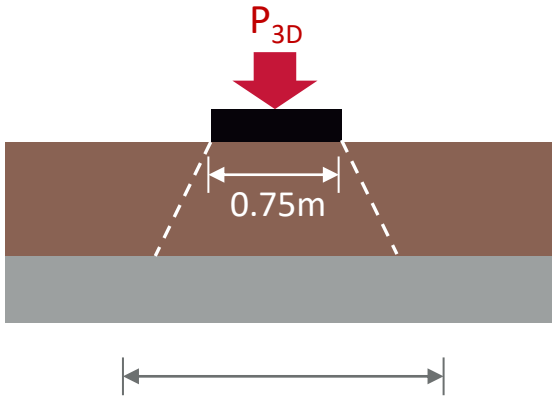
Effective width study

Numerical results

3D vs 2D models – effective width

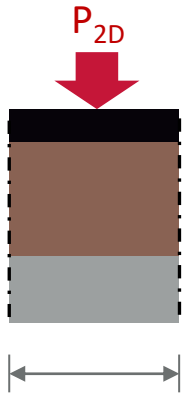
Engineering and Physical Sciences Research Council

3D model:



Effective width = ?

2D model:



Width = 1m

$$\textbf{Effective width (single wheel)} = \frac{P_{3D}}{P_{2D}} \times 1\text{m}$$

Numerical results

3D vs 2D models – effective width

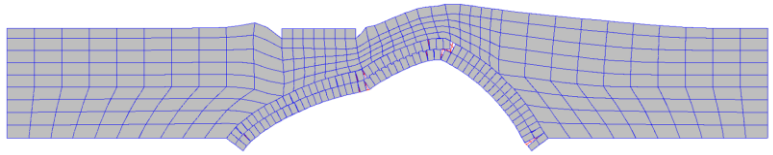
Engineering and Physical Sciences Research Council

Effective width depends on

- Load position
- Backfill characteristics
- 3D arch behaviour

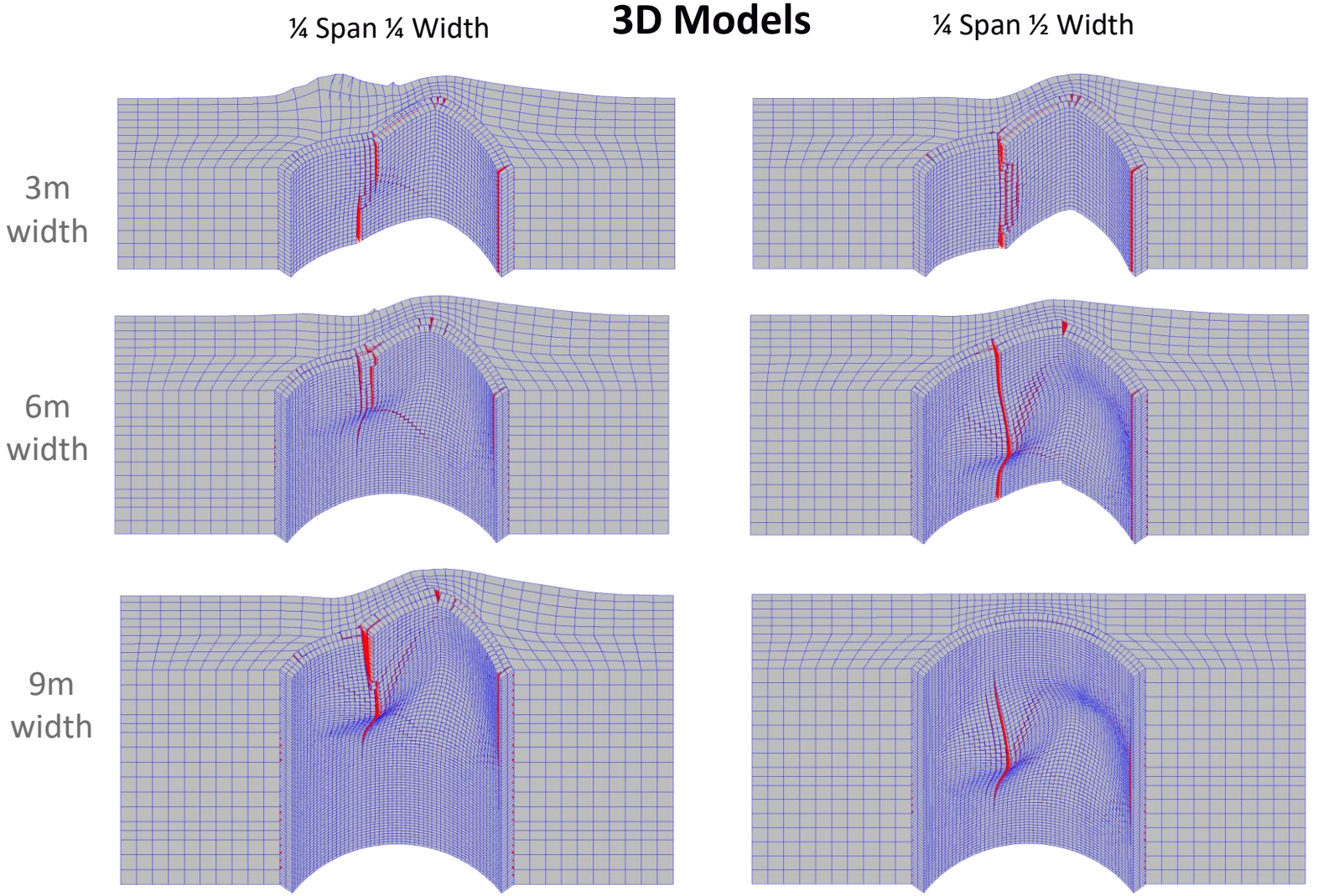
2D Model

¼ Span



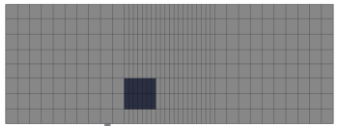
3m span, stretcher bond

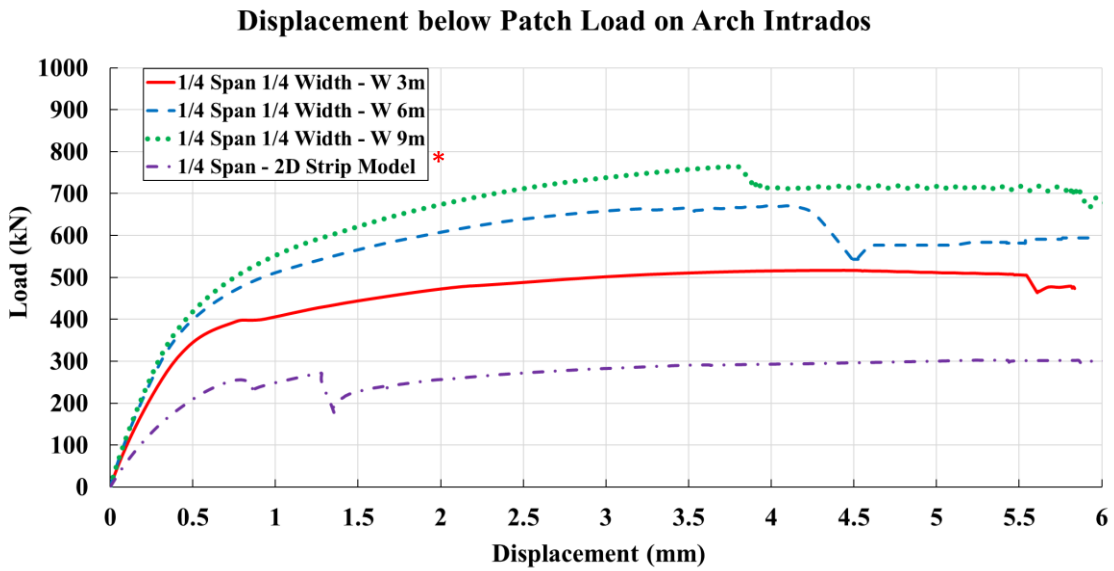
3D Models

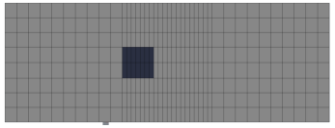


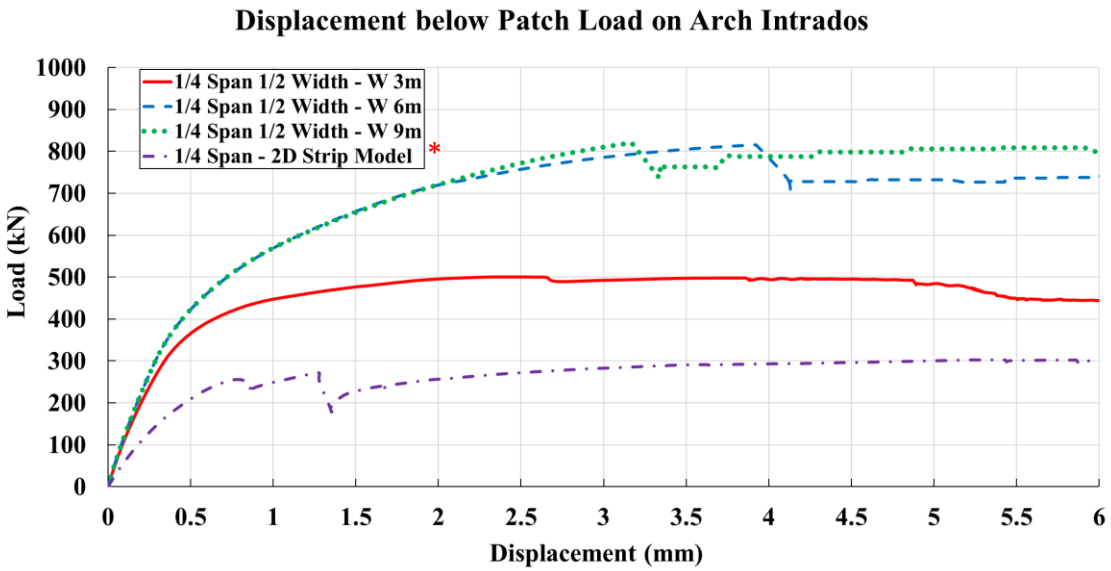
Numerical results

3D vs 2D models – effective width







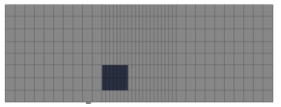


*Load predicted by 2D model assuming 1m width

- Higher load capacity for 6m and 9m widths (3D response of masonry arch)

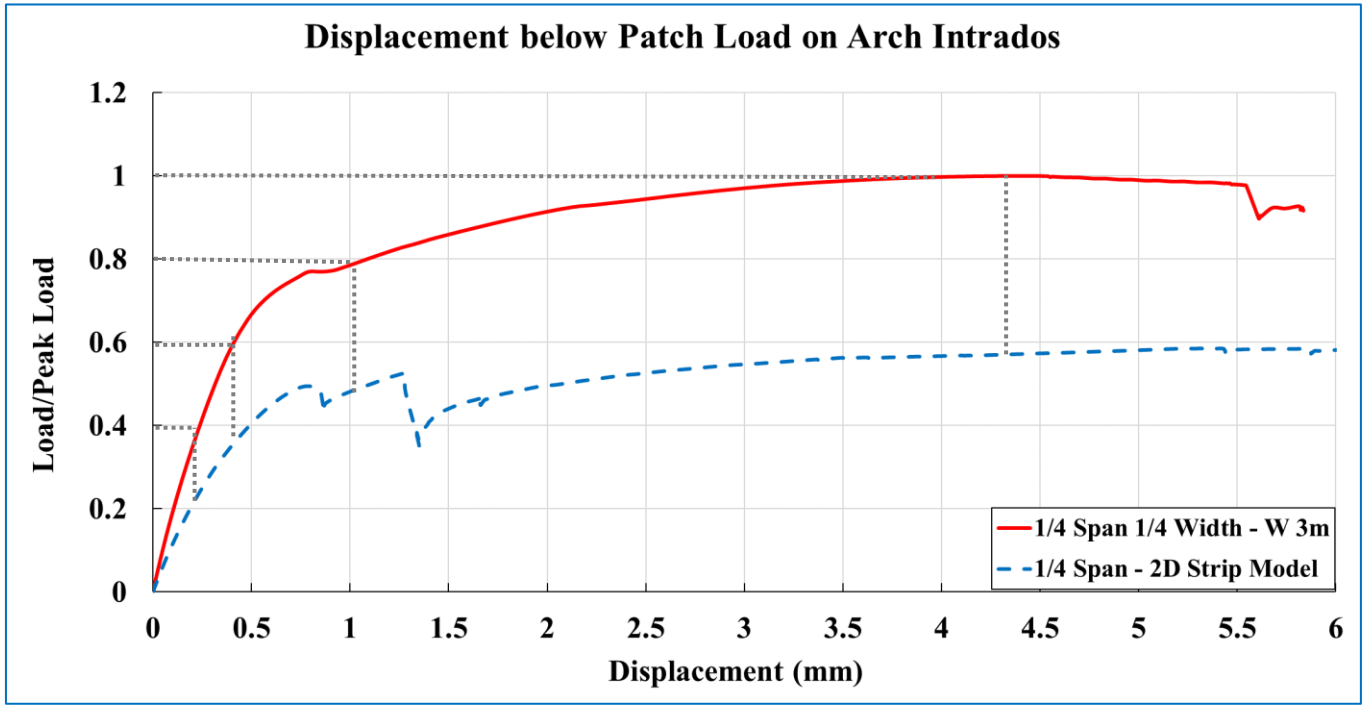
Numerical results

3D vs 2D models – effective width



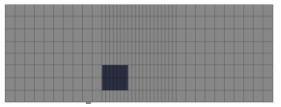
Patch 750mm×750mm at ¼ Span ¼ Width – 3m Width

Patch 750x750	Norm. Load 3D Model	Corresp.Displ. (mm)	Norm. Load 2D Model	Effective Width (m)
1/4 Span - 1/4 Width - Stretcher - **W 3m**	0.2	0.097	0.10	**1.92**
	0.4	0.230	0.23	**1.73**
	0.6	0.405	0.34	**1.74**
	0.8	1.085	0.48	**1.66**
	1	4.429	0.58	**1.71**
1/4 Span - 1/4 Width - Stretcher - W 6m	0.2	0.106	0.09	**2.29**
	0.4	0.265	0.20	**2.04**
	0.6	0.491	0.30	**2.01**
	0.8	1.195	0.38	**2.08**
	1	3.984	0.44	**2.25**
1/4 Span - 1/4 Width - Stretcher - W 9m	0.2	0.126	0.09	**2.11**
	0.4	0.277	0.18	**2.21**
	0.6	0.603	0.30	**2.03**
	0.8	1.406	0.36	**2.22**
	1	3.783	0.39	**2.59**



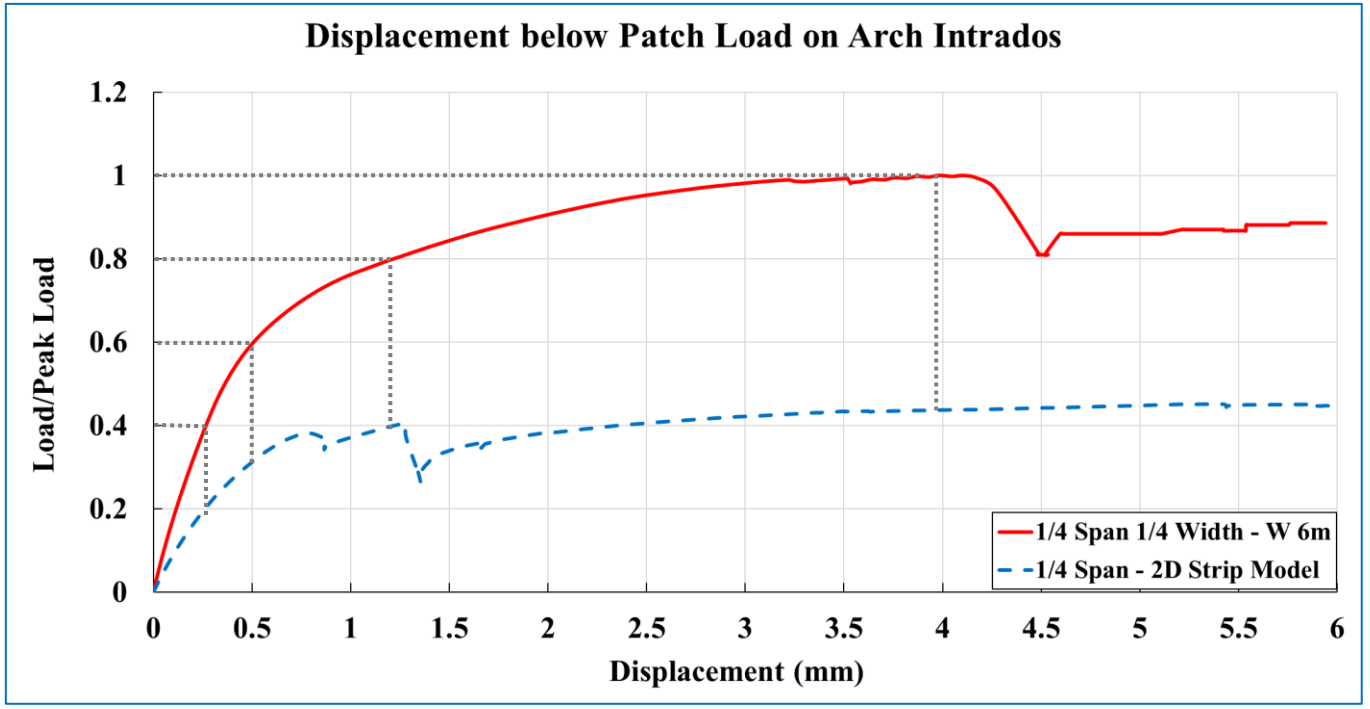
Numerical results

3D vs 2D models – effective width



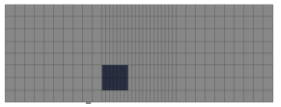
Patch 750mm×750mm at ¼ Span ¼ Width – 6m Width

Patch 750x750	Norm. Load 3D Model	Corresp.Displ. (mm)	Norm. Load 2D Model	Effective Width (m)
1/4 Span - 1/4 Width - Stretcher - W 3m	0.2	0.097	0.10	**1.92**
	0.4	0.230	0.23	**1.73**
	0.6	0.405	0.34	**1.74**
	0.8	1.085	0.48	**1.66**
	1	4.429	0.58	**1.71**
1/4 Span - 1/4 Width - Stretcher - **W 6m**	0.2	0.106	0.09	**2.29**
	0.4	0.265	0.20	**2.04**
	0.6	0.491	0.30	**2.01**
	0.8	1.195	0.38	**2.08**
	1	3.984	0.44	**2.25**
1/4 Span - 1/4 Width - Stretcher - W 9m	0.2	0.126	0.09	**2.11**
	0.4	0.277	0.18	**2.21**
	0.6	0.603	0.30	**2.03**
	0.8	1.406	0.36	**2.22**
	1	3.783	0.39	**2.59**



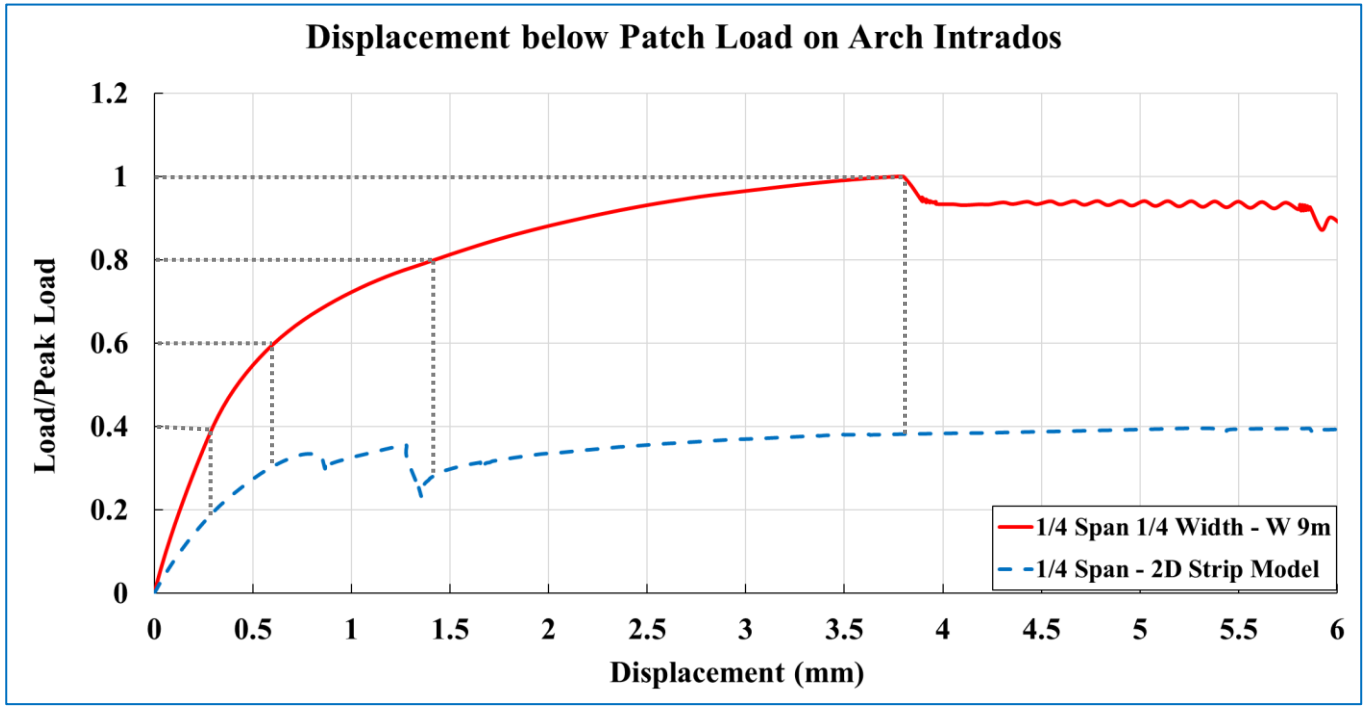
Numerical results

3D vs 2D models – effective width



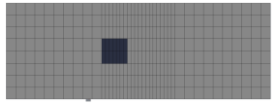
Patch 750mm×750mm at ¼ Span ¼ Width – 9m Width

Patch 750x750	Norm. Load 3D Model	Corresp.Displ. (mm)	Norm. Load 2D Model	Effective Width (m)
1/4 Span - 1/4 Width - Stretcher - W 3m	0.2	0.097	0.10	**1.92**
	0.4	0.230	0.23	**1.73**
	0.6	0.405	0.34	**1.74**
	0.8	1.085	0.48	**1.66**
	1	4.429	0.58	**1.71**
1/4 Span - 1/4 Width - Stretcher - W 6m	0.2	0.106	0.09	**2.29**
	0.4	0.265	0.20	**2.04**
	0.6	0.491	0.30	**2.01**
	0.8	1.195	0.38	**2.08**
	1	3.984	0.44	**2.25**
1/4 Span - 1/4 Width - Stretcher - **W 9m**	0.2	0.126	0.09	**2.11**
	0.4	0.277	0.18	**2.21**
	0.6	0.603	0.30	**2.03**
	0.8	1.406	0.36	**2.22**
	1	3.783	0.39	**2.59**



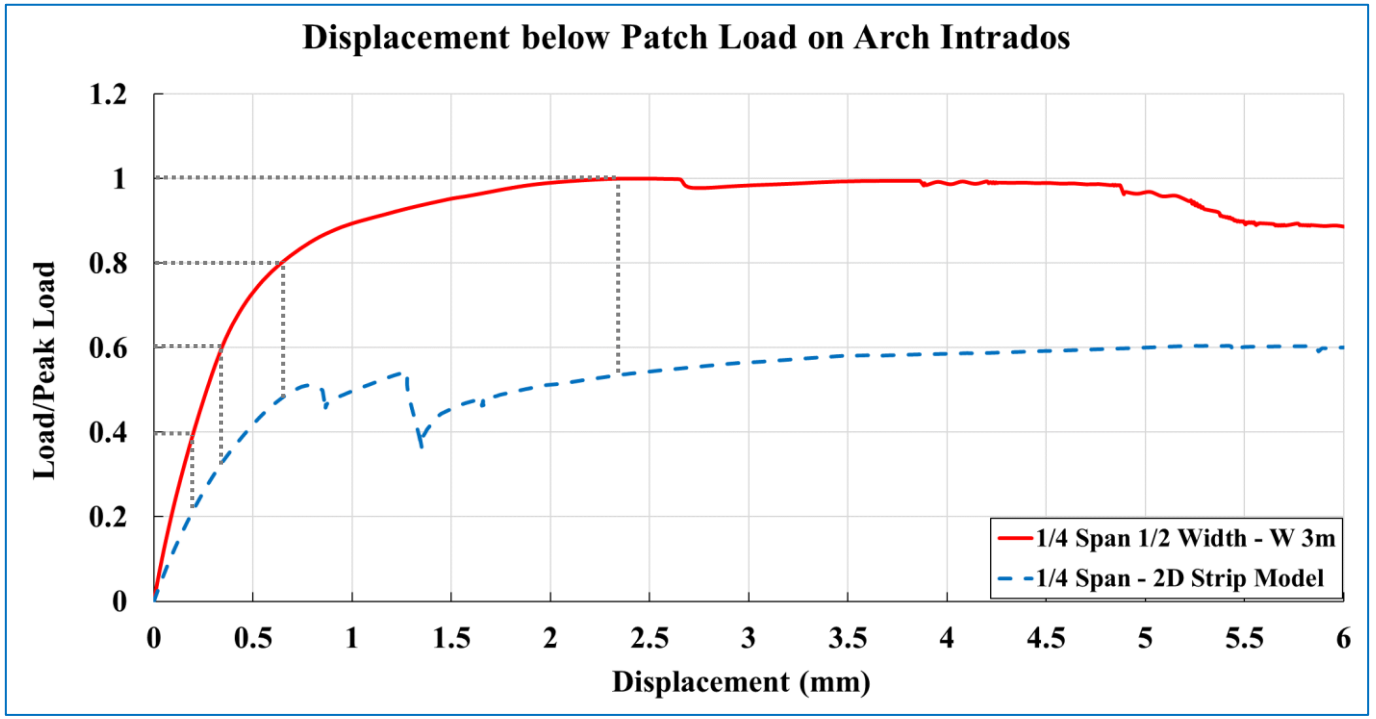
Numerical results

3D vs 2D models – effective width



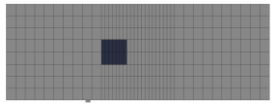
Patch 750mm×750mm at ¼ Span ½ Width – 3m Width

Patch 750x750	Norm. Load 3D Model	Corresp.Displ. (mm)	Norm. Load 2D Model	Effective Width (m)
1/4 Span - 1/2 Width - Stretcher - **W 3m**	0.2	0.087	0.10	**2.03**
	0.4	0.182	0.20	**2.03**
	0.6	0.341	0.32	**1.90**
	0.8	0.640	0.47	**1.71**
	1	2.407	0.53	**1.88**
1/4 Span - 1/2 Width - Stretcher - W 6m	0.2	0.124	0.08	**2.40**
	0.4	0.319	0.18	**2.16**
	0.6	0.663	0.29	**2.07**
	0.8	1.452	0.34	**2.34**
	1	3.924	0.36	**2.74**
1/4 Span - 1/2 Width - Stretcher - W 9m	0.2	0.125	0.09	**2.26**
	0.4	0.322	0.18	**2.18**
	0.6	0.671	0.29	**2.06**
	0.8	1.483	0.34	**2.34**
	1	3.169	0.35	**2.89**



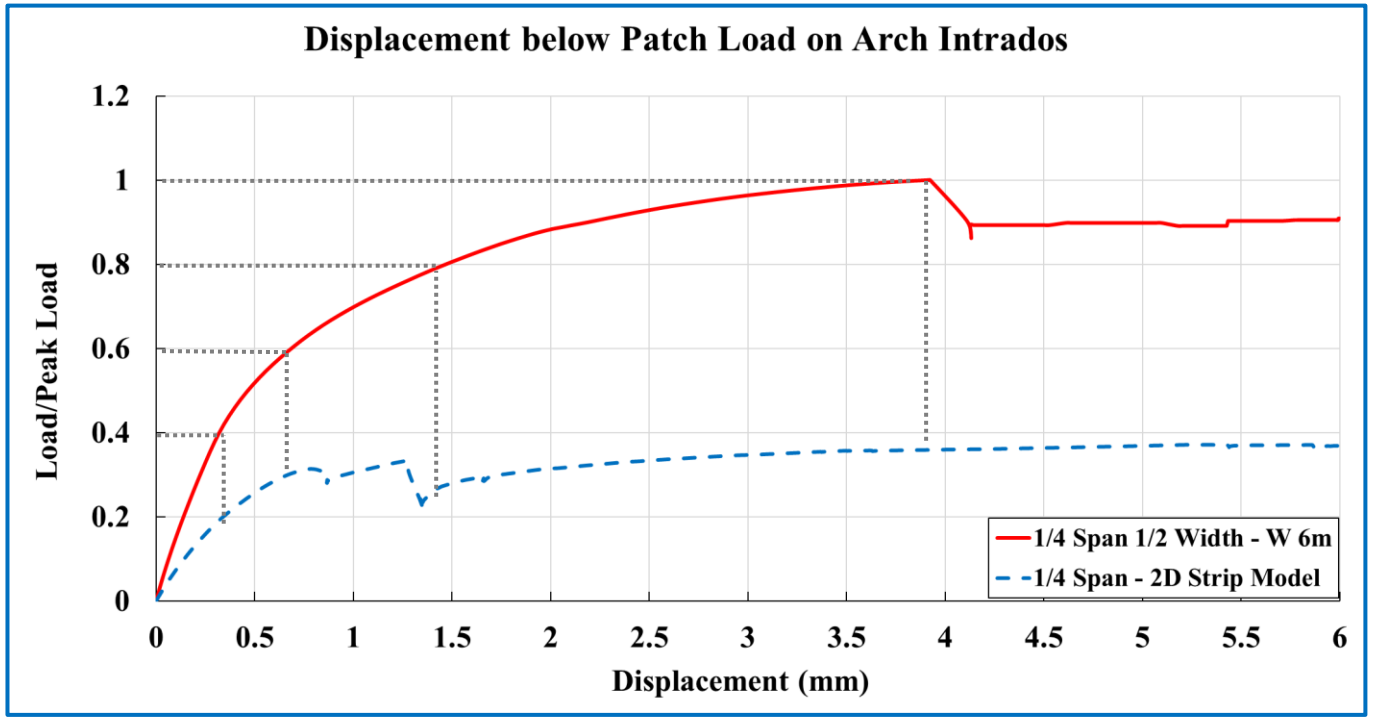
Numerical results

3D vs 2D models – effective width



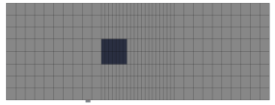
Patch 750mm×750mm at ¼ Span ½ Width – 6m Width

Patch 750x750	Norm. Load 3D Model	Corresp.Displ. (mm)	Norm. Load 2D Model	Effective Width (m)
1/4 Span - 1/2 Width - Stretcher - W 3m	0.2	0.087	0.10	**2.03**
	0.4	0.182	0.20	**2.03**
	0.6	0.341	0.32	**1.90**
	0.8	0.640	0.47	**1.71**
	1	2.407	0.53	**1.88**
1/4 Span - 1/2 Width - Stretcher - **W 6m**	0.2	0.124	0.08	**2.40**
	0.4	0.319	0.18	**2.16**
	0.6	0.663	0.29	**2.07**
	0.8	1.452	0.34	**2.34**
	1	3.924	0.36	**2.74**
1/4 Span - 1/2 Width - Stretcher - W 9m	0.2	0.125	0.09	**2.26**
	0.4	0.322	0.18	**2.18**
	0.6	0.671	0.29	**2.06**
	0.8	1.483	0.34	**2.34**
	1	3.169	0.35	**2.89**



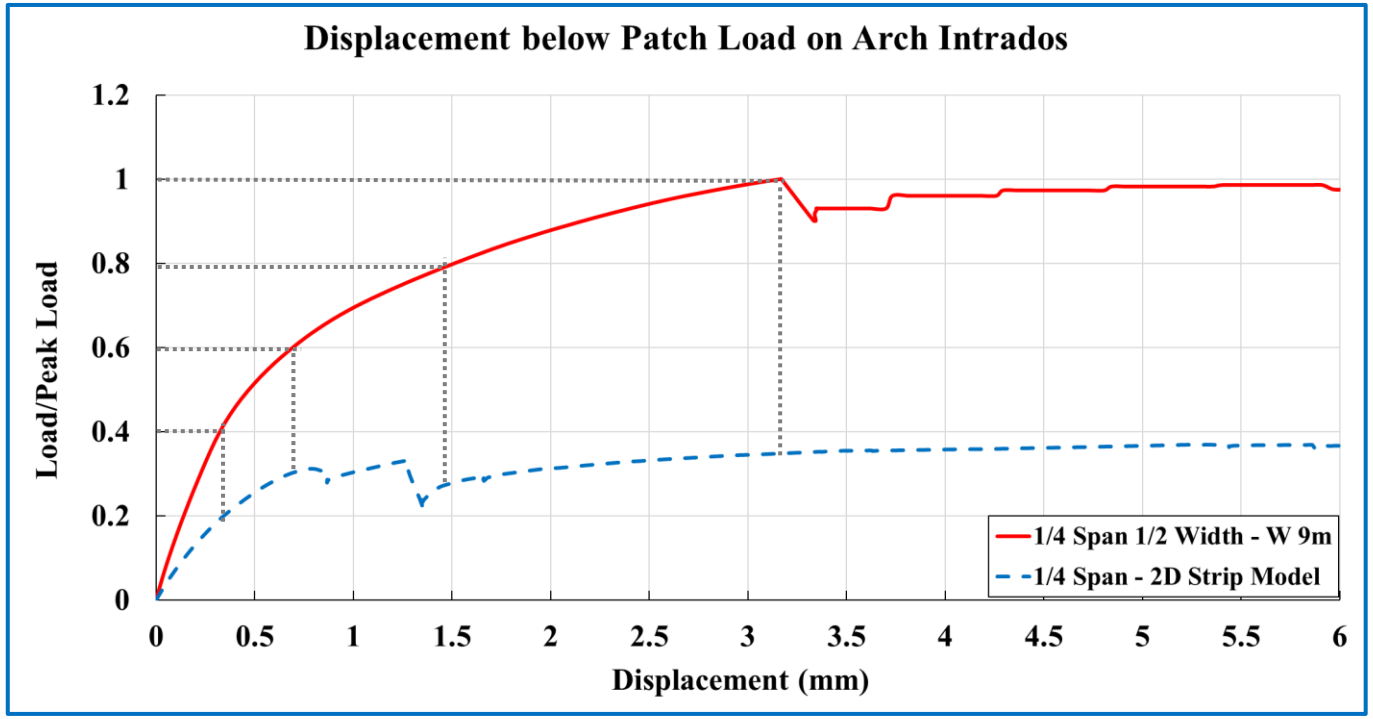
Numerical results

3D vs 2D models – effective width



Patch 750mm×750mm at ¼ Span ½ Width – 9m Width

Patch 750x750	Norm. Load 3D Model	Corresp.Displ. (mm)	Norm. Load 2D Model	Effective Width (m)
1/4 Span - 1/2 Width - Stretcher - W 3m	0.2	0.087	0.10	**2.03**
	0.4	0.182	0.20	**2.03**
	0.6	0.341	0.32	**1.90**
	0.8	0.640	0.47	**1.71**
	1	2.407	0.53	**1.88**
1/4 Span - 1/2 Width - Stretcher - W 6m	0.2	0.124	0.08	**2.40**
	0.4	0.319	0.18	**2.16**
	0.6	0.663	0.29	**2.07**
	0.8	1.452	0.34	**2.34**
	1	3.924	0.36	**2.74**
1/4 Span - 1/2 Width - Stretcher - **W 9m**	0.2	0.125	0.09	**2.26**
	0.4	0.322	0.18	**2.18**
	0.6	0.671	0.29	**2.06**
	0.8	1.483	0.34	**2.34**
	1	3.169	0.35	**2.89**



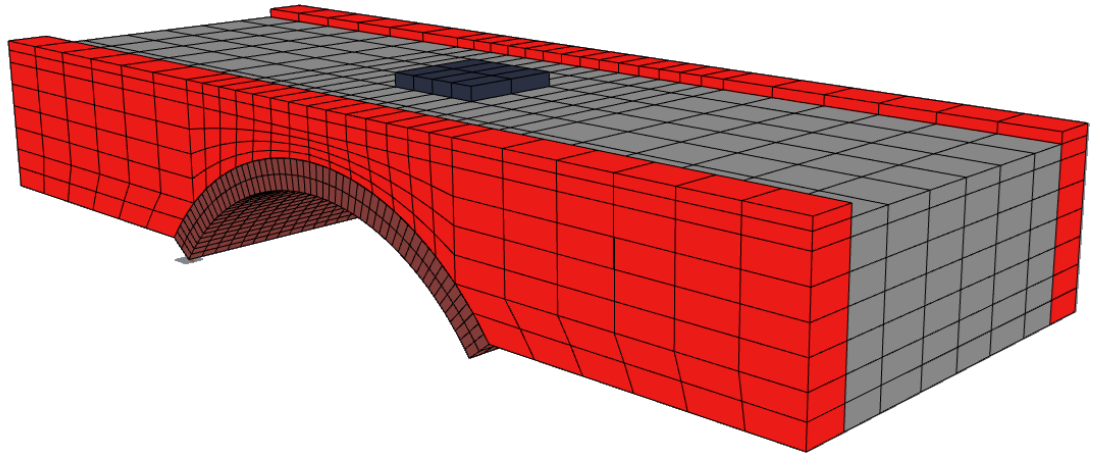
Model complexity study

Numerical results

3D Meso vs Macroscale Models

Engineering and Physical Sciences Research Council

3D macroscale model



Material macroscale parameters for masonry*

Brick units		
E (Young's modulus)	N/mm^2	69000
ν (Poison's ratio)		0.15
Mortar Interfaces		
E (Young's modulus)	N/mm2	15900
n (Poison ratio)		0.15
Ψm (Dilatancy angle)	Deg	30
Ft0 (Initial uniaxial tensile strength)	N/mm2	0.21
Fc (Maximum uniaxial compressive strength)	N/mm2	23.8
Gft (Fracture energy in uniaxial tension)	Nmm/mm2	0.01

*from material tests (Melbourne & Gilbert 1995) used for model validation

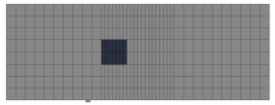
Material parameters for backfill*

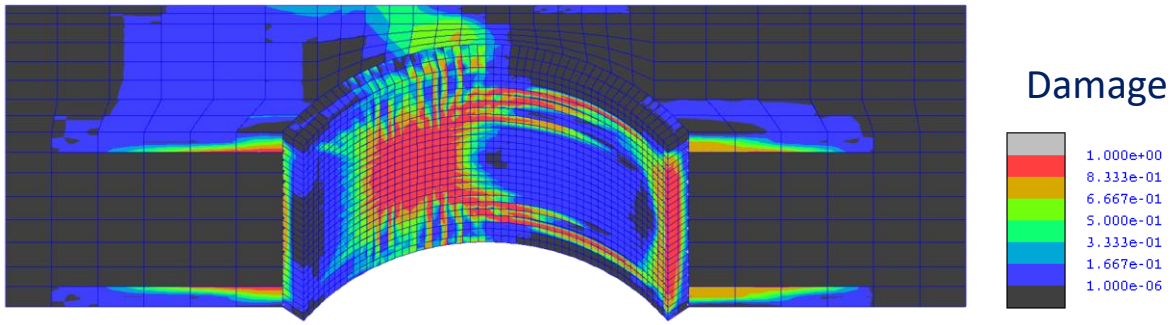
Backfill		
Ef (Young's modulus)	N/mm^2	200
ν (Poison's ratio)		0.2
c (cohesion)	N/mm^2	0.001
φf (friction angle)	rad	1.047
Ψf (dilatancy angle)	rad	0.5236

Numerical results

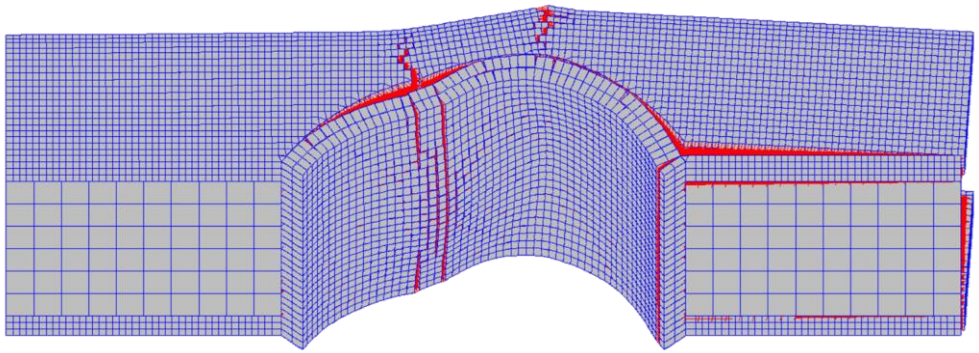
3D Meso vs Macroscale Models

Patch 750mm×750mm at ¼ Span ½ Width

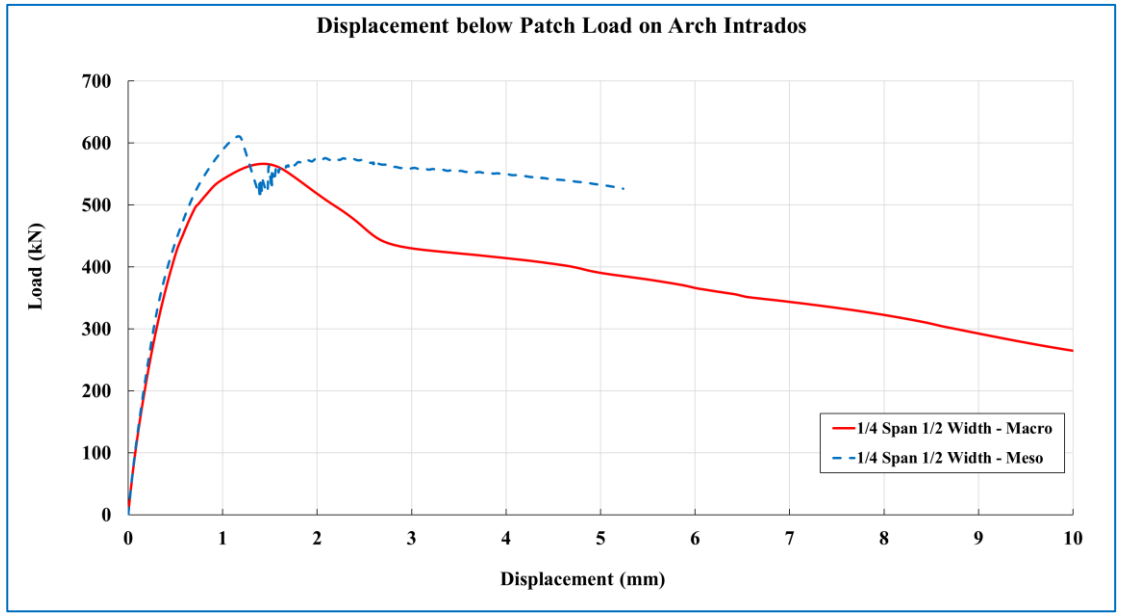




3D macroscale model



3D mesoscale model (stretcher)

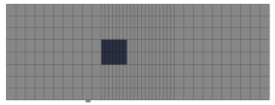


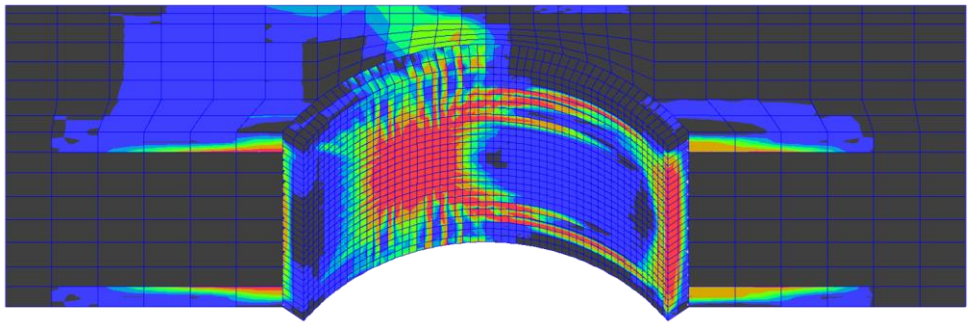
Numerical results

3D Meso vs Macroscale Models

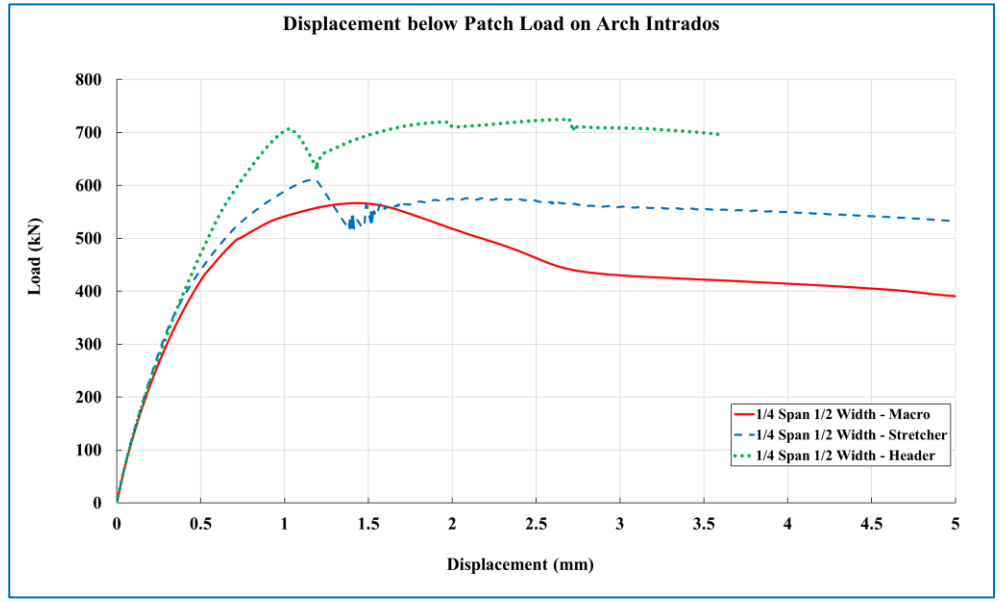
Engineering and Physical Sciences Research Council

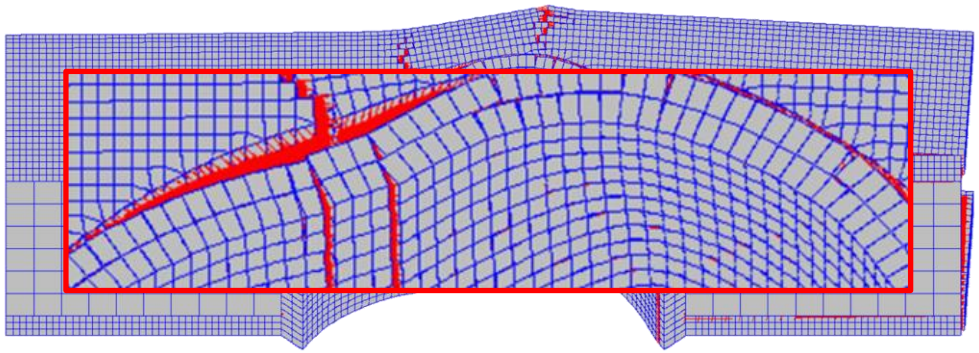
Patch 750mm×750mm at ¼ Span ½ Width



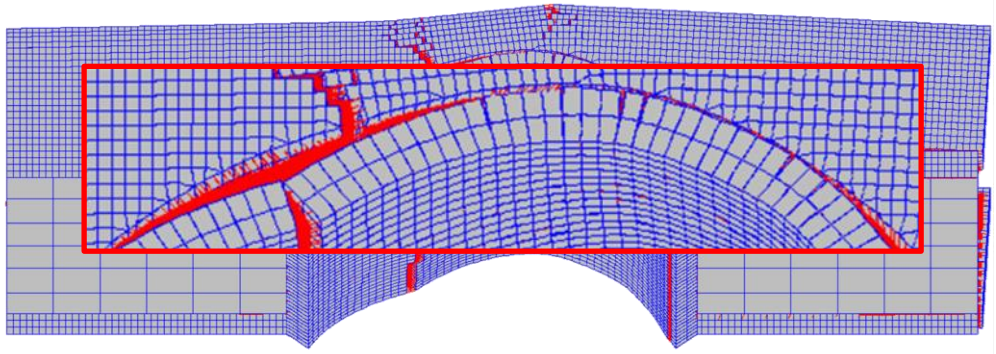


3D macroscale model





3D mesoscale model (stretcher)

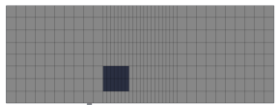


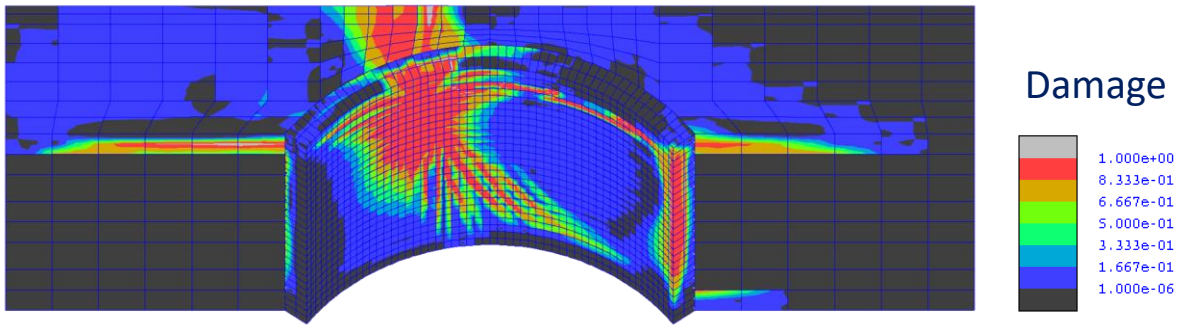
3D mesoscale model (header)

Numerical results

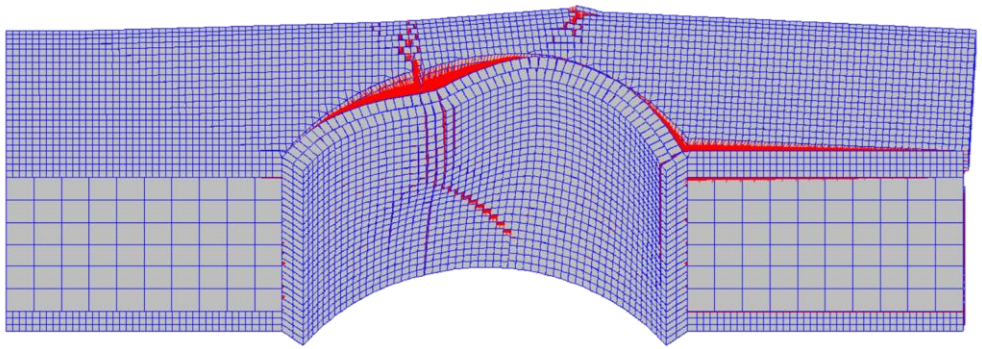
3D Meso vs Macroscale Models

Patch 750mm×750mm at ¼ Span ¼ Width

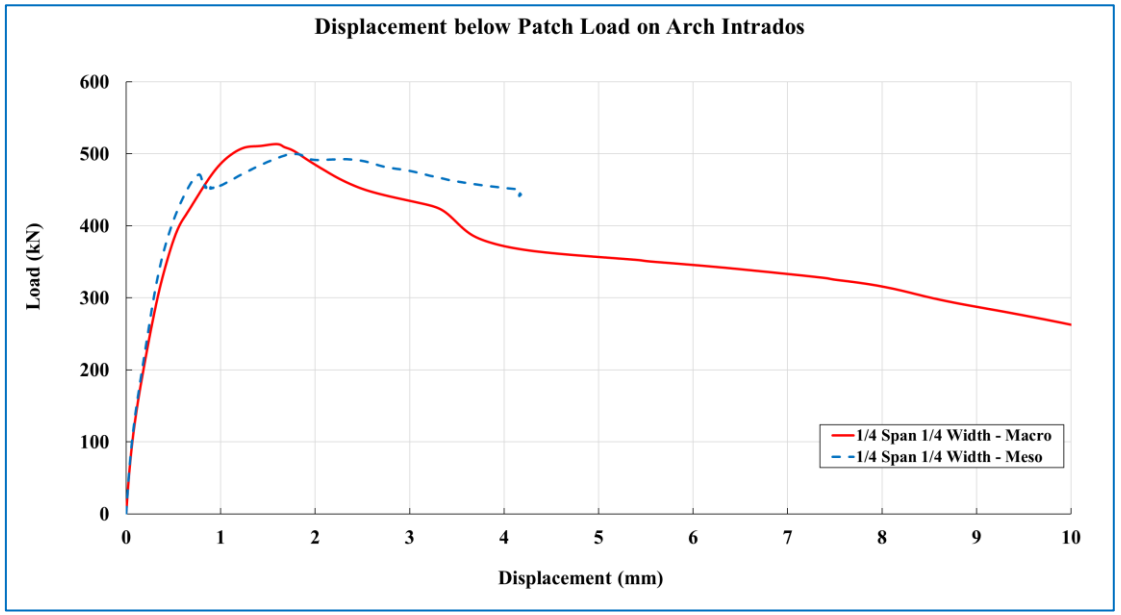




3D macroscale model



3D mesoscale model (stretcher)

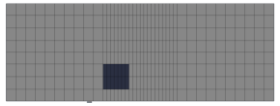


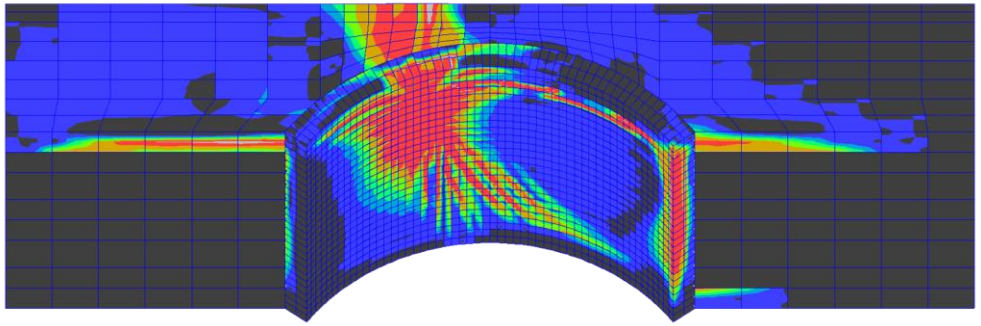
Numerical results

3D Meso vs Macroscale Models

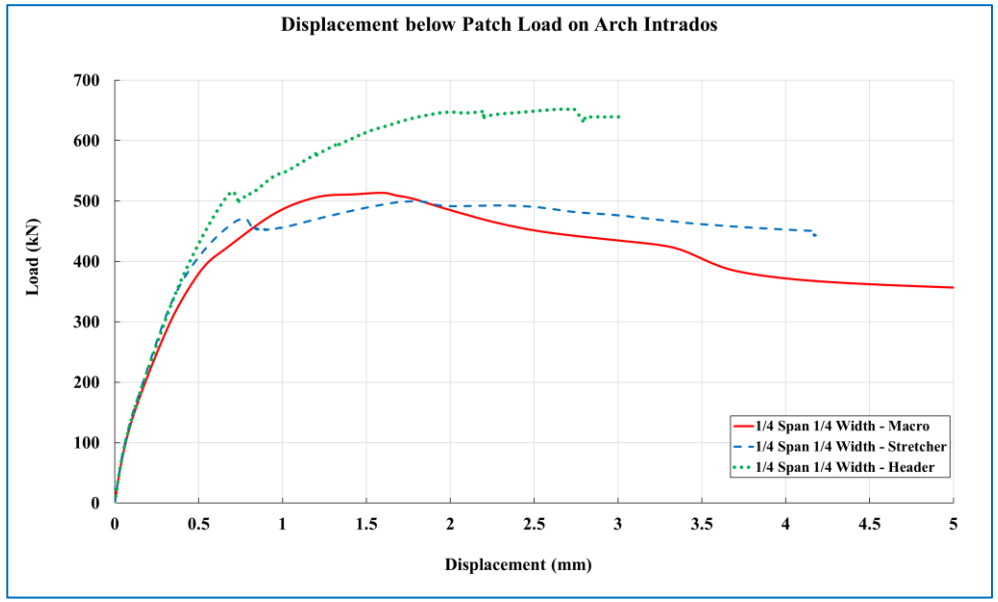
Engineering and Physical Sciences Research Council

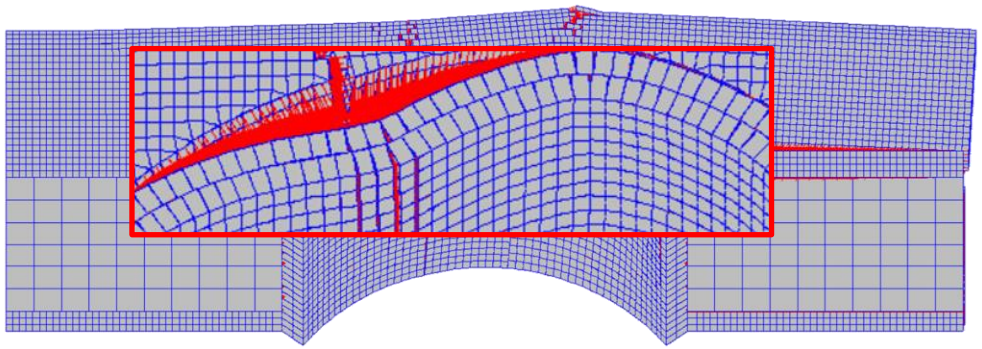
Patch 750mm×750mm at ¼ Span ¼ Width



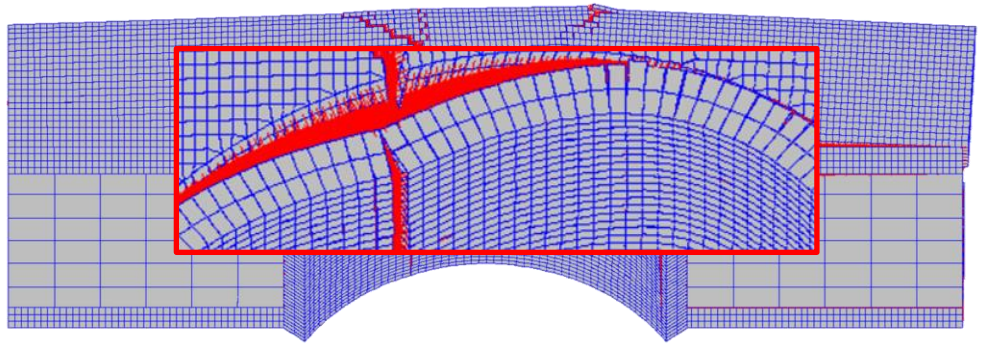


3D macroscale model





3D mesoscale model (stretcher)



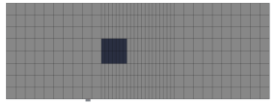
3D mesoscale model (header)

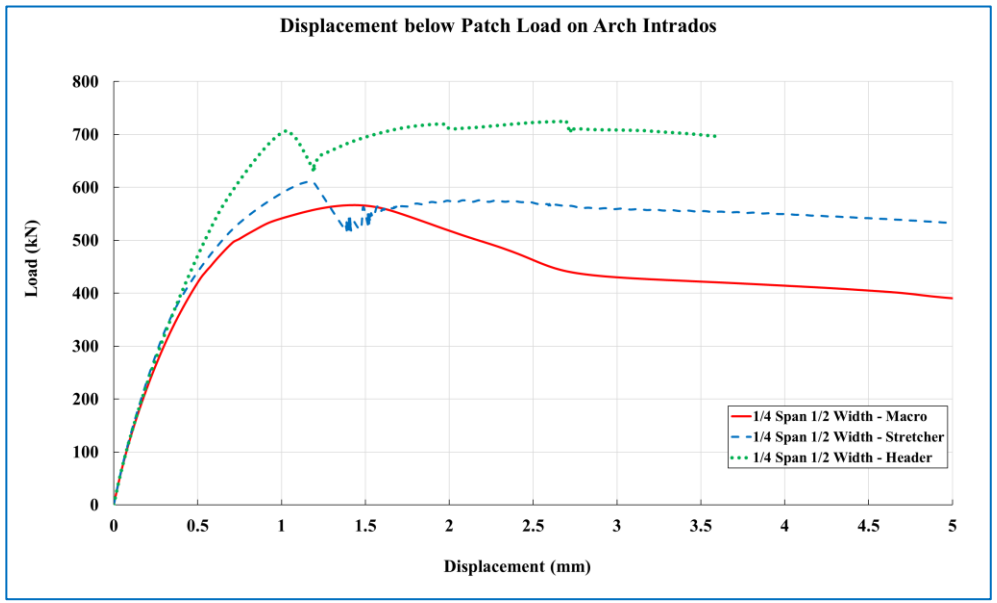
Numerical results

3D Meso vs Macroscale Models

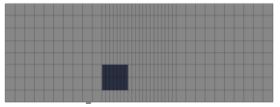
Engineering and Physical Sciences Research Council

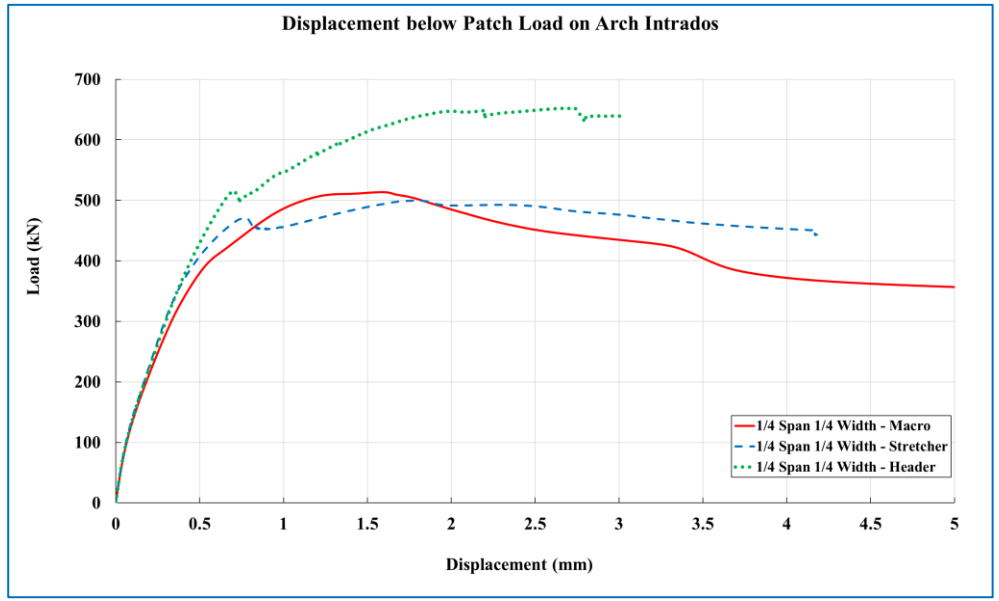
Patch 750mm×750mm at ¼ Span ½ Width





Patch 750mm×750mm at ¼ Span ¼ Width





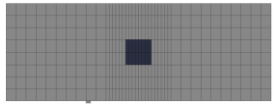
- Standard macroscale masonry models cannot represent failure modes associated with a specific masonry bond

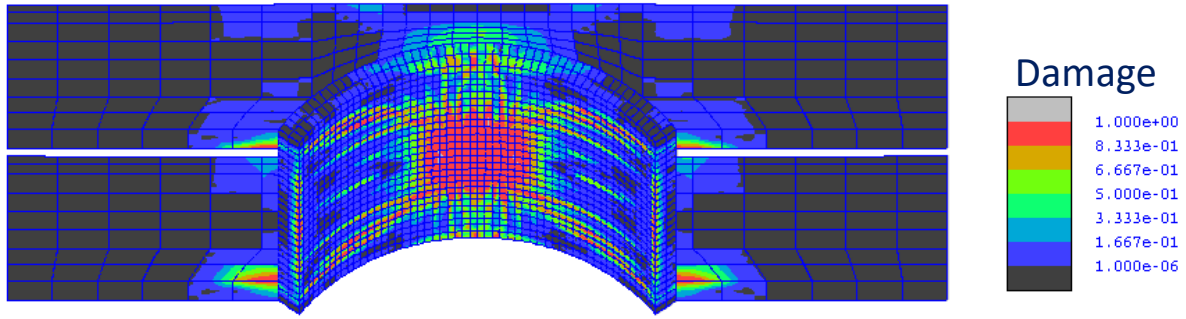
Numerical results

3D Meso vs Macroscale Models

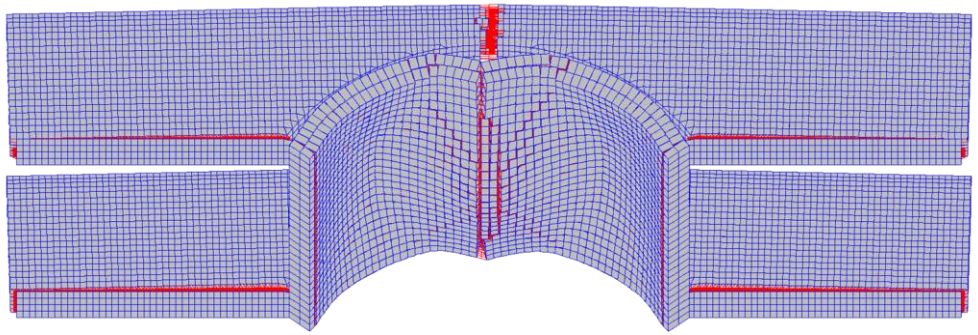
Engineering and Physical Sciences Research Council

Patch 750mm×750mm at ½ Span ½ Width

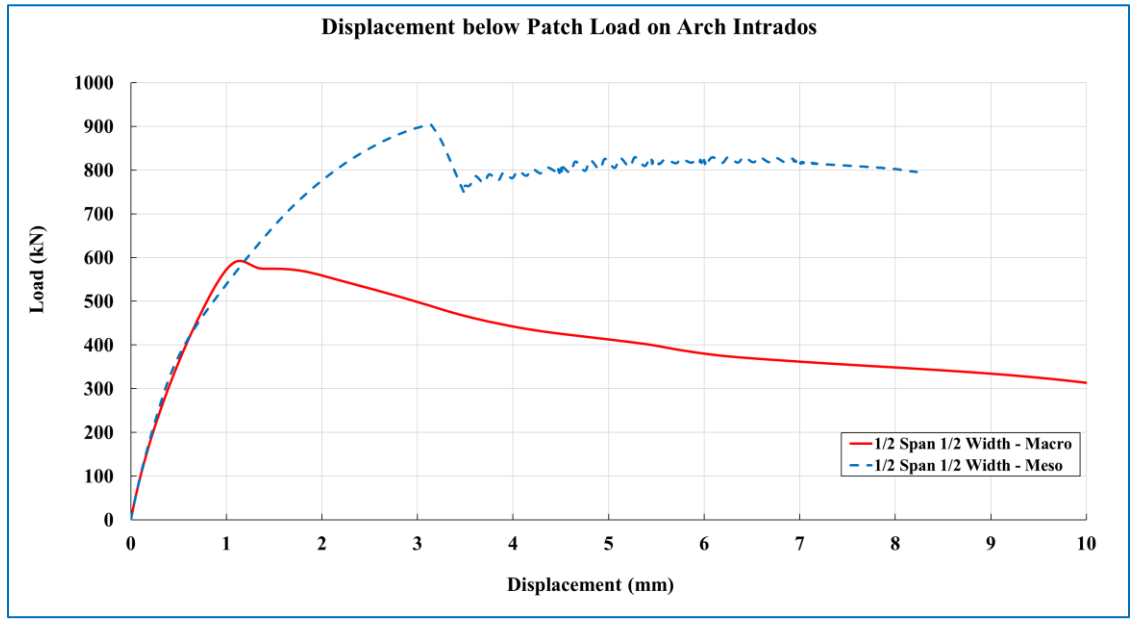




3D macroscale model



3D mesoscale model (stretcher)



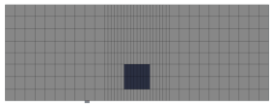
- Macroscale model predicts unrealistic punching shear failure in the arch under the load!

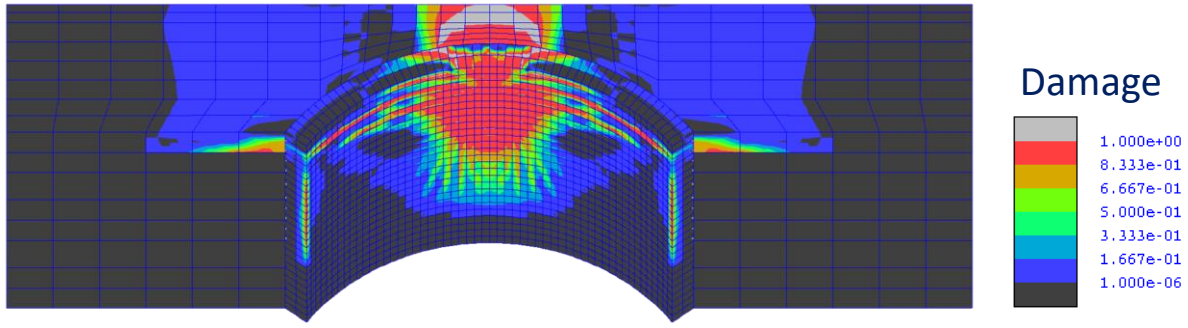
Numerical results

3D Meso vs Macroscale Models

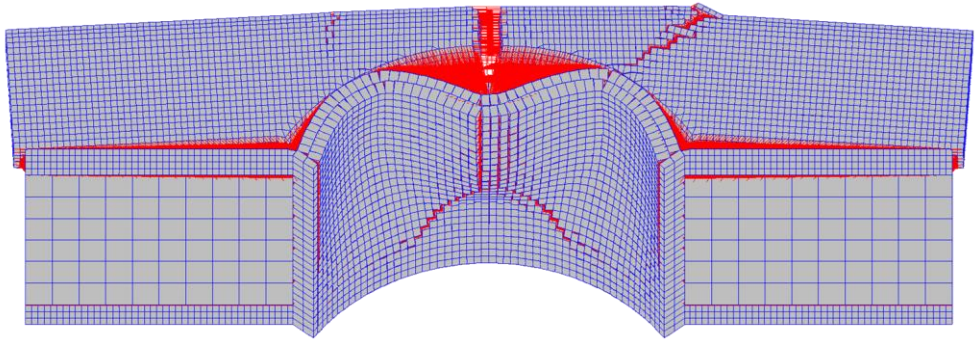
Engineering and Physical Sciences Research Council

Patch 750mm×750mm at ½ Span ¼ Width

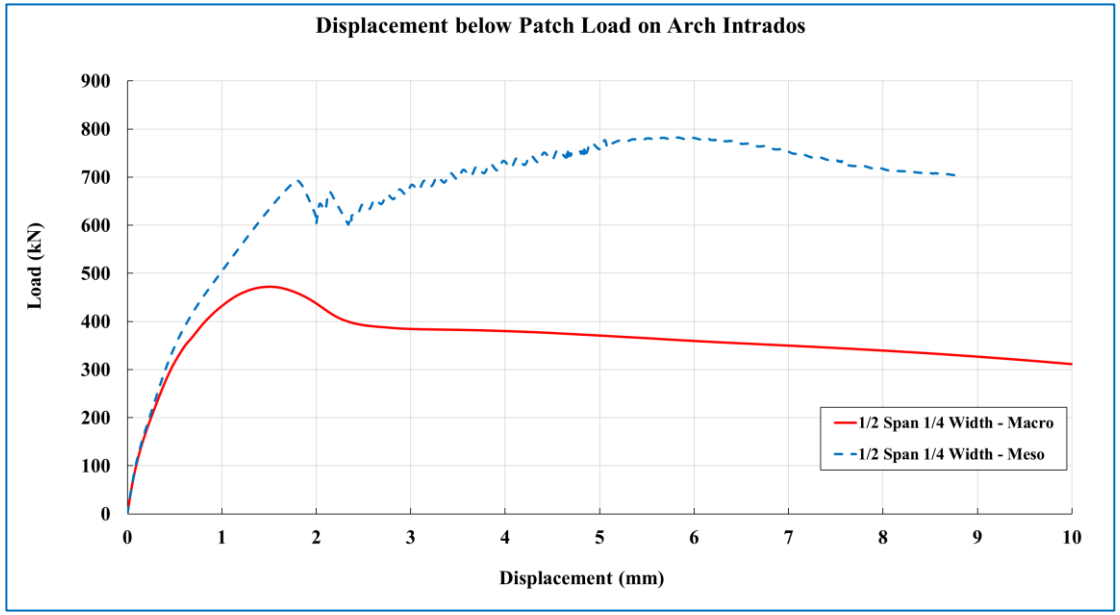




3D macroscale model



3D mesoscale model (stretcher)



- Macroscale model predicts unrealistic punching shear failure in the arch under the load!

Conclusions

Conclusions

- High-fidelity models provide baseline response data for the development of a consistent multi-level assessment framework and for the calibration of more efficient models.

- Safe assessment should consider the interaction between the different components, including spandrel walls. Weak spandrel walls may suffer early damage, hampering backfill confinement, and leading to reduced load capacity.

- The effective width used in 2D assessment models depends on load position and magnitude, backfill characteristics and on 3D arch behaviour.

Conclusions

- The use of nonlinear 3D models with simplified representations of the masonry can lead to inconsistent results. It can be mitigated by using enhanced anisotropic macroscale models (e.g. Pantò et al. 2022a), or refined calibration strategies (e.g. Pantò et al. 2022b).

References

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