UNIVERSITY OF LEEDS

Laboratory testing of a full scale masonry arch bridge

Vasilis Sarhosis

School of Civil Engineering, University of Leeds

6th September 2023

UKRI Engineering and Physical Sciences Research Council

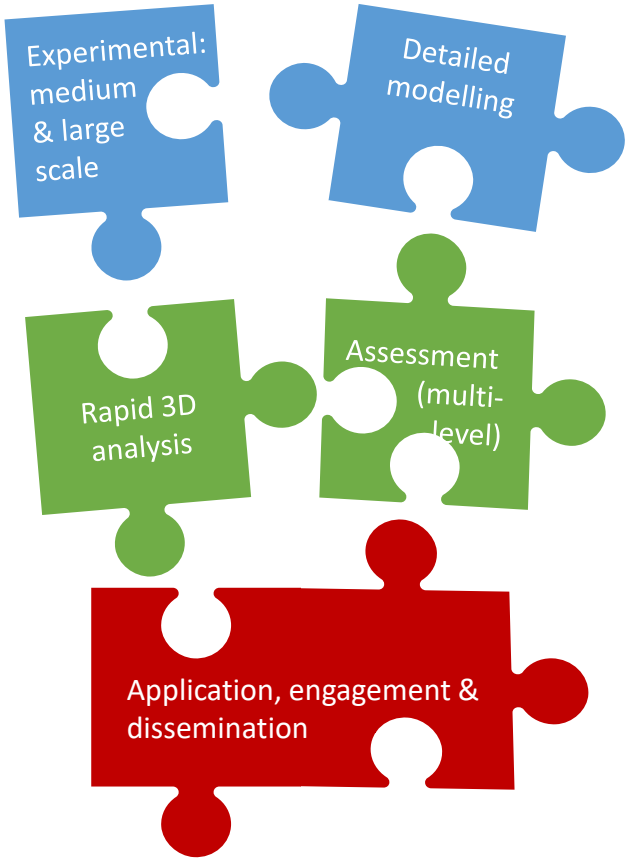
ERMABI project context

UNIVERSITY OF LEEDS

Understanding:

Practical tools:

Impact:



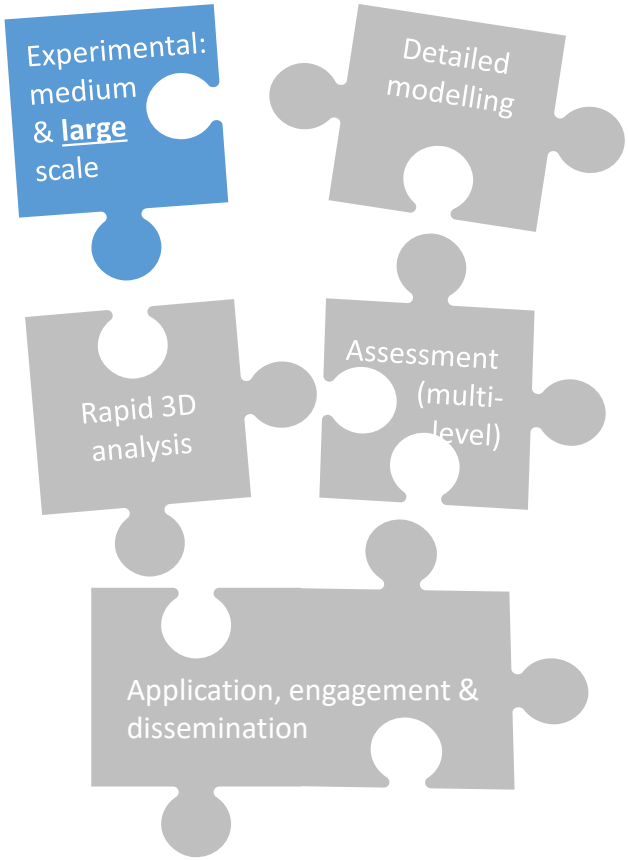
ERMABI project context

UNIVERSITY OF LEEDS

Understanding:

Practical tools:

Impact:



Large-Scale Testing

UNIVERSITY OF LEEDS

Principal aim: obtain an extensive experimental dataset via testing a large-scale bridge, with focus on:

(i) 3D response,
(ii) understand accumulation of damage and
(iii) support development of high-fidelity models

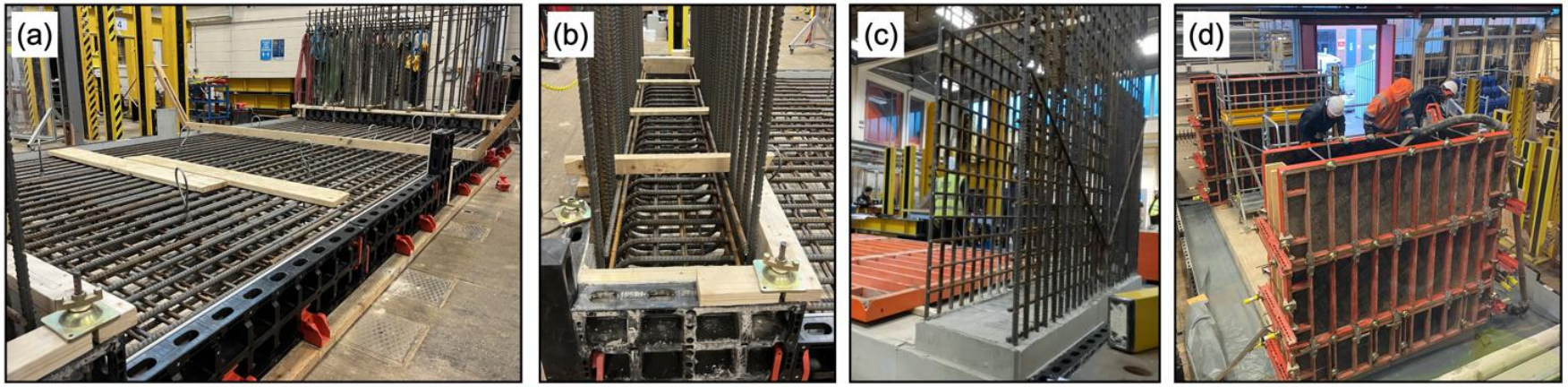
- Bridge span = 3m, with backfill and spandrels
- Bridge constructed on a stiff U-shaped RC test bed
- High strength, low water absorption bricks
- Backfill type: crushed limestone (granular)
- Loading: various point load positions / magnitudes

The George Earle Laboratory (Leeds)

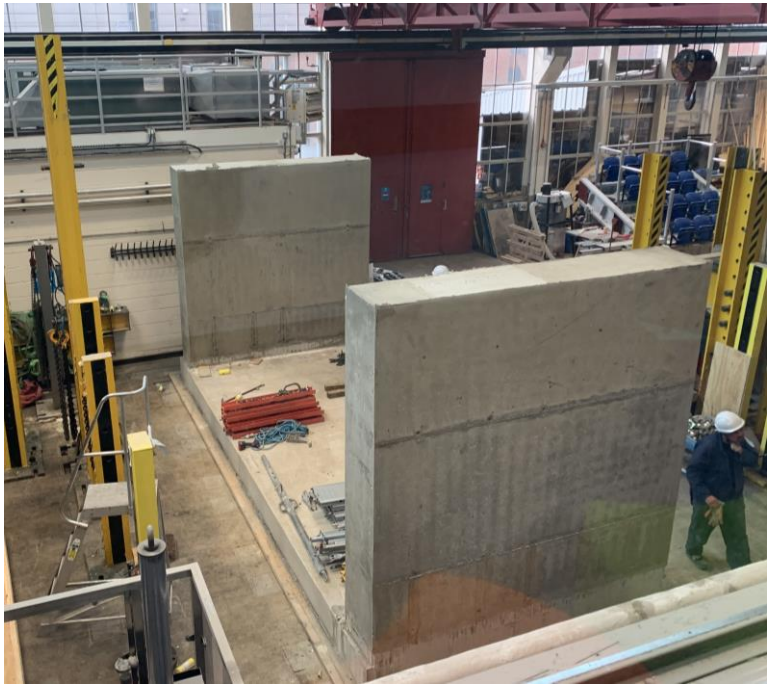
RC Strong floor with regular array of anchorage points (@ 1.55m centres) & cyclic load testing infrastructure

U-shaped RC test bed

UNIVERSITY OF LEEDS



Construction of RC base slab with end walls

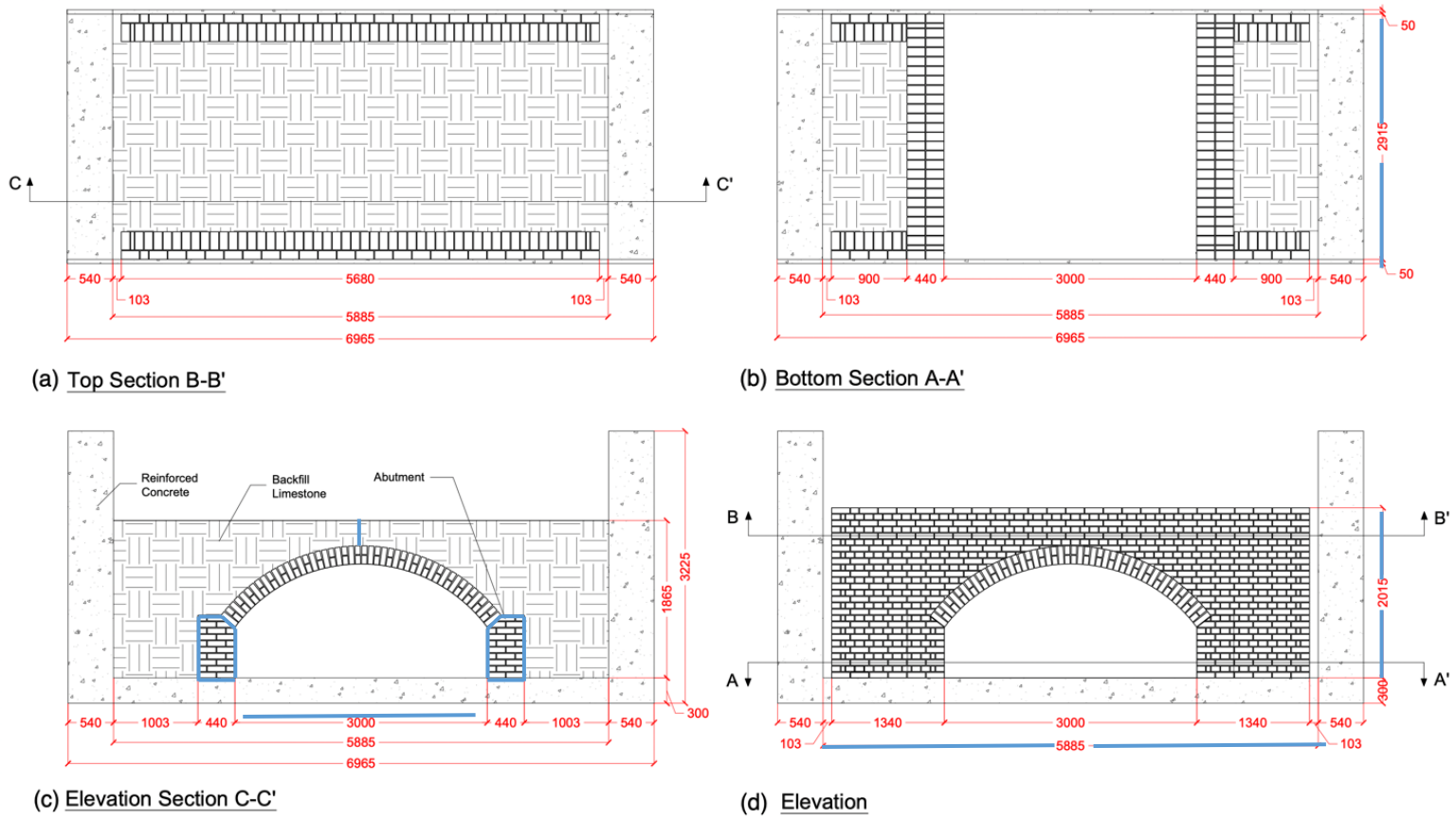


- **Dense reinforcement arrangement** adopted for the RC base slab and end walls to enhance stiffness.
- **Thickness of base slab** = 300 mm; **thickness of walls** = 540 mm.
- C30-grade concrete used for construction.

Design and construction of masonry arch bridge

UNIVERSITY OF LEEDS

Construction Drawings



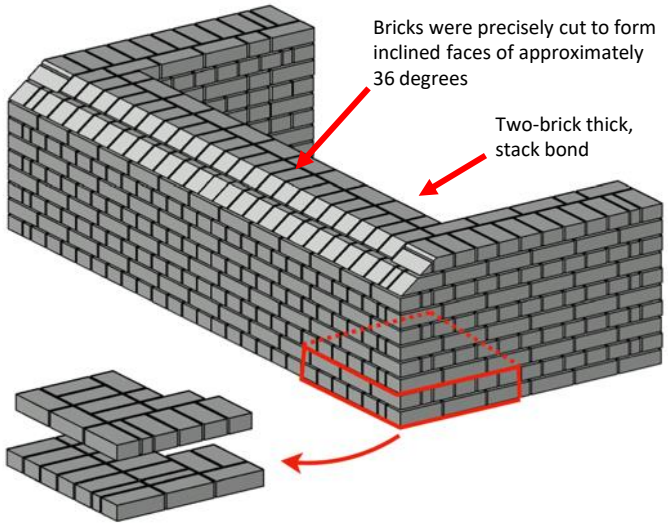
Key parameters:

- Dimensions of the bridge approx. **5.9 m length by 2 m height by 3 m width**
- **Arch barrel**: 3m span single-ring header-bonded arch barrel (215 mm thickness); **4 to 1 span-to-rise ratio**
- Height of **abutment**: 600 mm (8 courses). Thickness of abutment: 440 mm (two brick thick)
- **Backfill**: Crushed limestone; Backfill Depth: 300 mm over the crown of the arch barrel
- **Type A** engineering bricks bonded with 10 mm thick **type O mortar** joints (OPC:Lime:Sand 1:2:9)

Design and construction of masonry arch bridge

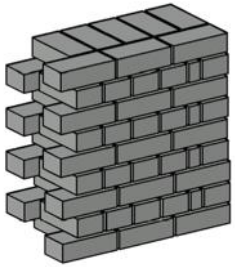
UNIVERSITY OF LEEDS

(b) Abutment and lower part of spandrel walls

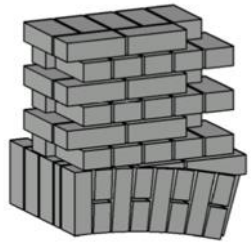


Note: to ensure consistency, and minimize variability due to workmanship, the bridge was constructed using a single bricklayer

(c) Single-ring arch barrel with a header bond (215 mm thick)



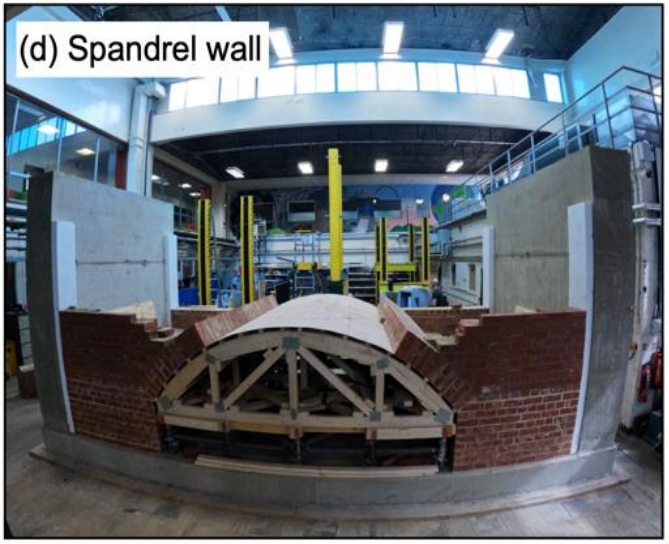
(d) One and half brick thick spandrel wall (English bond)

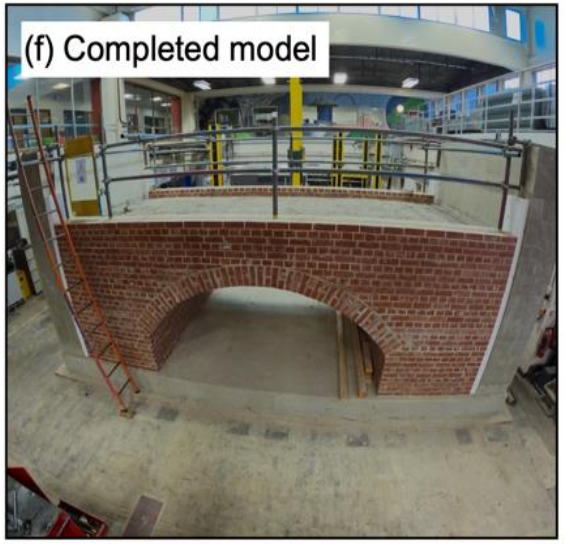


(e) Arch-spandrel wall connection

Construction process

UNIVERSITY OF LEEDS





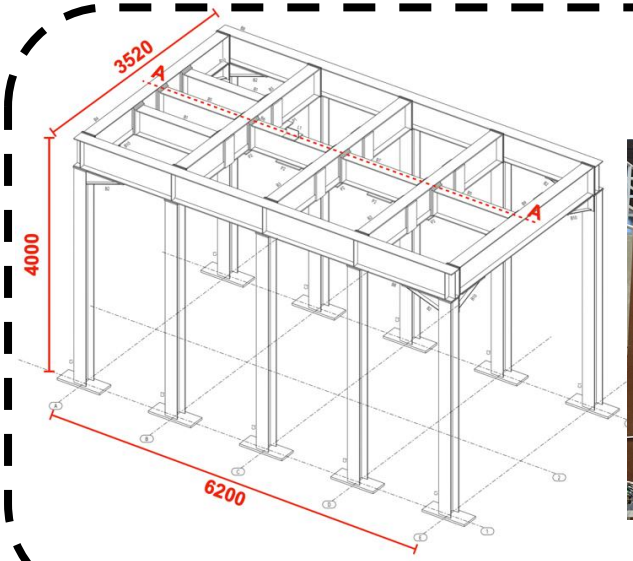
Timelapse – Bridge construction

UNIVERSITY OF LEEDS

3D reconstruction model:
https://sketchfab.com/3d-models/arch-bridge-state1-filtered-200k-8t8k-986bfcd8aabb463ca041fc43dd592395

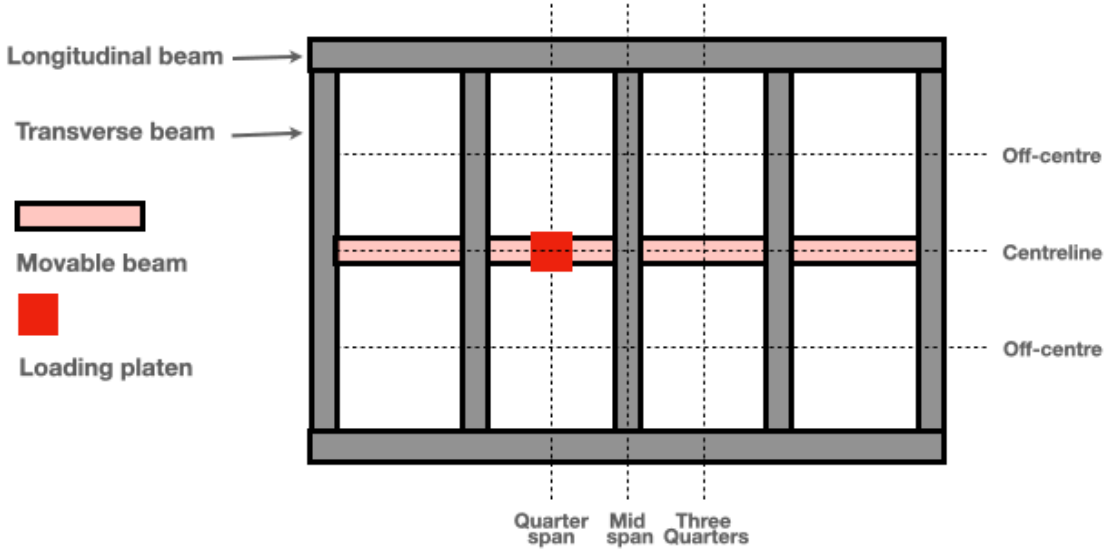
Steel reaction frame

UNIVERSITY OF LEEDS



- A steel reaction frame was specifically designed for mounting the hydraulic actuator and applying vertical static/cyclic loads

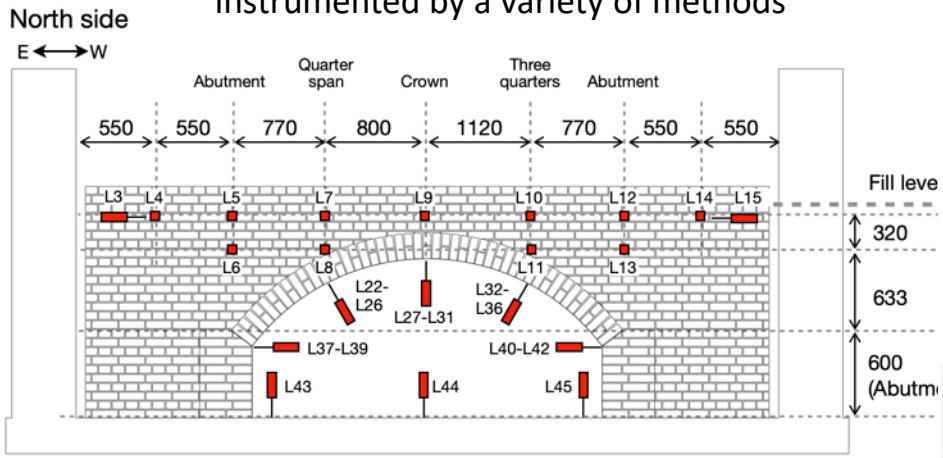
- Steel frame was rigid
- Beams and columns were steel I-sections.
- Actuators can be mounted at the short beams
- The short beams can move transversely for the application of various loading scenarios;

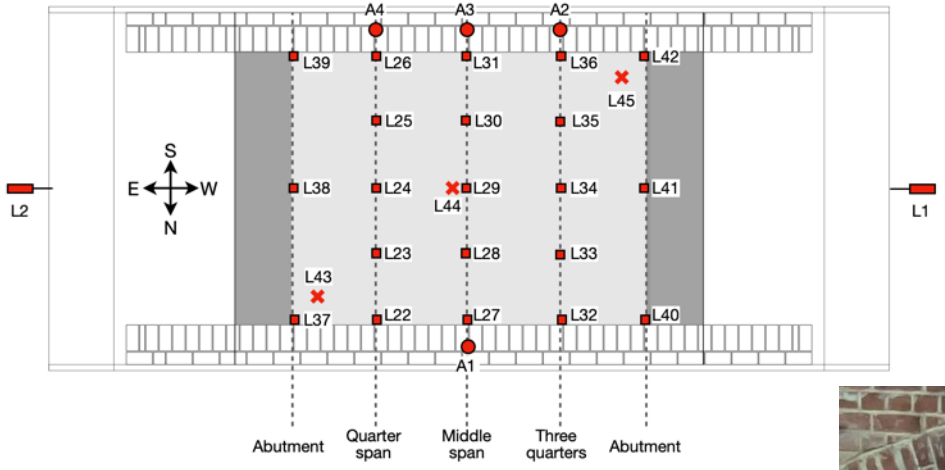


Instrumentation layout

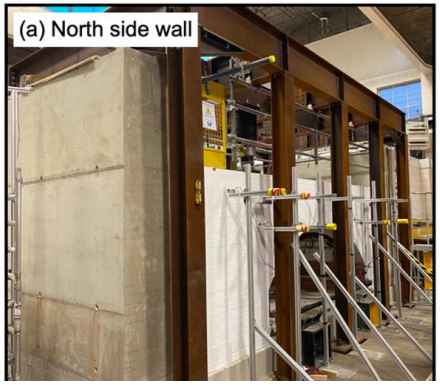
UNIVERSITY OF LEEDS

- The masonry arch bridge was well instrumented by a variety of methods





	Numbers
LVDTs	46
Accelerometers	4



(d) Accelerometers

(e) GPR survey

(f) 3D DIC system

(g) Use of Laser scanning and photogrammetry

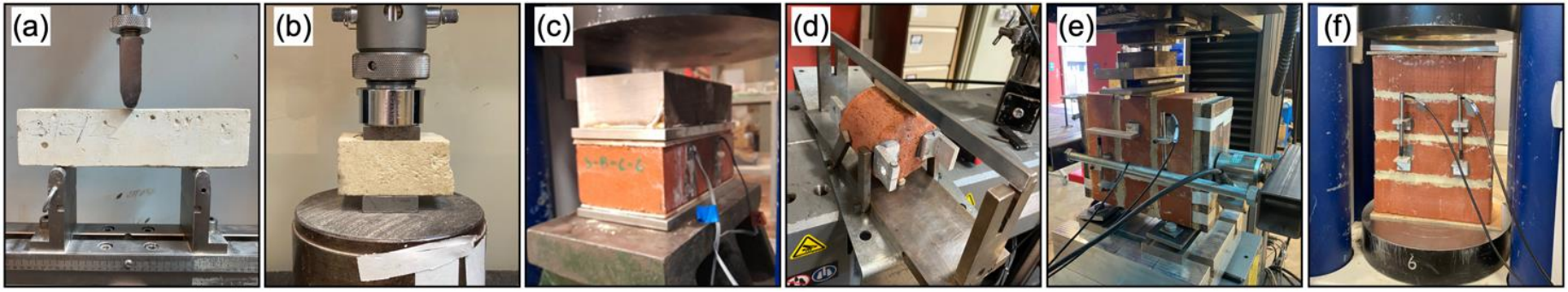
Material characterisation

UNIVERSITY OF LEEDS

Table 1. Material and mechanical properties of bricks, mortar, masonry, and the backfill material.

Properties	Units	No. of tests	Mean values	CV
Compressive strength of brick, $f_{c,u}$	MPa	9	111.3	6.2%
Young's modulus of brick, E_u	MPa	9	31762	15.7%
Tensile strength of brick, $f_{t,u}$	MPa	9	6.730	13.5%
Brick density, ρ_u	kg/m^3	9	2470	1.3%
Flexural strength of mortar, $f_{b,j}$	MPa	20	0.627	20.9%
Compressive strength of mortar, $f_{c,j}$	MPa	40	1.736	25.7%
Young's modulus of mortar, E_j	MPa	40	128.6	35.3%
Mortar density, ρ_j	kg/m^3	20	1680	2.3%
Friction angle at brick-to-mortar interface, φ	Degree	3	44.9	-
Cohesion at brick-to-mortar interface, C	MPa	3	0.40	-
Compressive strength of masonry, $f_{c,m}$	MPa	3	30.84	24.2%
Young's modulus of masonry, E_m	MPa	3	10128	48.4%
Friction angle of limestone, φ_b	Degree	6	47.8	-
Limestone density (bulk), ρ_b	kg/m^3	-	2150	-

- All specimens **constructed at the same time as the construction** of the masonry arch bridge, and tested at the time of testing the bridge i.e. same curing conditions.
- Designed in close **association with colleagues** developing numerical models

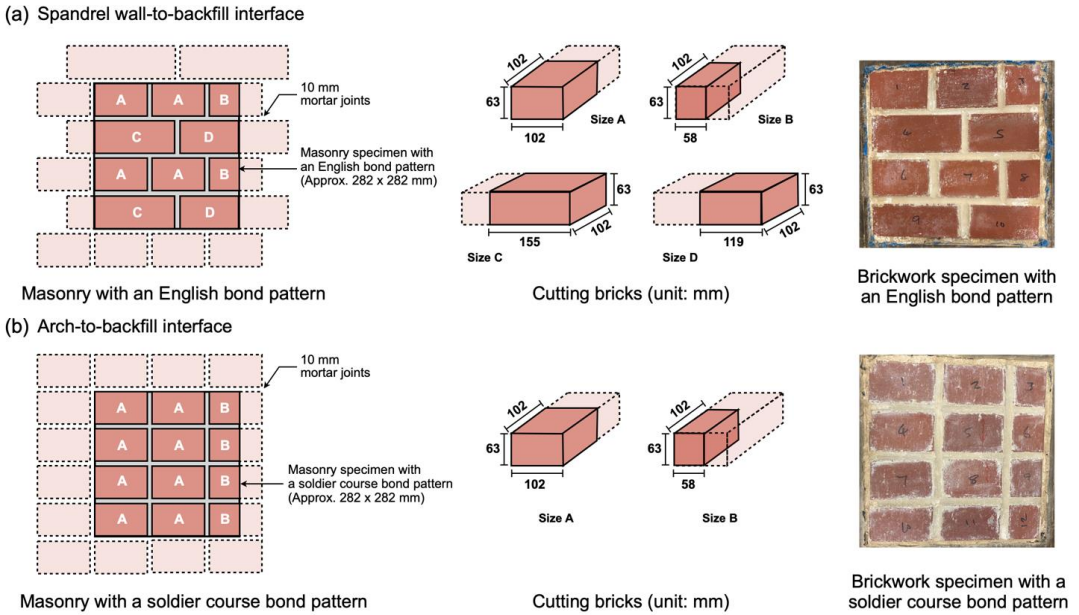


Small-scale testing for material characterisation

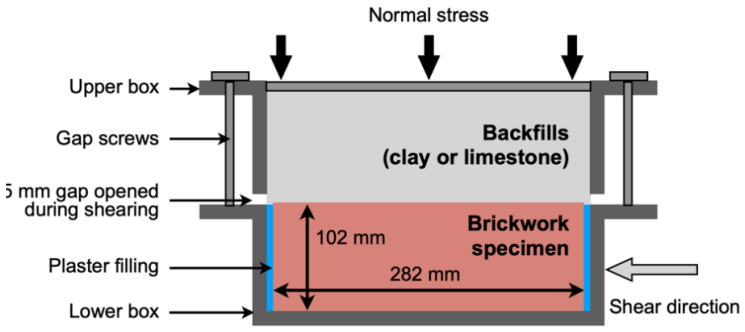
(a) three-point bending tests on mortar prisms; (b)compression tests on mortar cubes; (c) compression tests on bricks; (d) Brazilian tests on brick cylinders; (e) triplet shear tests; (f) compression tests on masonry prisms.

Frictional parameters of brickwork-backfill interface

UNIVERSITY OF LEEDS



Design of masonry specimens



Interface shear box test setup

More info, please refer to :

- Liu et al. 2023. *Construction and Building Materials*, 397, https://doi.org/10.1016/j.conbuildmat.2023.132347.
- Liu et al. 2023. *Engineering Structures*, 292,
- https://doi.org/10.1016/j.engstruct.2023.116531.

Samples/interfaces		**Friction angle** (°)	**Cohesion** (kPa)	R^2	φ_i/φ
Clay		37.2	30.0	0.950	-
Limestone		47.8	0	0.994	-
EC interface	With cohesion	14.5	16.7	0.942	0.39
	Zero-cohesion	19.2	0	0.993	0.52
SC interface	With cohesion	12.9	20.9	0.967	0.35
	Zero-cohesion	18.9	0	0.991	0.51
EL interface		33.3	0	0.994	0.70
SL interface		35.7	0	0.999	0.75

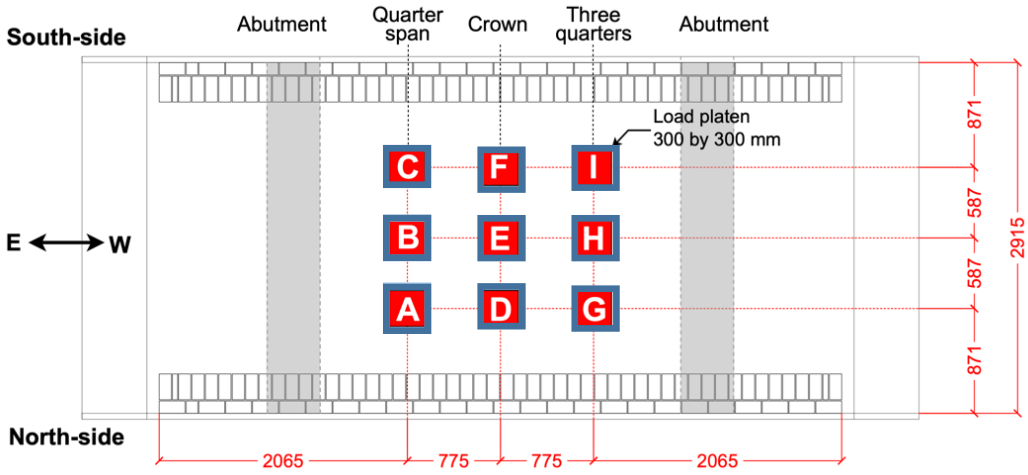
Loading protocol: Induce increasing level of damage

UNIVERSITY OF LEEDS

9 loading locations (point A to point I)
First load was quasi-static, then 3 quasi-static cycle

- **Low-level**: 150 kN (elastic limit)
- **Mid-level**: 250 kN (less than 50% of ULS)
- **High-level**: 560 kN;
- **Failure-level tests**: until failure

Specification for the loading area
300 by 300 mm for the low- and mid-level
300 by 750 mm for the high-level and ultimate



Testing sequence →																								
Location	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**	**T21**	**T22**	**T23**	**T24**	**T25**
A																									
B																									
C																									
D																									
E																									
F																									
G																									
H																									
I																									

Low-level static
Low-level three cycles
Mid-level static
Mid-level three cycles
High-level static
Failure-level static

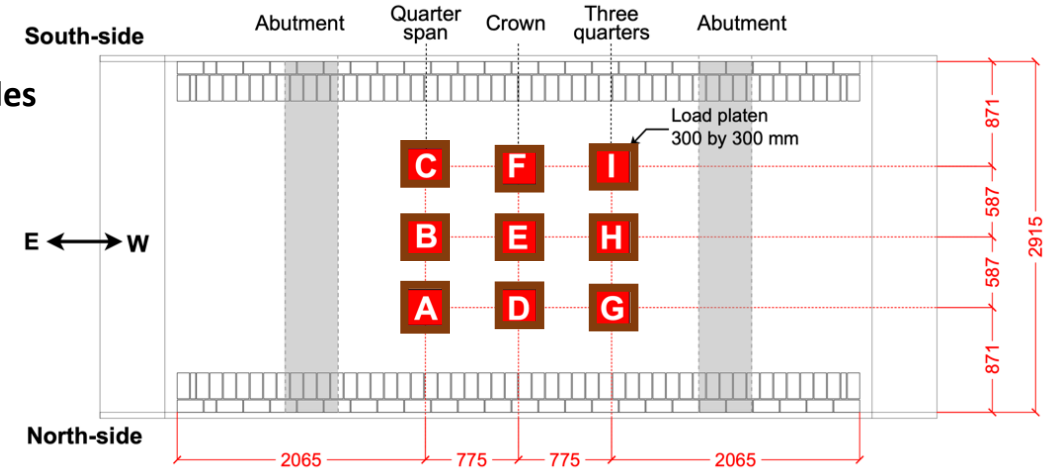
Loading protocol: Induce increasing level of damage

UNIVERSITY OF LEEDS

9 loading locations (point A to point I)
First load was quasi-static, then 3 quasi-static cycles

- **Low-level**: 150 kN (elastic limit)
- **Mid-level**: 250 kN (less than 50% of ULS)
- **High-level**: 560 kN
- **Failure-level tests**: until failure

Specification for the loading area
300 by 300 mm for the low- and mid-level
300 by 750 mm for the high-level and ultimate



Testing sequence →																								
Location	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**	**T21**	**T22**	**T23**	**T24**	**T25**
A																									
B																									
C																									
D																									
E																									
F																									
G																									
H																									
I																									

Low-level static
Low-level three cycles
Mid-level static
Mid-level three cycles
High-level static
Failure-level static

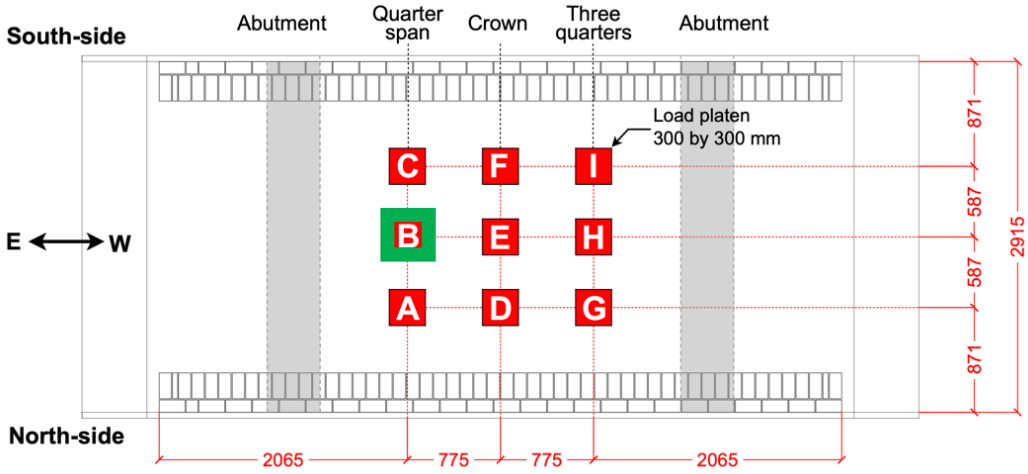
Loading protocol: Induce increasing level of damage

UNIVERSITY OF LEEDS

9 loading locations (point A to point I)
First load was quasi-static, then 3 quasi-static cycle

- **Low-level**: 150 kN (elastic limit)
- **Mid-level**: 250 kN (less than 50% of ULS)
- **High-level: 560 kN**
- **Failure-level tests**: until failure

Specification for the loading area
300 by 300 mm for the low- and mid-level
300 by 750 mm for the high-level and ultimate



Testing sequence →																								
Location	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**	**T21**	**T22**	**T23**	**T24**	**T25**
A																									
B																									
C																									
D																									
E																									
F																									
G																									
H																									
I																									

Low-level static
Low-level three cycles
Mid-level static
Mid-level three cycles
High-level static
Failure-level static

Loading protocol: Induce increasing level of damage

UNIVERSITY OF LEEDS

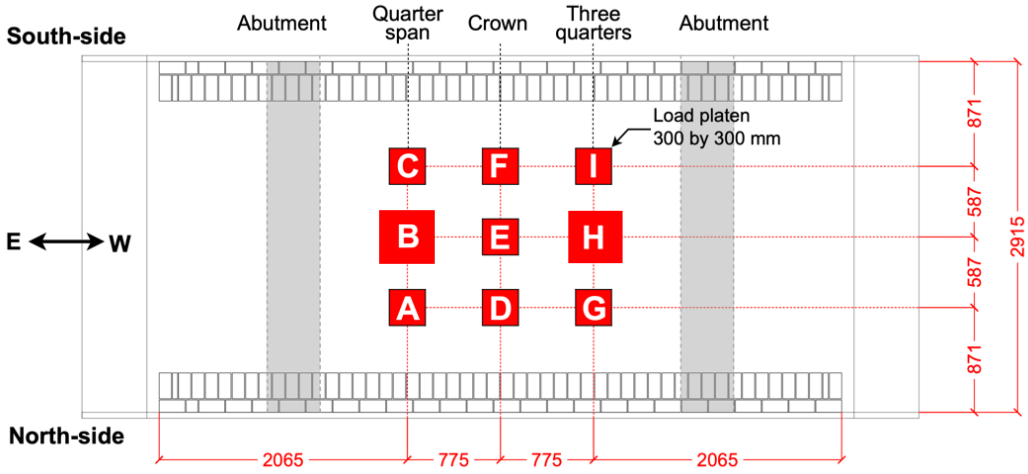
9 loading locations (point A to point I)

- **Low-level**: 150 kN (elastic limit)
- **Mid-level**: 250 kN (less than 50% of ULS,
- **High-level**: 560 kN;
- **Failure-level tests: until failure**

Specification for the loading area

300 by 300 mm for the low- and mid-level

300 by 750 mm for the high-level and ultimate



Testing sequence →																								
Location	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**	**T21**	**T22**	**T23**	**T24**	**T25**
A																									
B																									
C																									
D																									
E																									
F																									
G																									
H																									
I																									

Low-level static

Low-level three cycles

Mid-level static

Mid-level three cycles

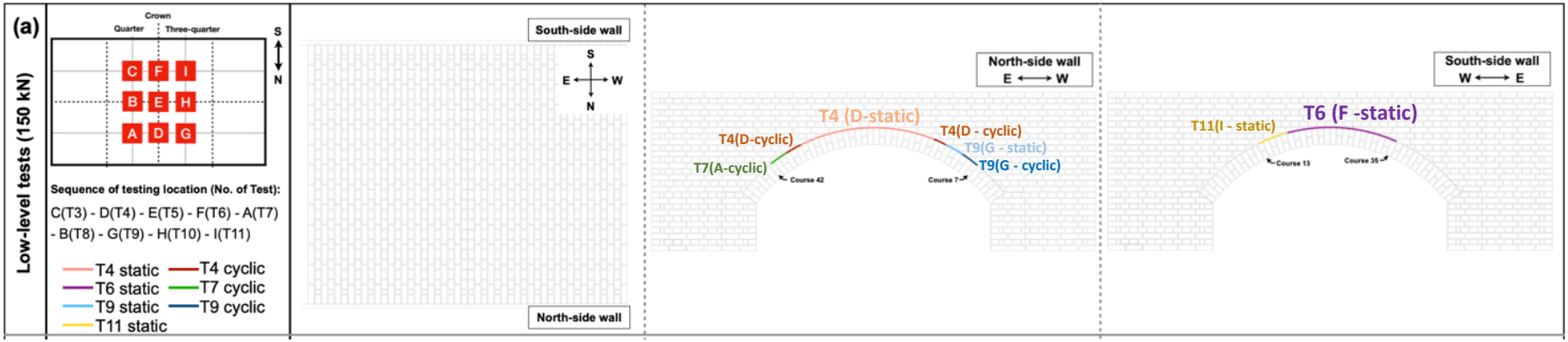
High-level static

Failure-level static

Results: Crack propagation – damage evolution

UNIVERSITY OF LEEDS

Arch intrados | North side | South side

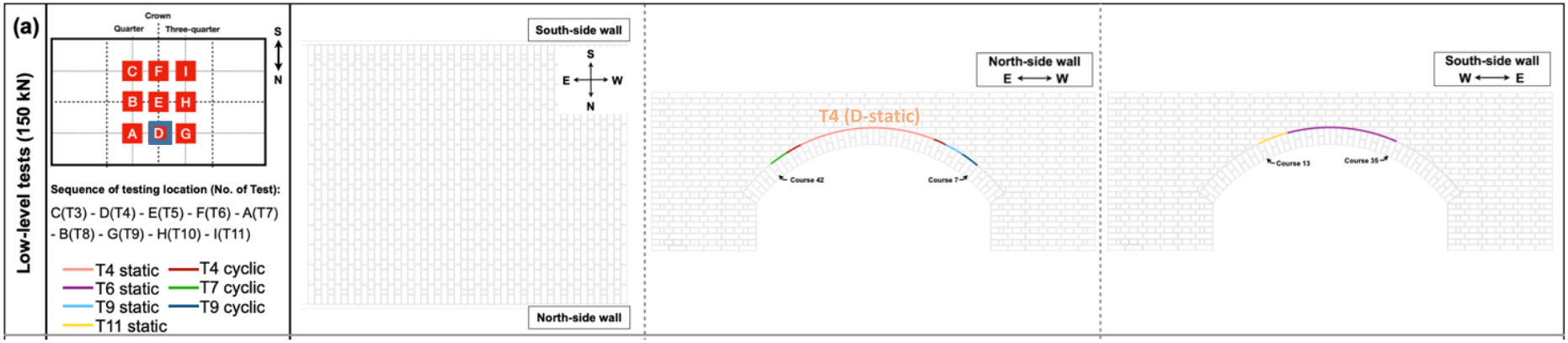


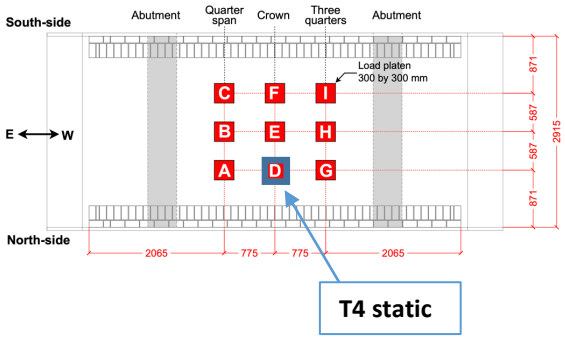
Low-level: 150 kN

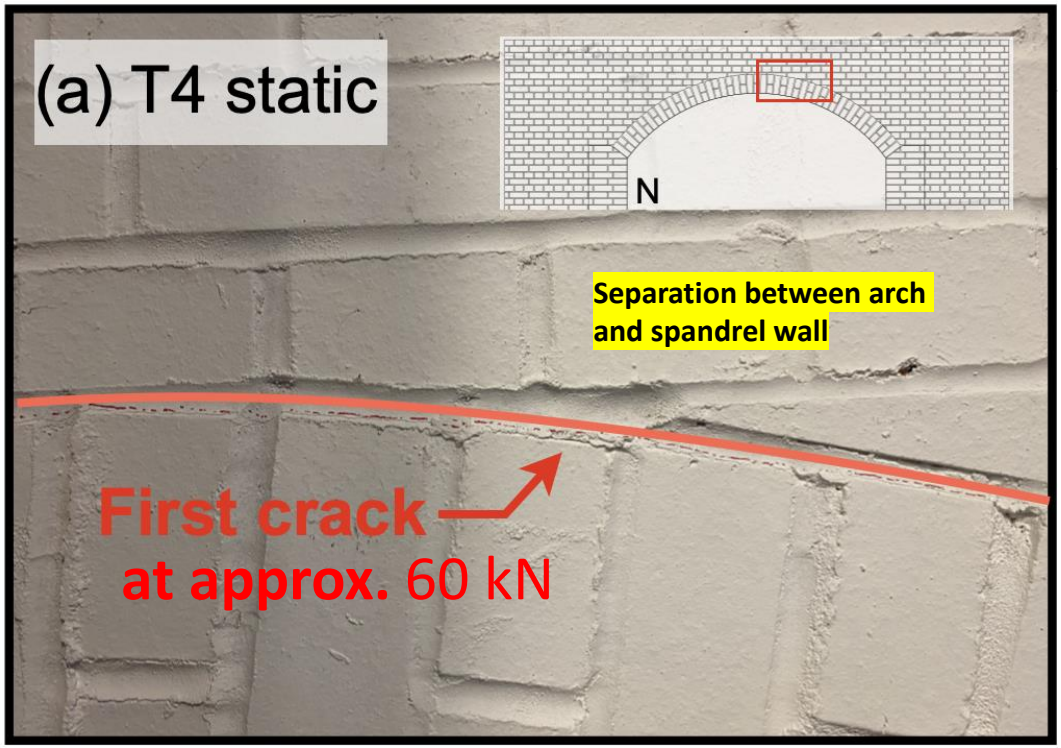
- At low level of loads, cracks were very thin (hairline cracks).
- With the removal of the load, cracks closed.
- First crack observed when load applied at the crown close to the spandrel wall (Point D).
- The first crack was a detachment of the arch ring from the spandrel wall.

Results: Crack propagation – damage evolution

Arch intrados — North side — South side





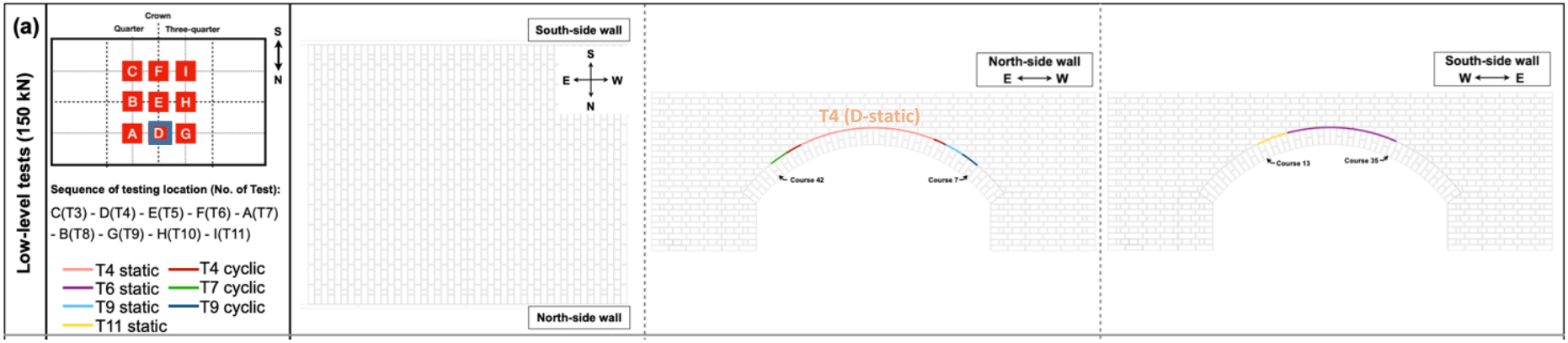


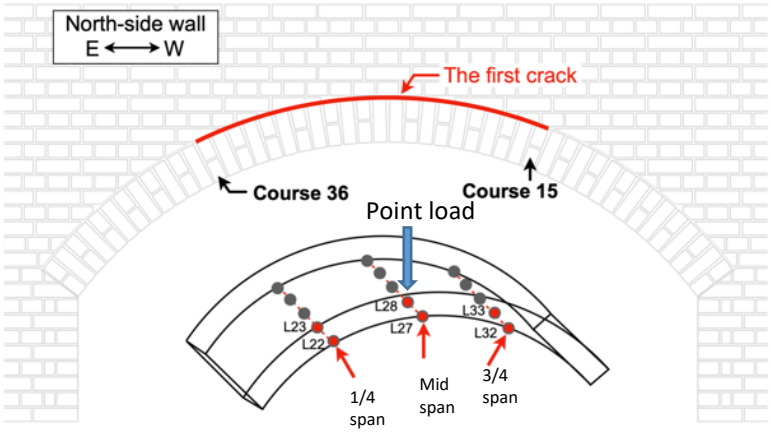
Low-level: 150 kN

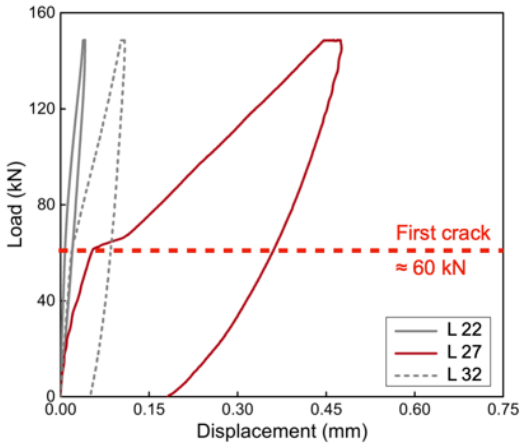
Results: Crack propagation – damage evolution

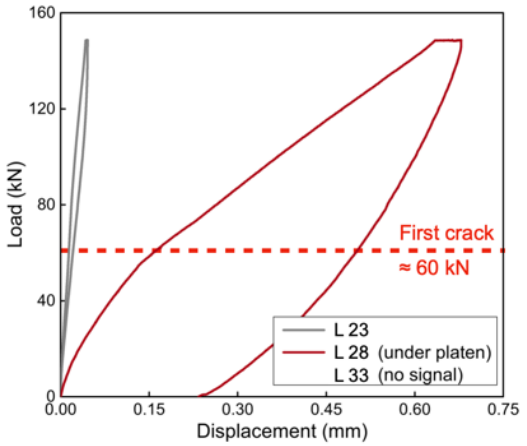
UNIVERSITY OF LEEDS

Arch intrados — North side — South side









- **The first crack**: separation between the arch barrel and spandrel wall
- **Loading location**: Point D
- **Cracking load**: approximately 60 kN

Displacement close to the edge of the arch ring (L27)

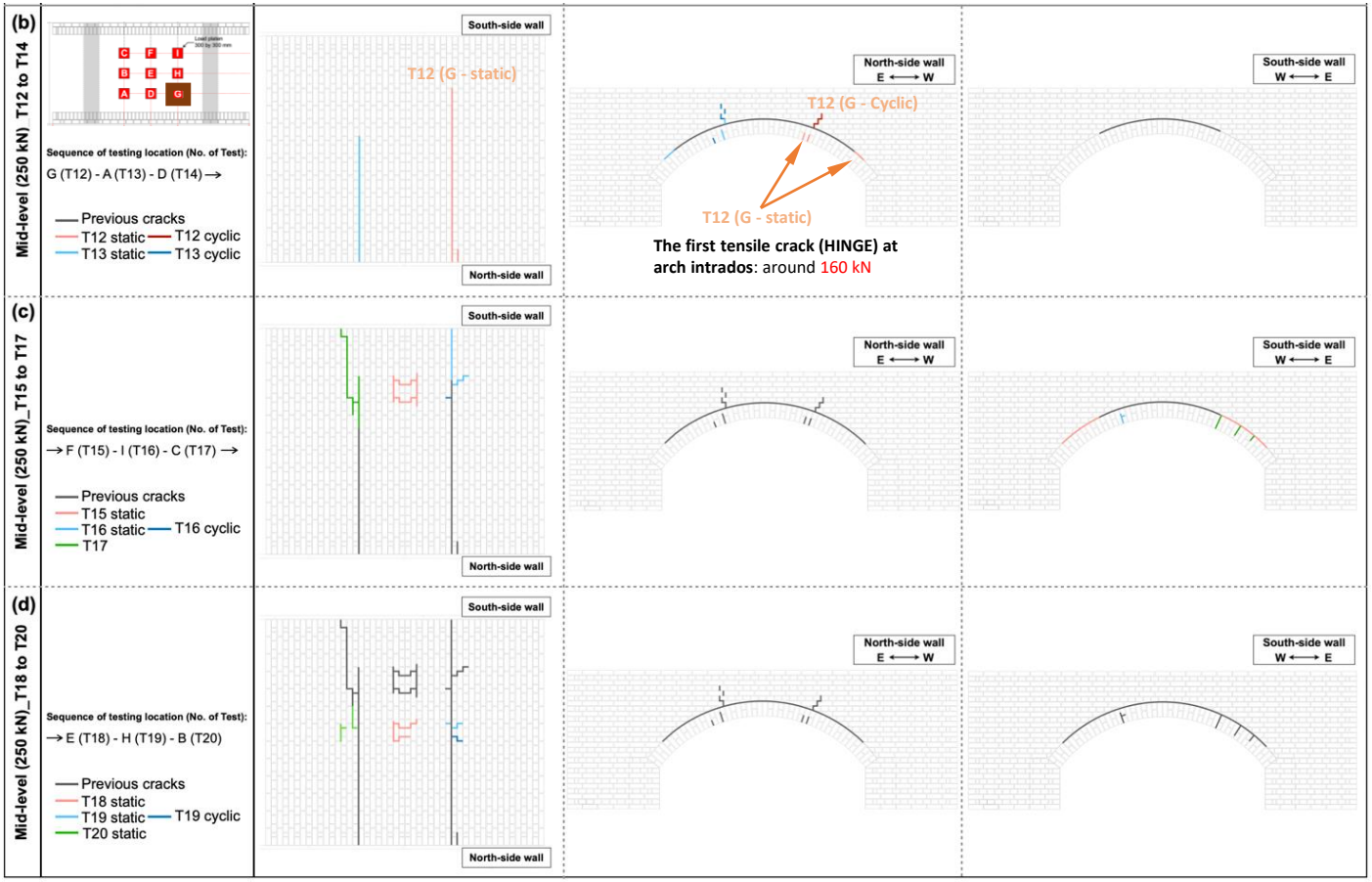
Displacement under point load (L28)

Results: Crack propagation – damage evolution

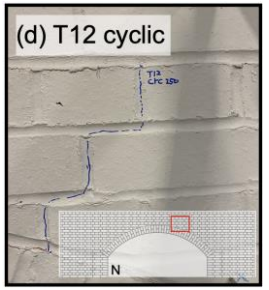
UNIVERSITY OF LEEDS

Arch intrados — North side — South side

- **Mid-level**: 250 kN (less than 50% of ULS



Diagonal crack at spandrel wall (G location)

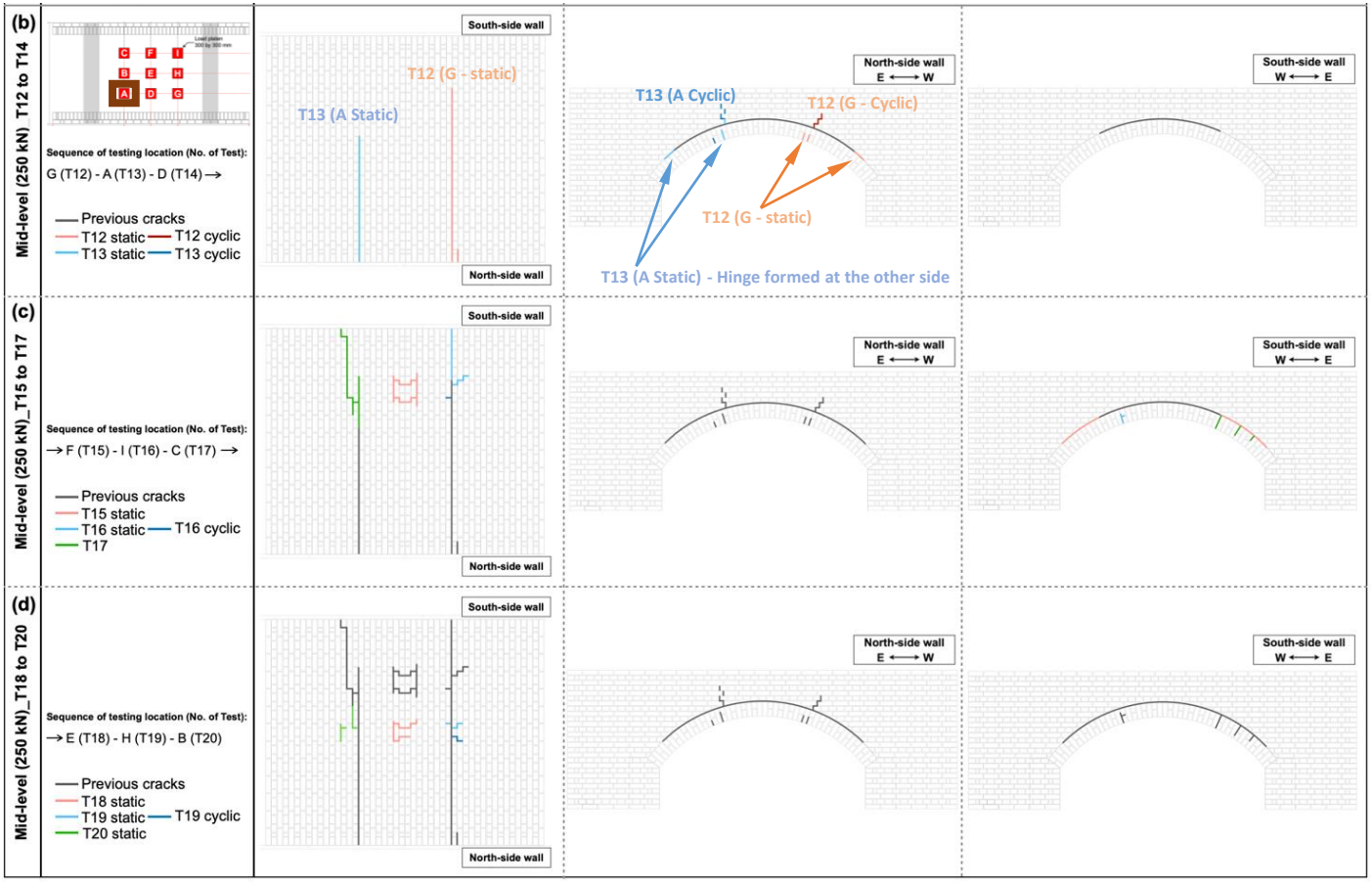


Results: Crack propagation – damage evolution

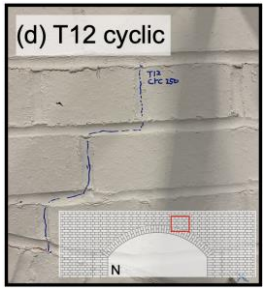
UNIVERSITY OF LEEDS

Arch intrados — North side — South side

- **Mid-level**: 250 kN (less than 50% of ULS



Diagonal crack at spandrel wall (G location)

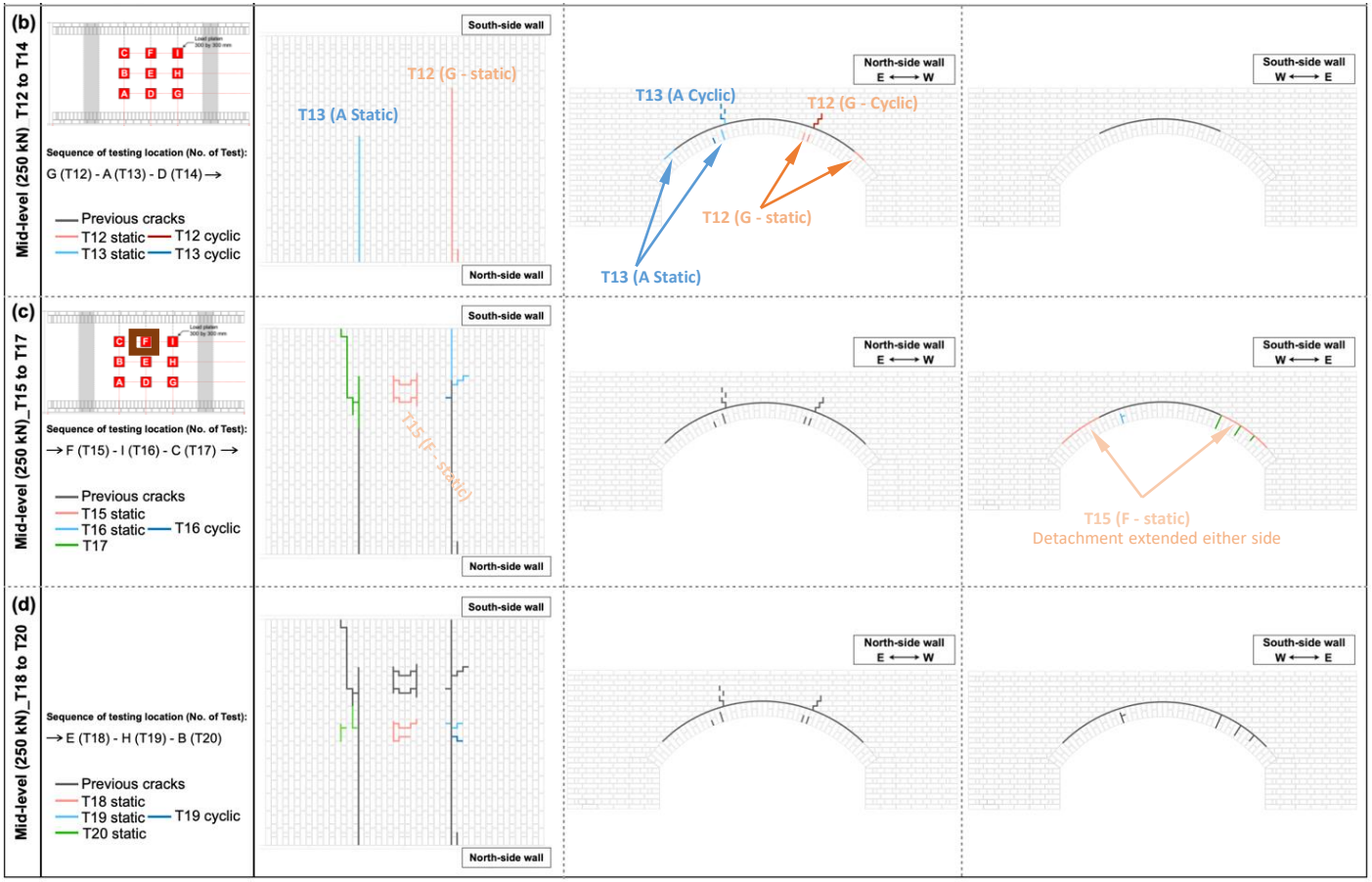


Results: Crack propagation – damage evolution

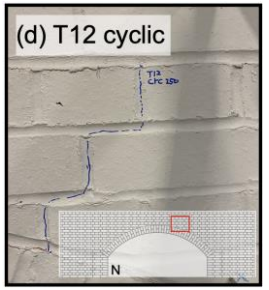
UNIVERSITY OF LEEDS

Arch intrados — North side — South side

- **Mid-level**: 250 kN (less than 50% of ULS



Diagonal crack at spandrel wall (G location)

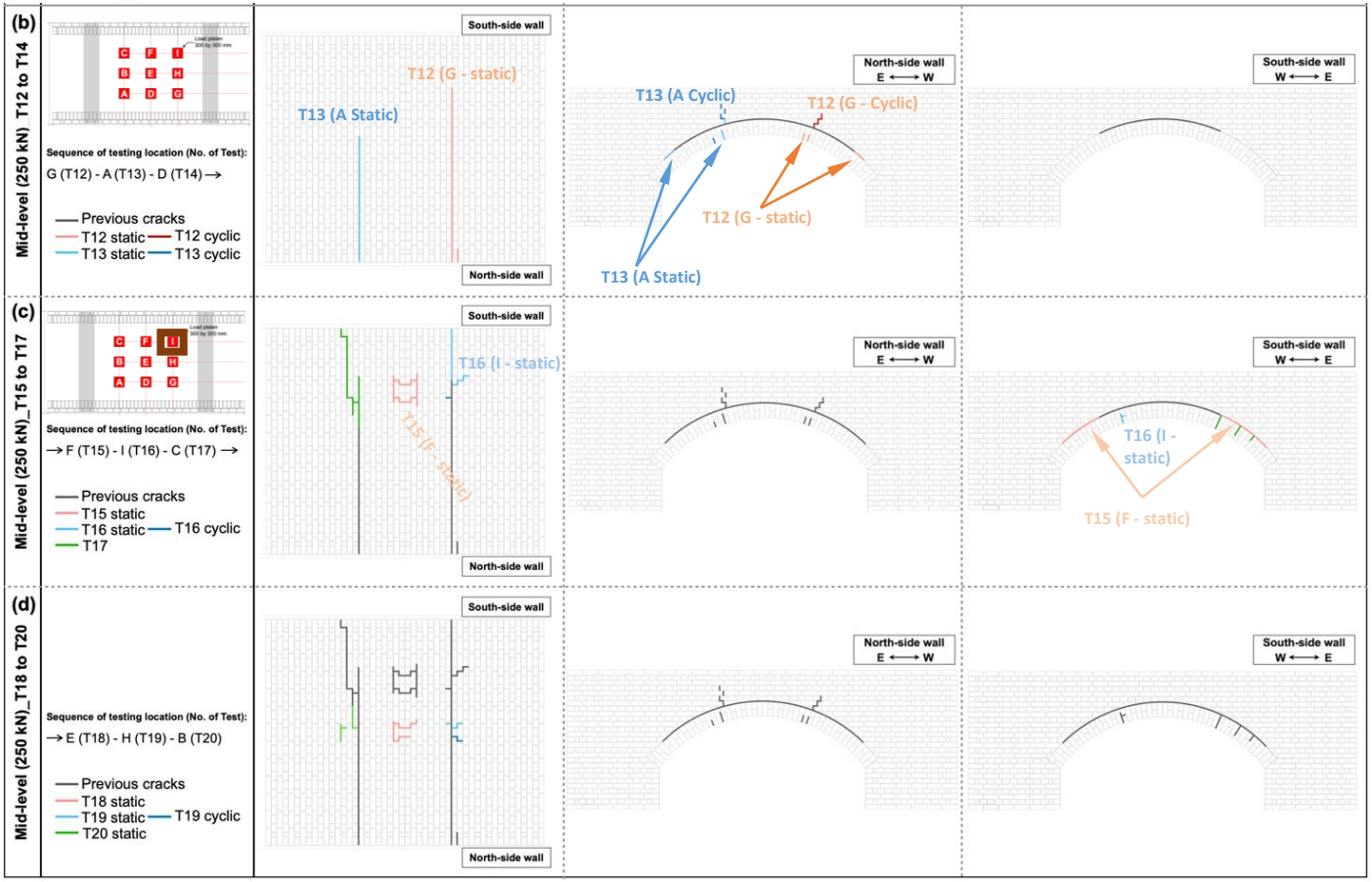


Results: Crack propagation – damage evolution

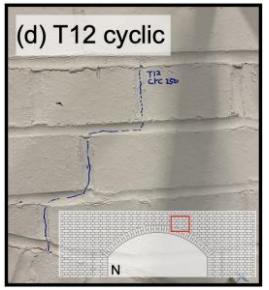
UNIVERSITY OF LEEDS

Arch intrados — North side — South side

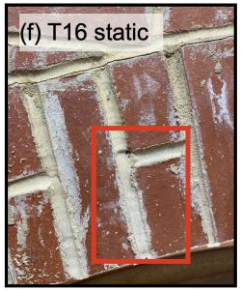
- **Mid-level**: 250 kN (less than 50% of ULS



Diagonal crack at spandrel wall (G location)



Tensile crack at arch intrados

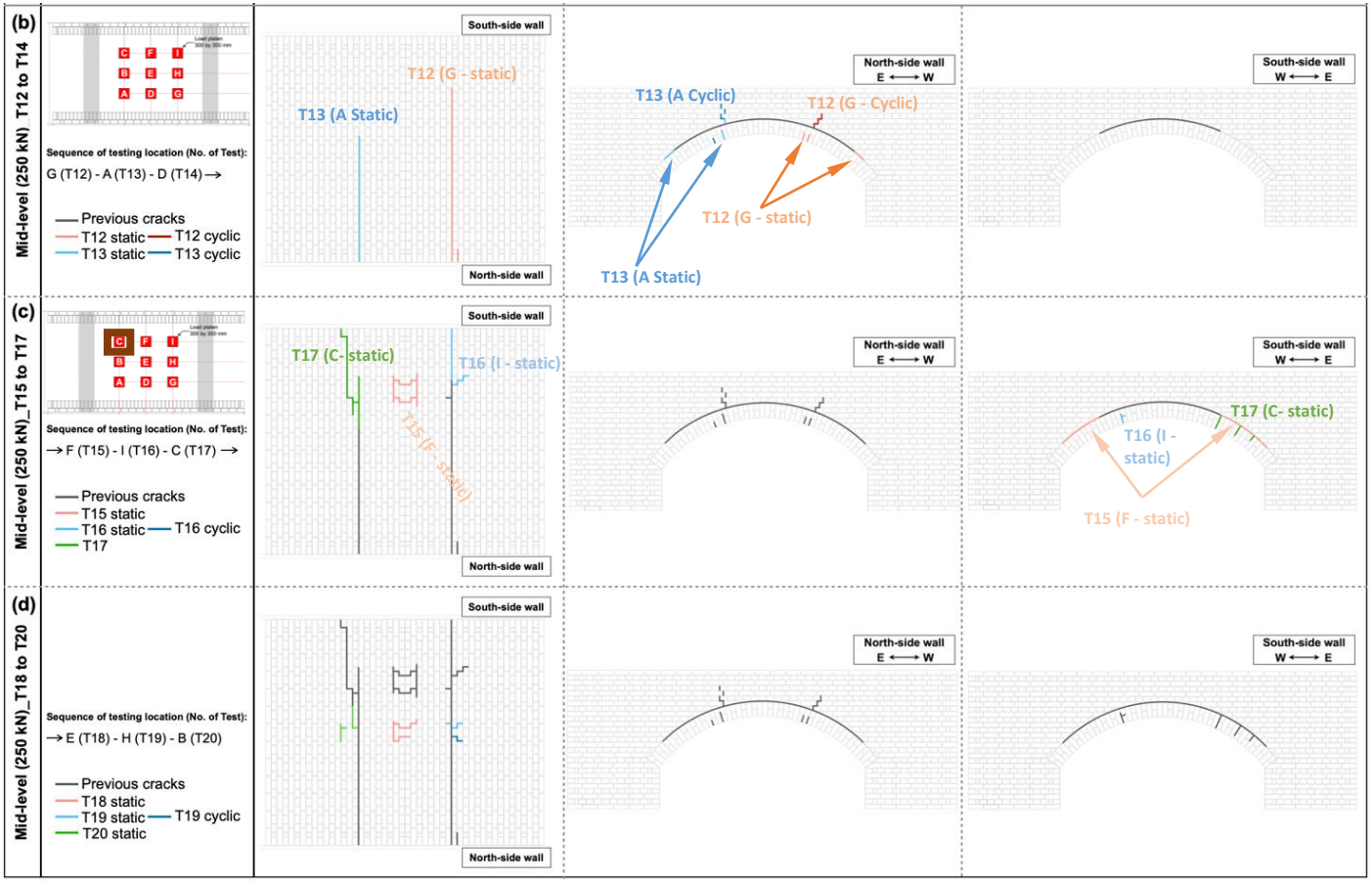


Results: Crack propagation – damage evolution

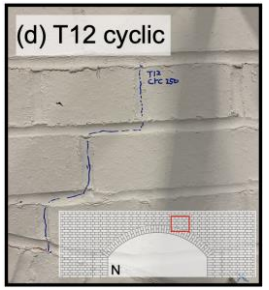
UNIVERSITY OF LEEDS

Arch intrados — North side — South side

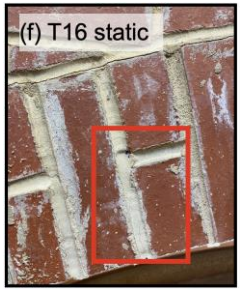
- **Mid-level**: 250 kN (less than 50% of ULS



Diagonal crack at spandrel wall (G location)



Tensile crack at arch intrados

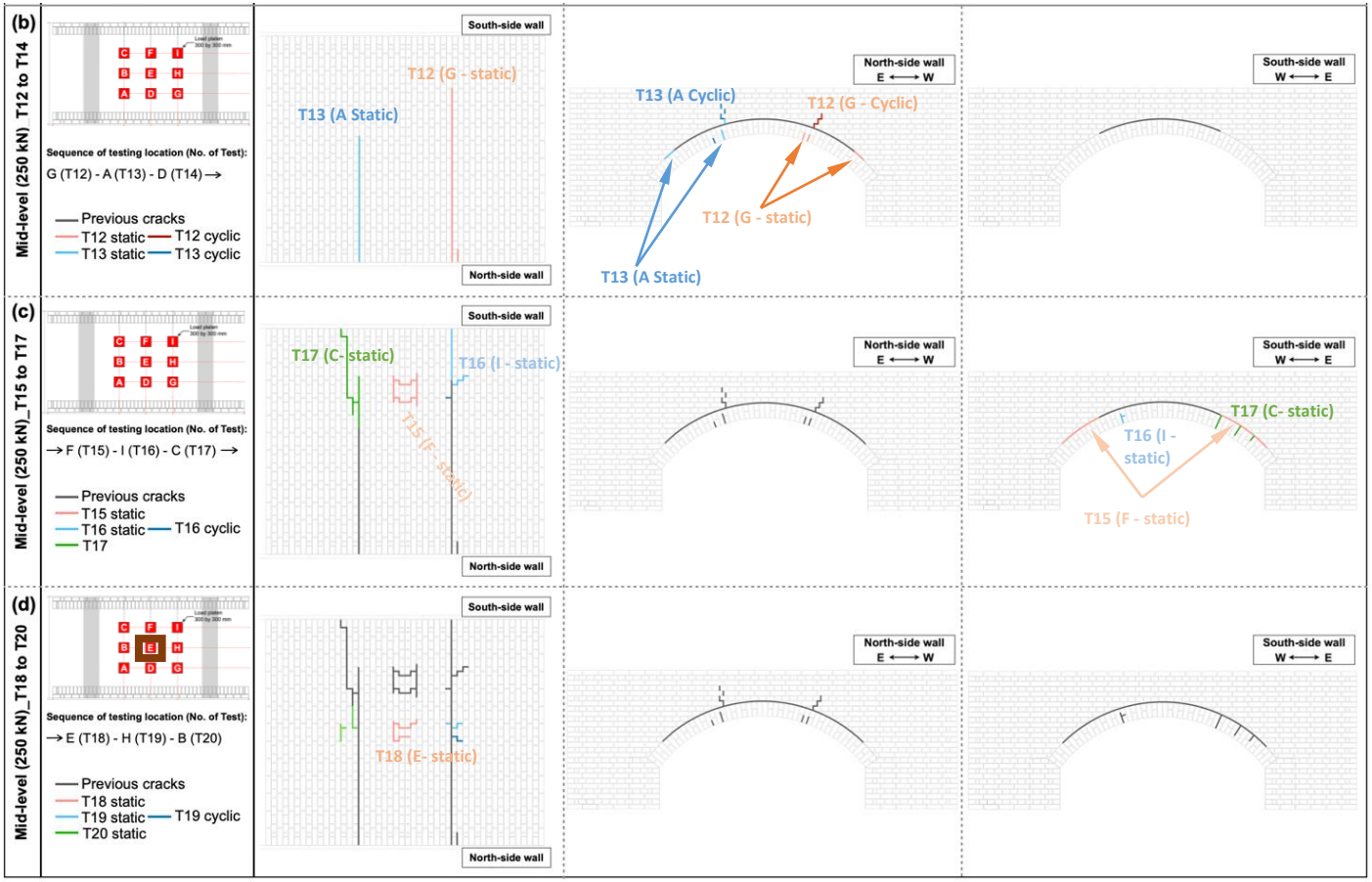


Results: Crack propagation – damage evolution

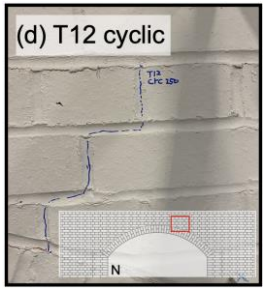
UNIVERSITY OF LEEDS

Arch intrados — North side — South side

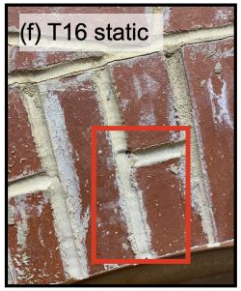
- **Mid-level**: 250 kN (less than 50% of ULS

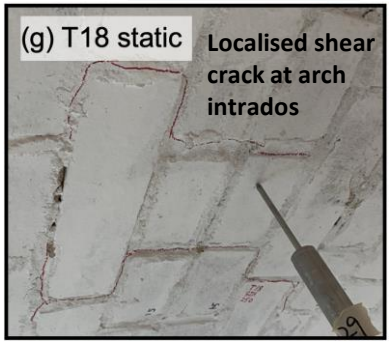


Diagonal crack at spandrel wall (G location)



Tensile crack at arch intrados



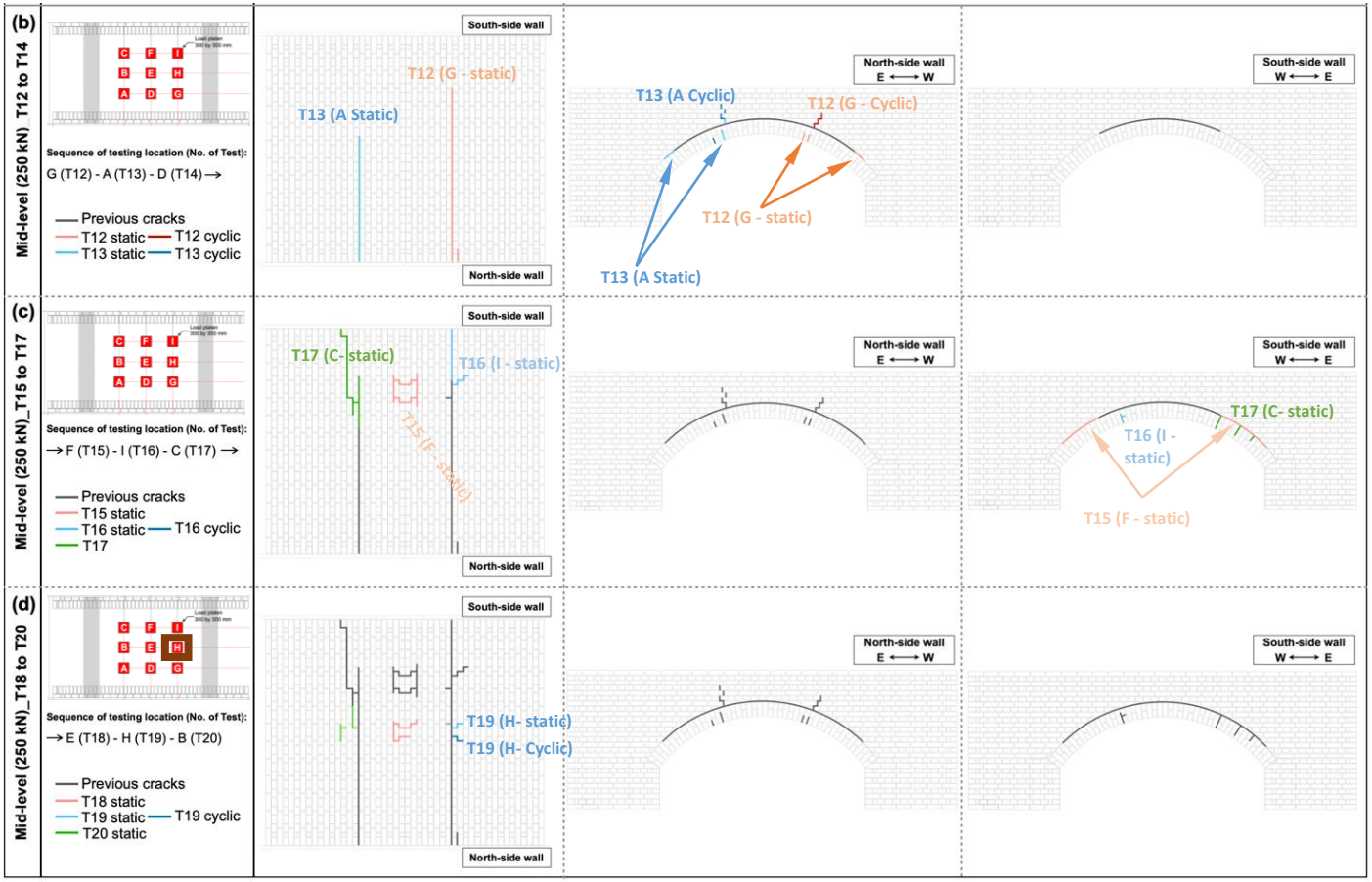


Results: Crack propagation – damage evolution

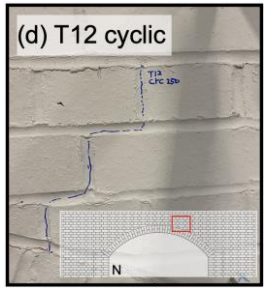
UNIVERSITY OF LEEDS

Arch intrados — North side — South side

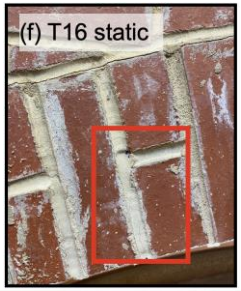
- **Mid-level**: 250 kN (less than 50% of ULS

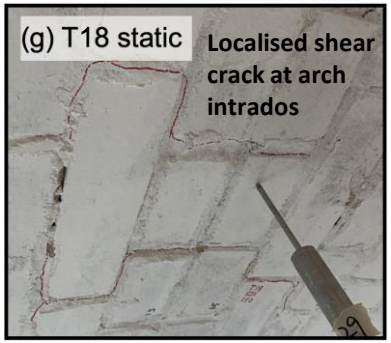


Diagonal crack at spandrel wall (G location)



Tensile crack at arch intrados



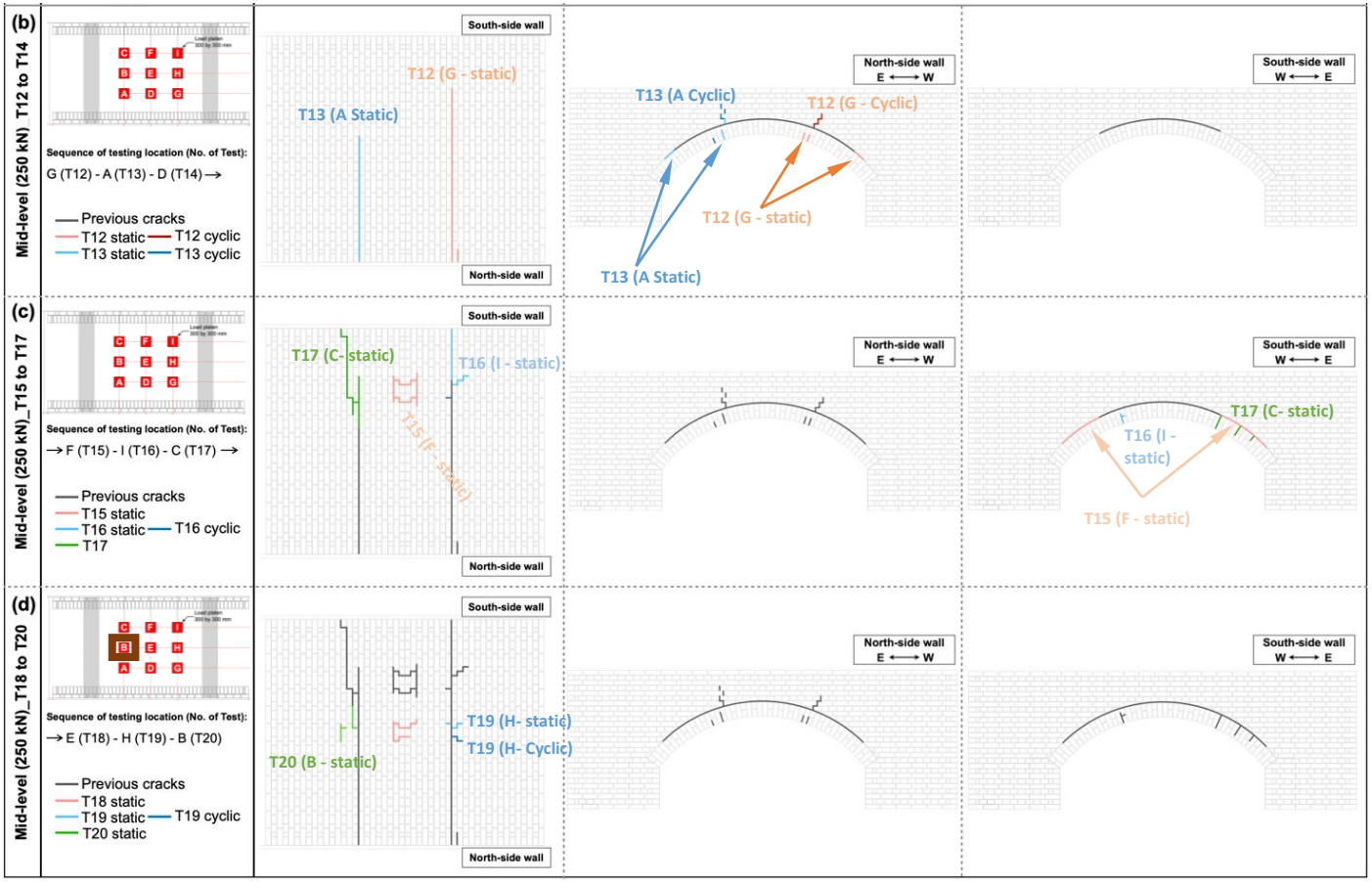


Results: Crack propagation – damage evolution

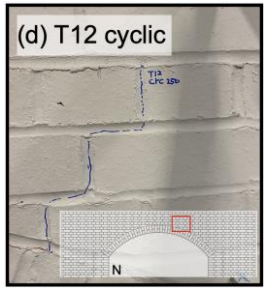
UNIVERSITY OF LEEDS

Arch intrados — North side — South side

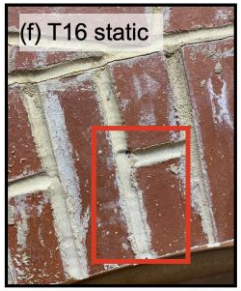
- **Mid-level**: 250 kN (less than 50% of ULS

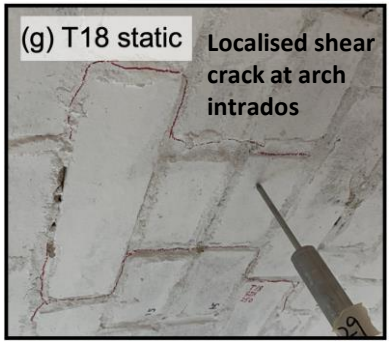


Diagonal crack at spandrel wall (G location)



Tensile crack at arch intrados

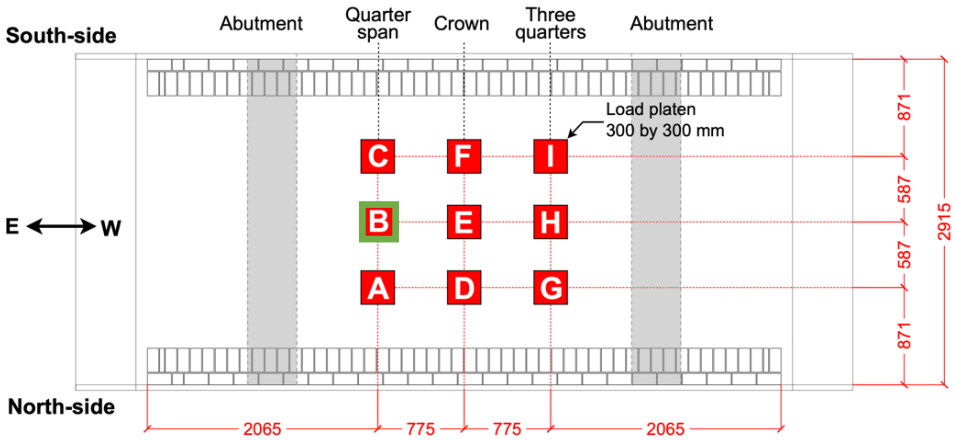




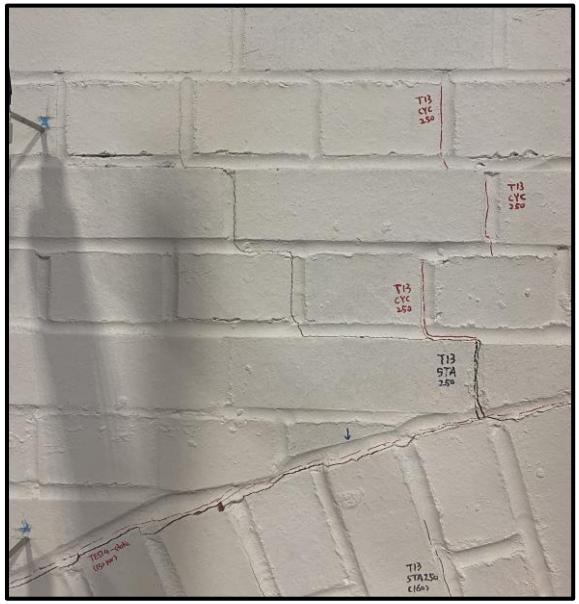
Results: Crack propagation

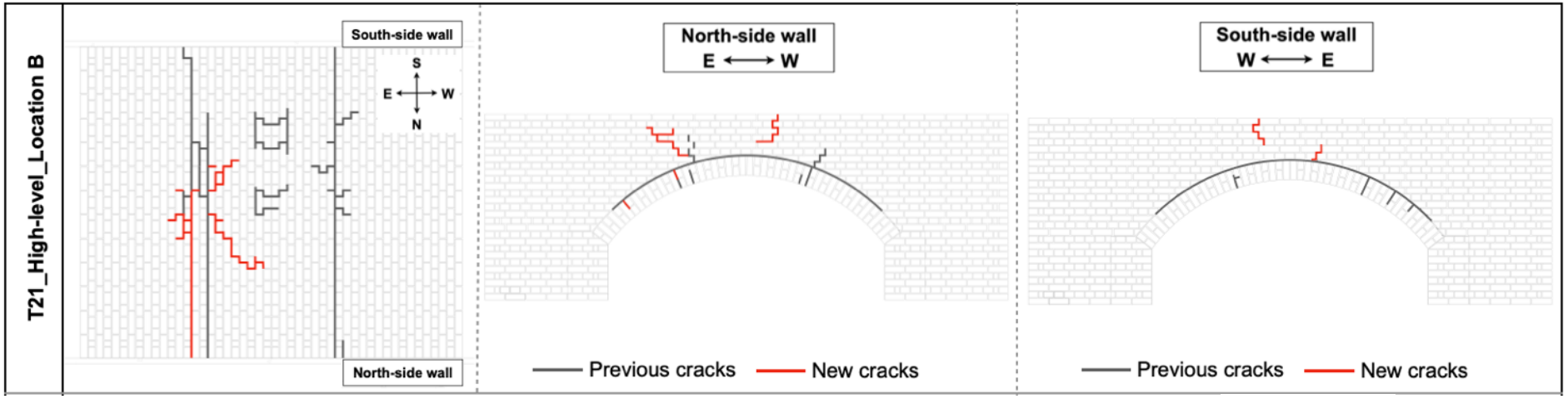
UNIVERSITY OF LEEDS

- **High-level: 560 kN**



Propagation of diagonal cracks at spandrel wall





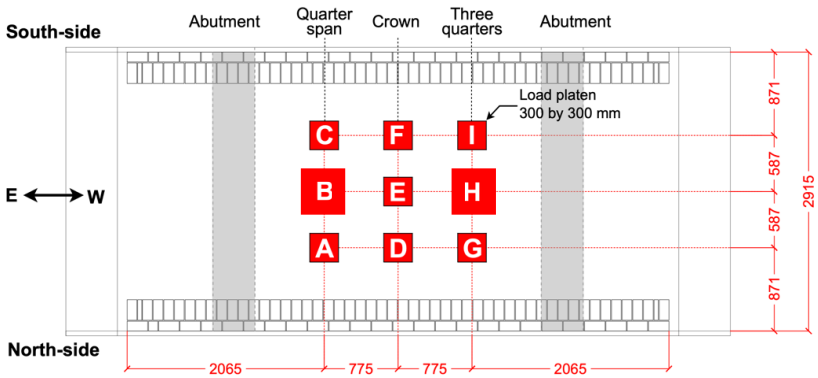
Arch intrados

North side

South side

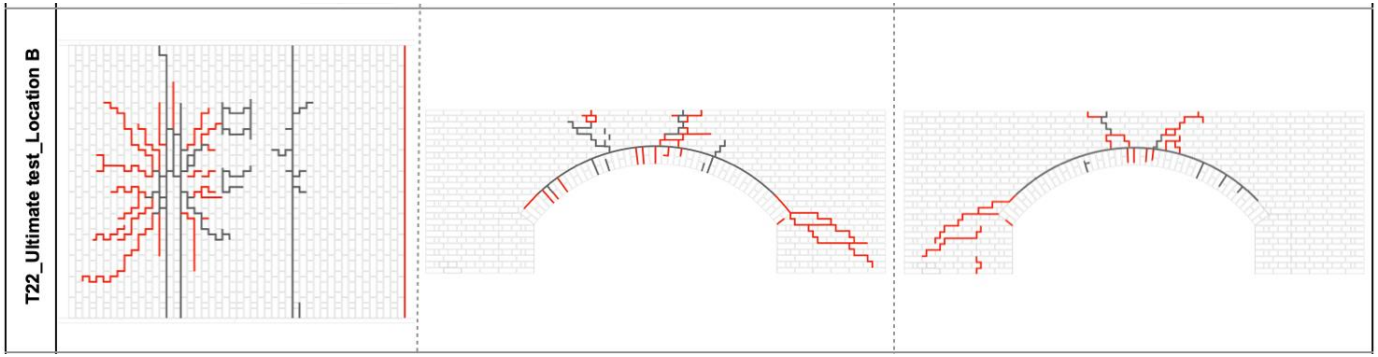
Results: Crack propagation

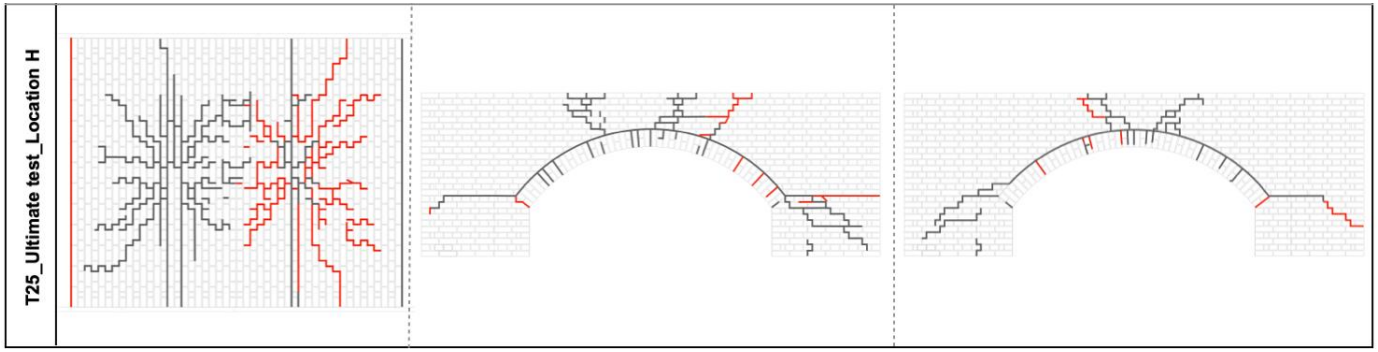
UNIVERSITY OF LEEDS

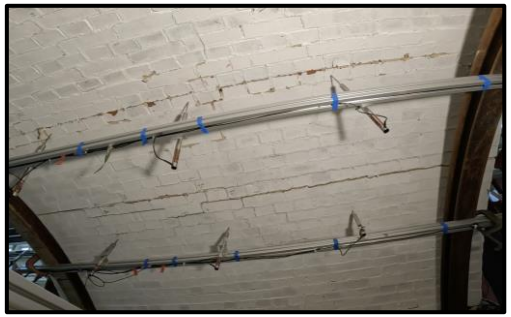


Failure-level tests

Hinge under loading location



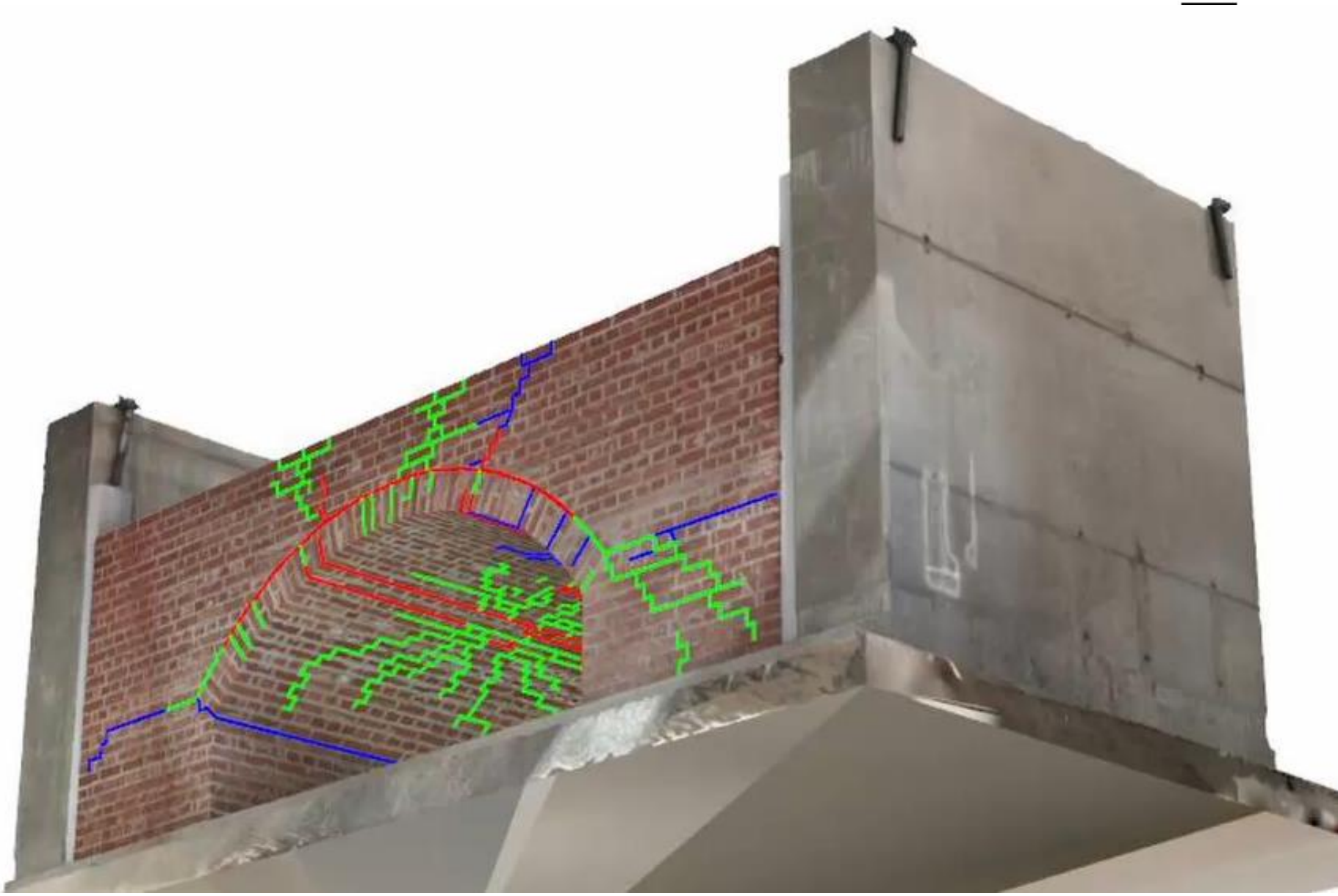




Arch intrados

North side

South side

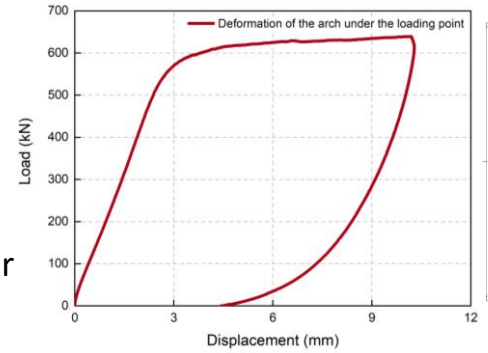


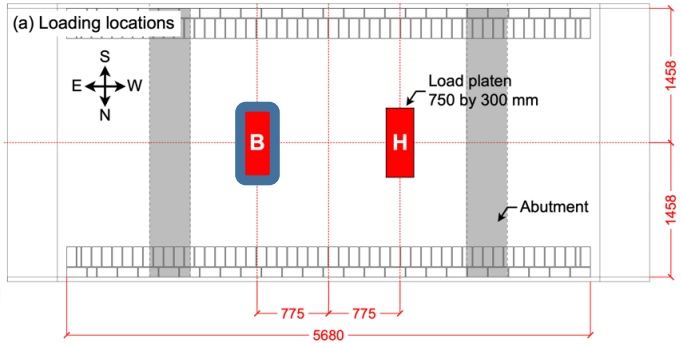
3D Cracking

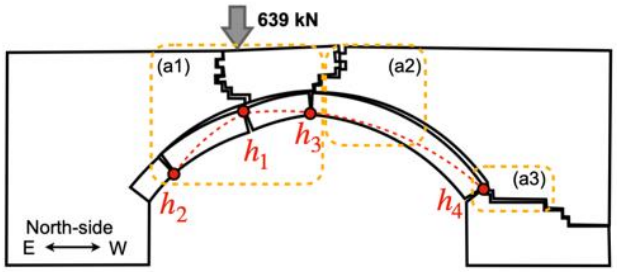
Results: load vs displacement and bridge failure mechanism

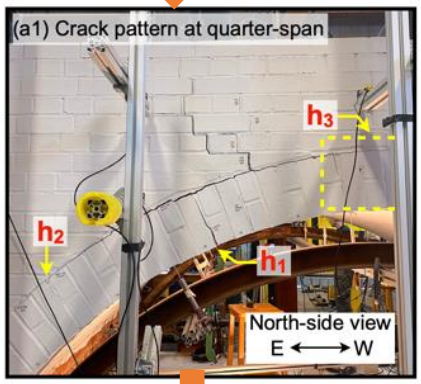
UNIVERSITY OF LEEDS

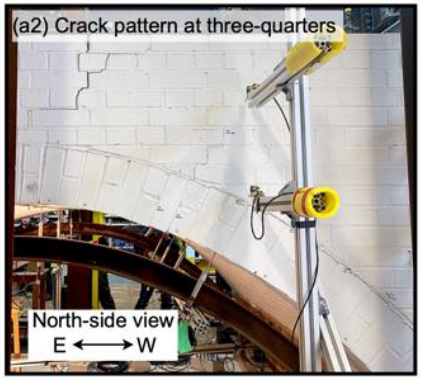
- **Loading location:** Point B
- **Peak load applied**: 639 kN
- **Loading area**: 300 by 750 mm
- **Failure mechanism**: four-hinge behaviour
- Hinge-3 at the mid-span region

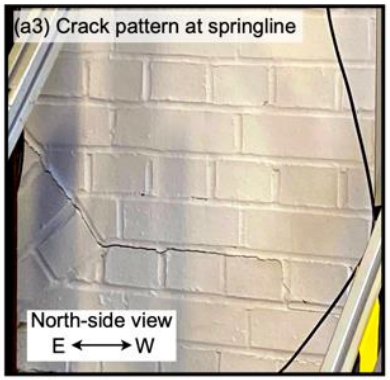


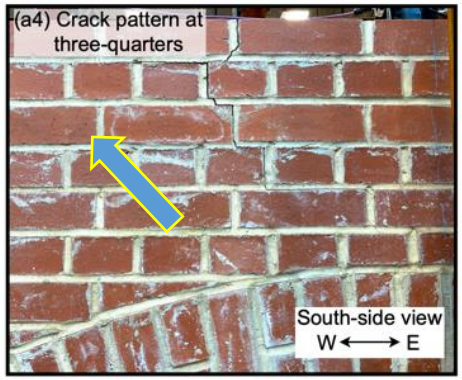


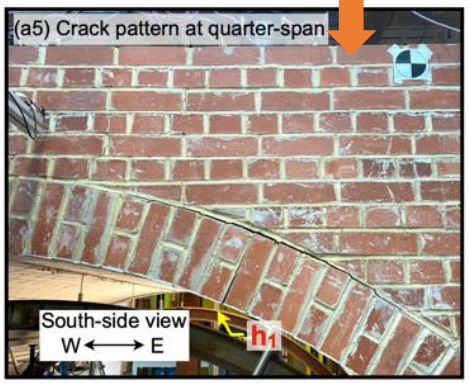


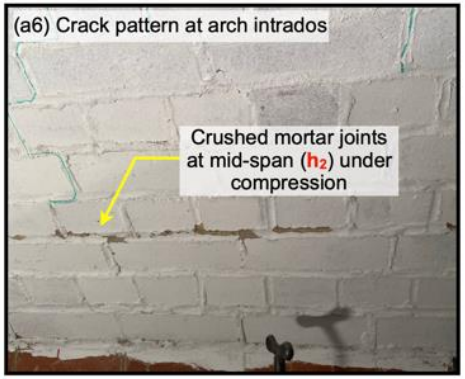


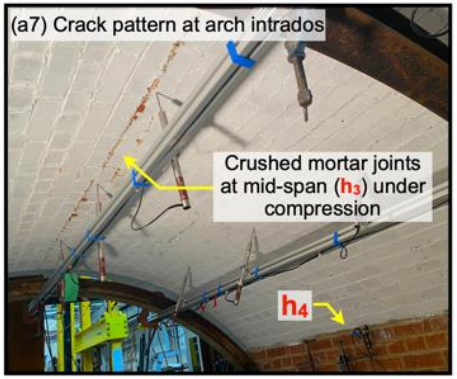








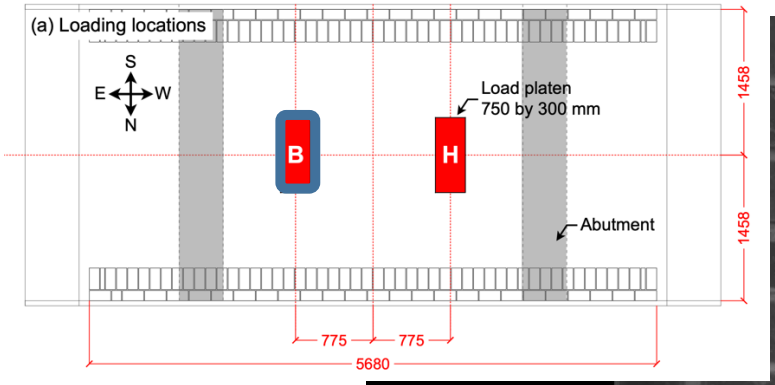




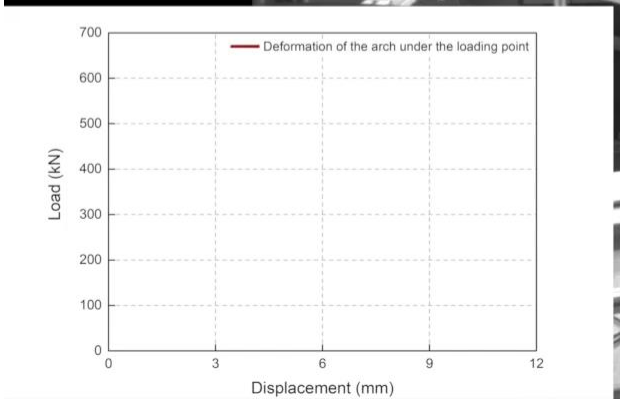
Results: Behaviour of the bridge: video recording

UNIVERSITY OF LEEDS

Application of load



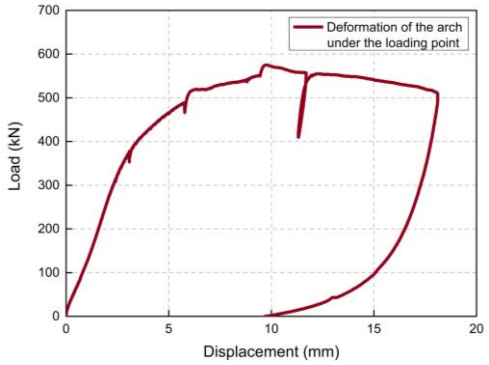
- T22
- 750 by 300 mm platen
- Loading at point B
- South right-hand side wall
- 639kN

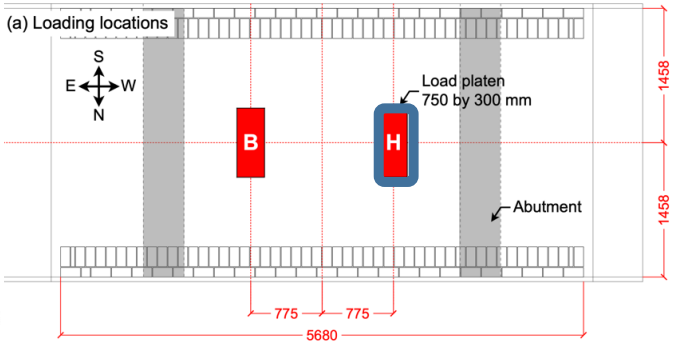


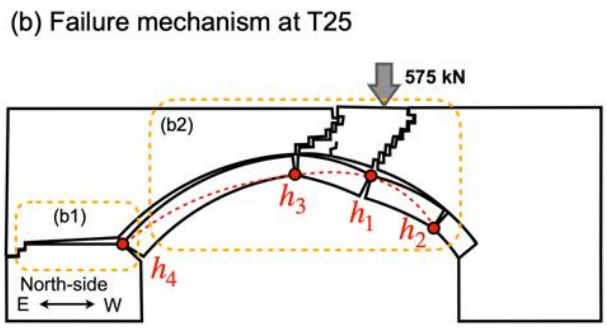
Results: Failure mechanism of the bridge

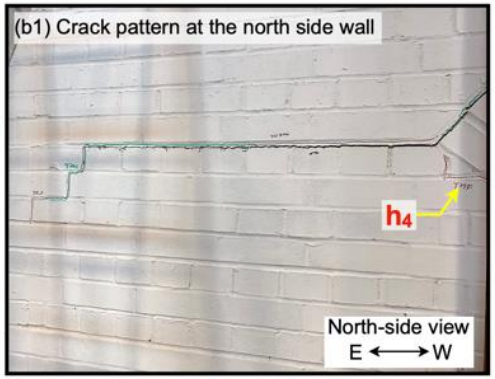
UNIVERSITY OF LEEDS

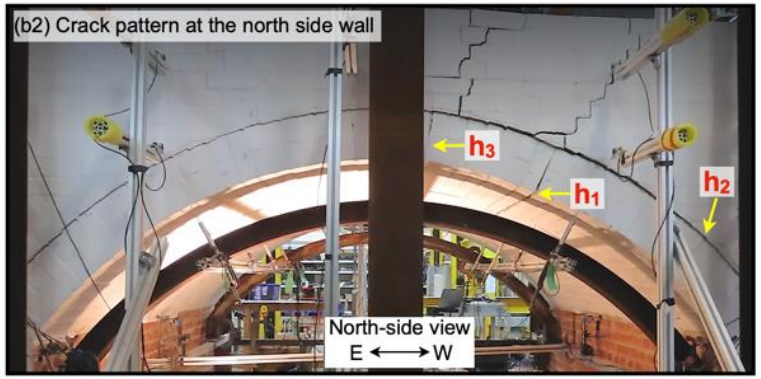
- **Loading location:** Point H
- **Peak load applied**: 575 kN
- **Loading area**: 300 by 750 mm
- **Failure mechanism**: four-hinge behaviour
- Hinge-3 at the mid-span region
- Diagonal crack observed in backfill

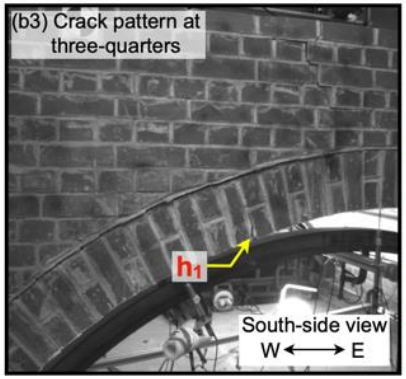


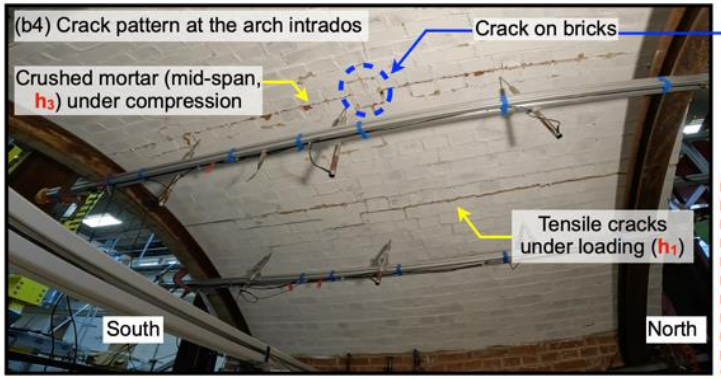


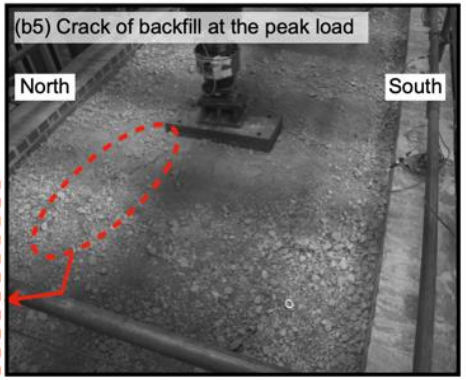










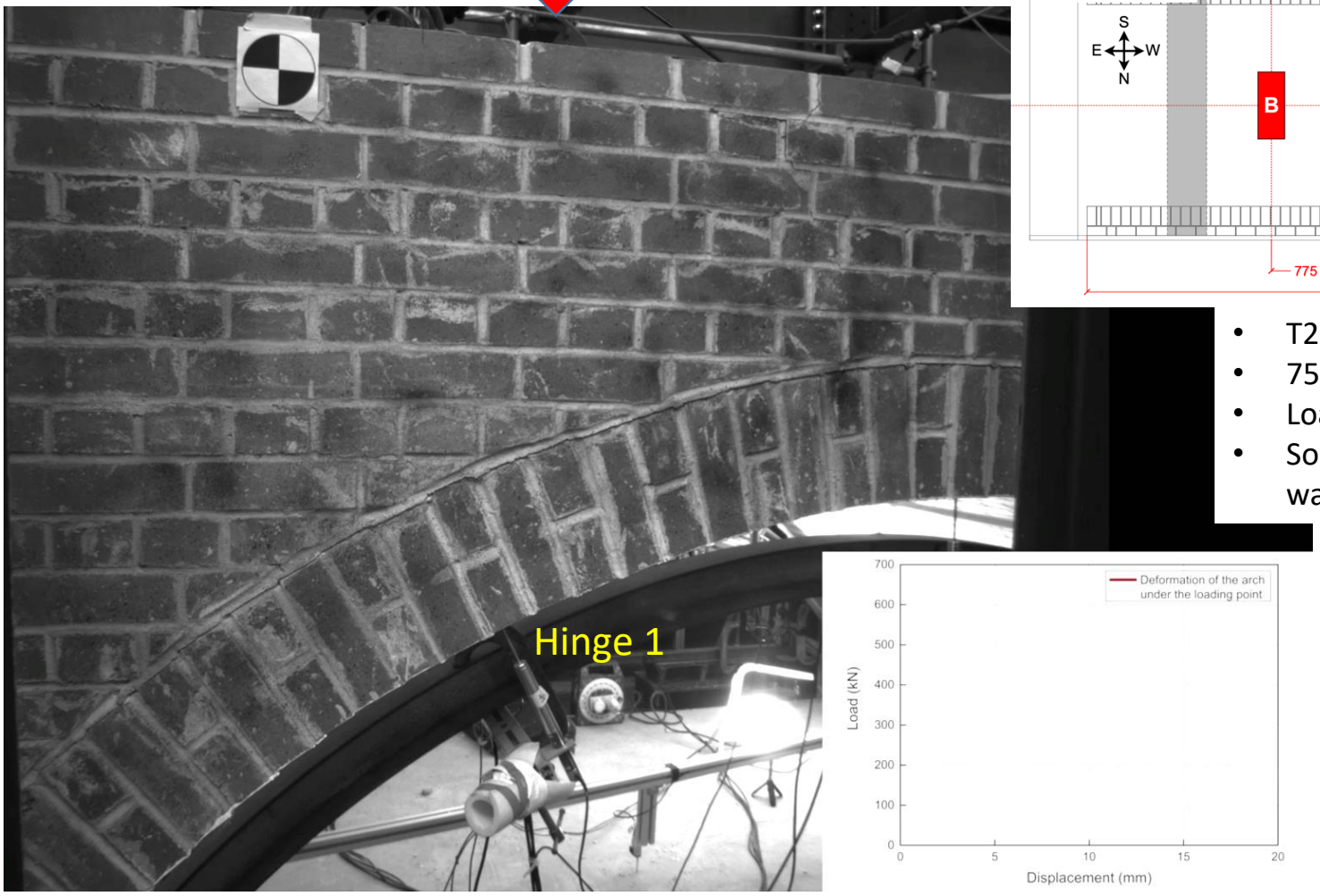


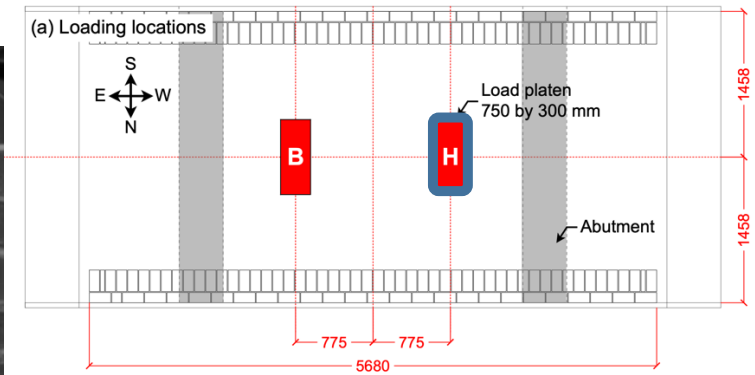

Crushing of mortar

Behaviour of the bridge: video recording

UNIVERSITY OF LEEDS

Application of load

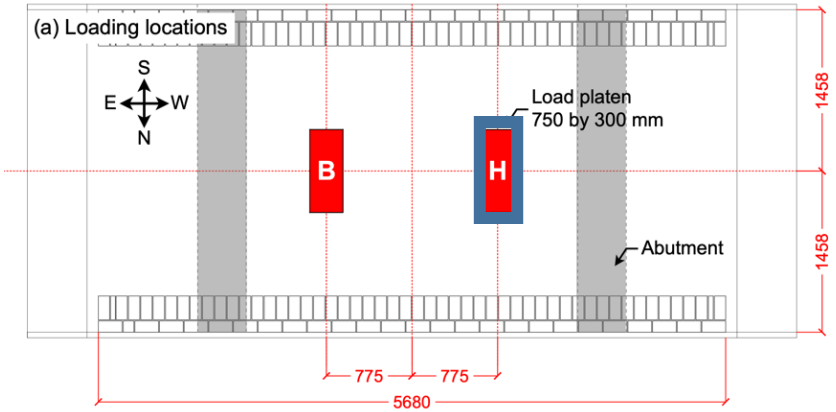




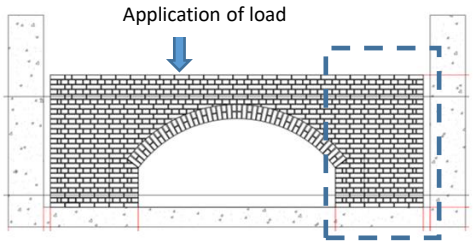
- T25
- 750 by 300 mm platen
- Loading at point H
- South left-side spandrel wall

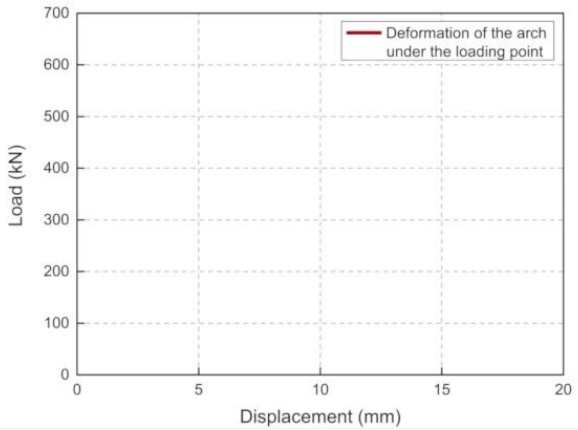
Behaviour of the bridge: video recording

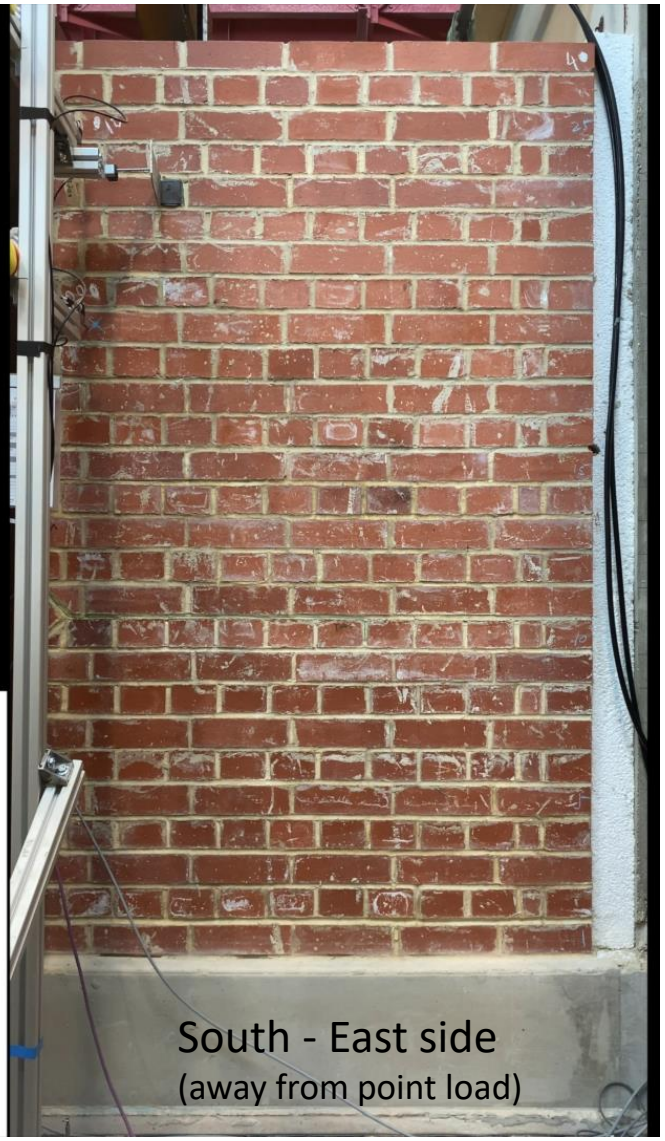
UNIVERSITY OF LEEDS



- T25
- 750 by 300 mm platen
- Loading at point H
- South-right-hand side wall
- 575 kN





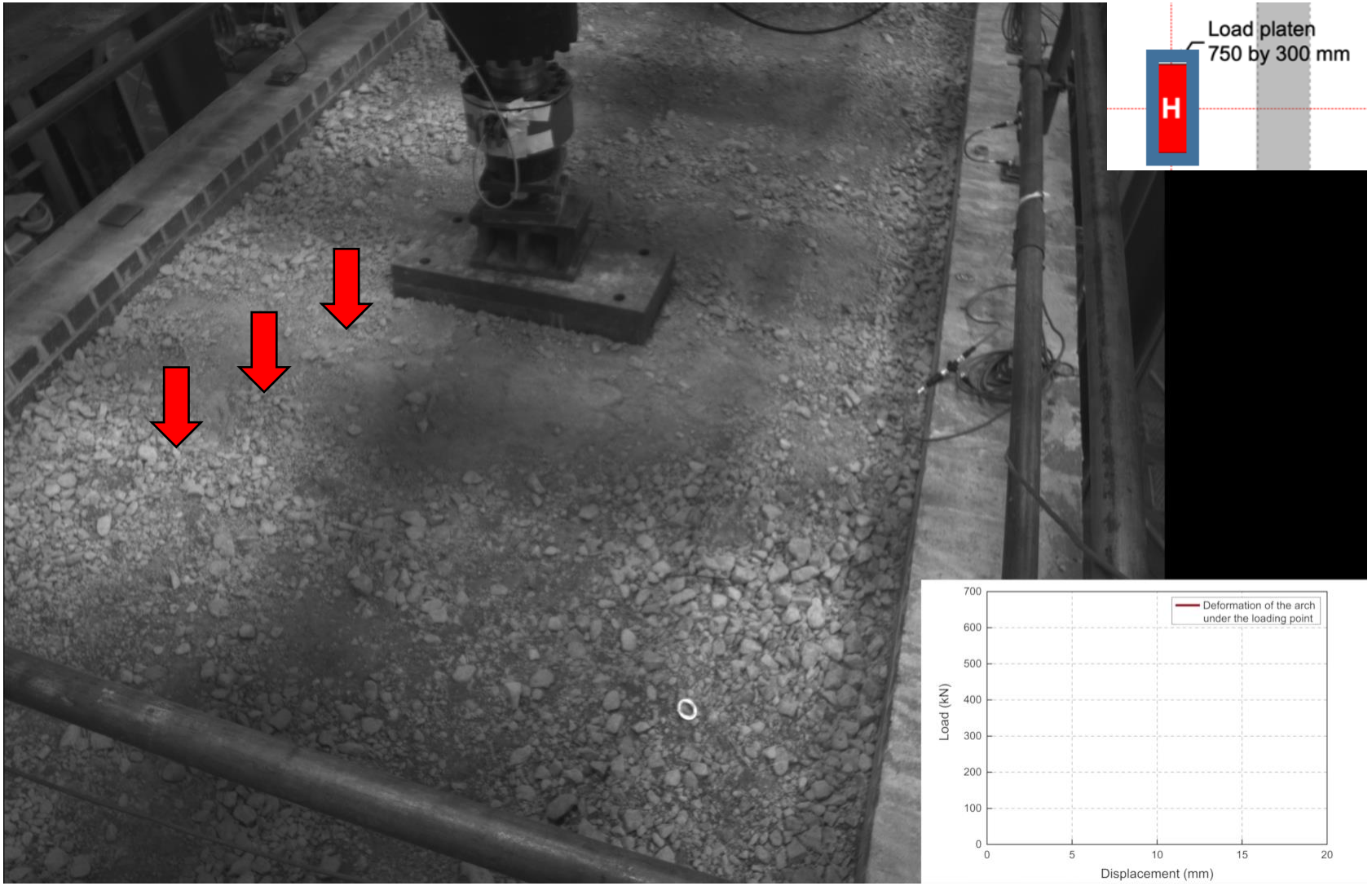


Behaviour of the bridge: video recording

UNIVERSITY OF LEEDS

Shear crack at backfill

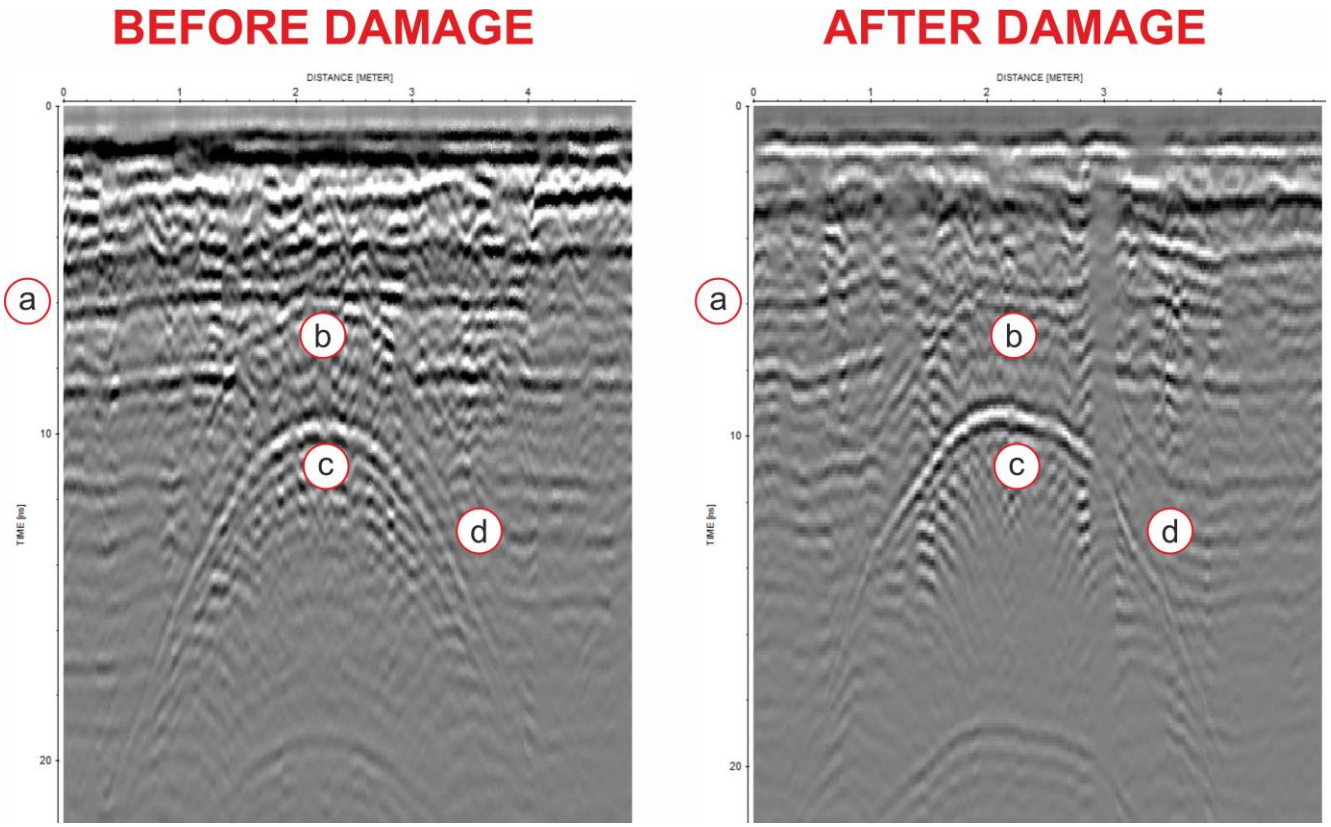
UNIVERSITY OF LEEDS



Cracking of backfill

GPR data

UNIVERSITY OF LEEDS



- Point a: reflections denote disturbance to the internal layering of the bridge
- Point b: change to the layering immediately above the arch
- Point c: arch rather less symmetrical after the damage,
- Point d: deflections particularly prominent in the flanks.

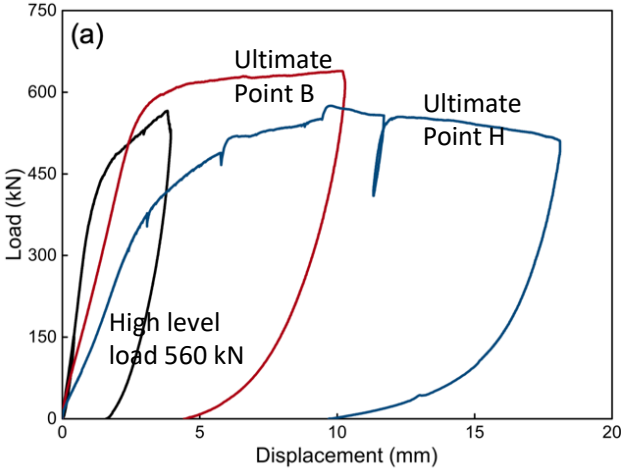
Results: Load-deflection response & stiffness

UNIVERSITY OF LEEDS

Load-deformation response during the high-level and ultimate tests

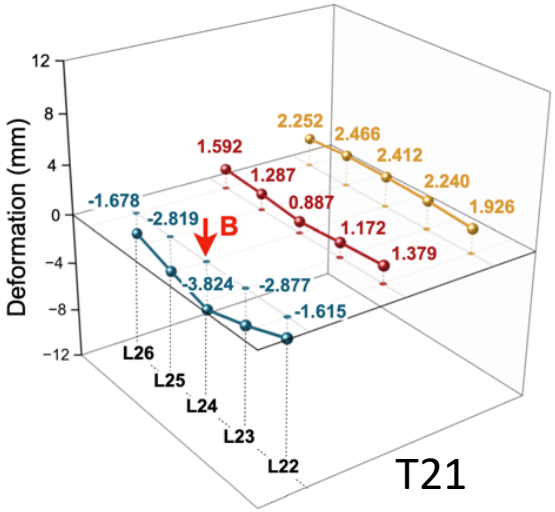
	T21 (high level) (Point B)	T22 (Ultimate 1) (Point B)	T25 (Ultimate 2) (Point H)
Peak load (kN)	535	639	575
Deformation at the peak load (mm)	3.2	10.2	7.4
Stiffness* (kN/mm)	215	195	127

* The values of stiffness were determined by calculating the slope of the load-deflection curve between 10% and 40% of the peak load.

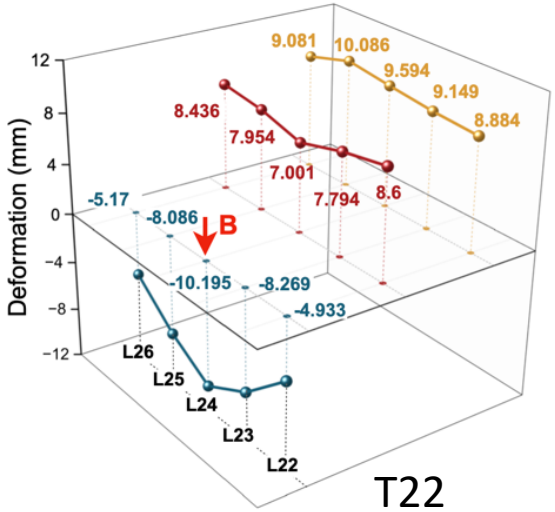


Load-deflection curves

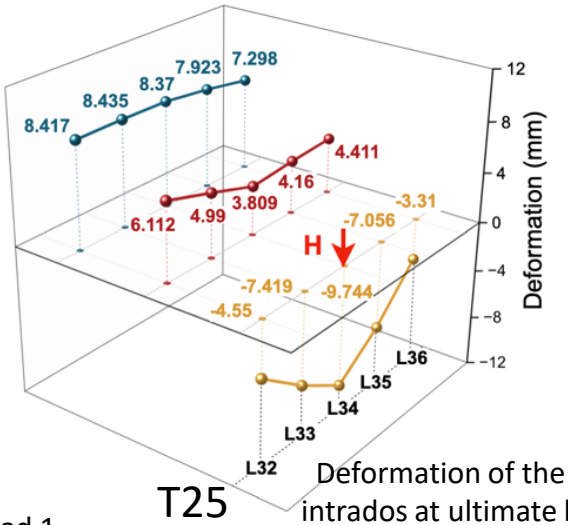
3D response was observed in the arch barrel under patch loading



High level load 560 kN



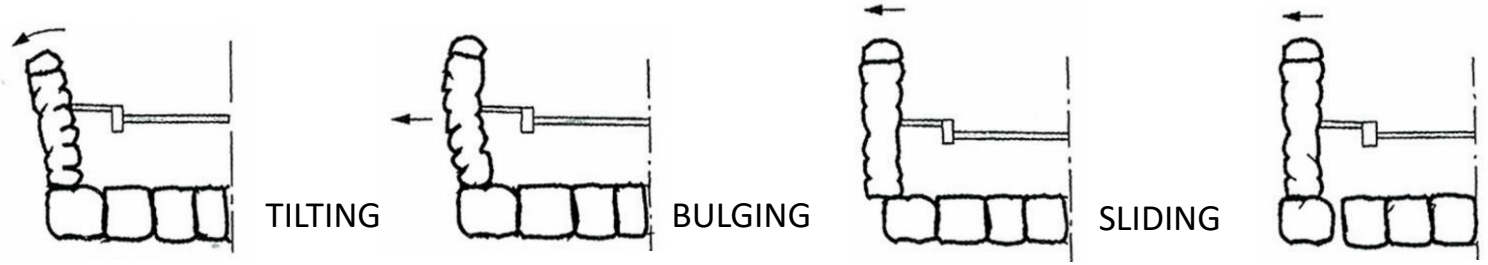
Deformation of the arch intrados at ultimate load 1



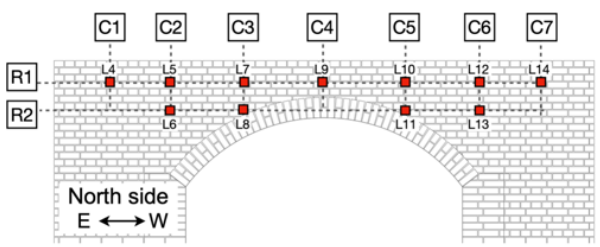
Deformation of the arch intrados at ultimate load 2

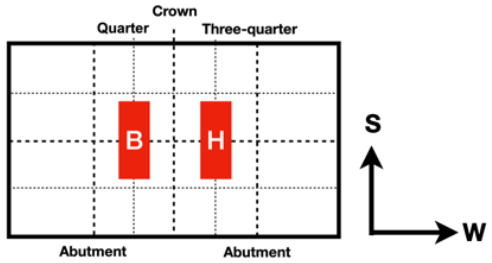
Results: Peak out-of-plane deformation of spandrel walls

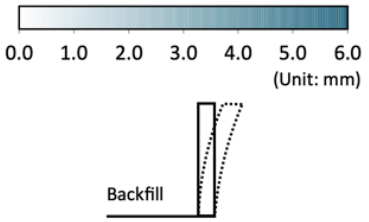
UNIVERSITY OF LEEDS



Learnt L. Spandrel walls - managing the risks. 2012.







(a) High-level test (T21, Location B)

	C1	C2	C3	C4	C5	C6	C7
R1	0.86	0.92	0.63	0.41	0.16	0.21	0.28
R2	-	0.63	0.87	-	0.22	0.2	-

(b) Ultimate test; (T22, Location B)

	C1	C2	C3	C4	C5	C6	C7
R1	2.59	2.34	1.9	1.87	0.54	0.3	0.7
R2	-	1.792	2.63	-	0.43	0.72	-

(c) Ultimate test; (T25, Location H)

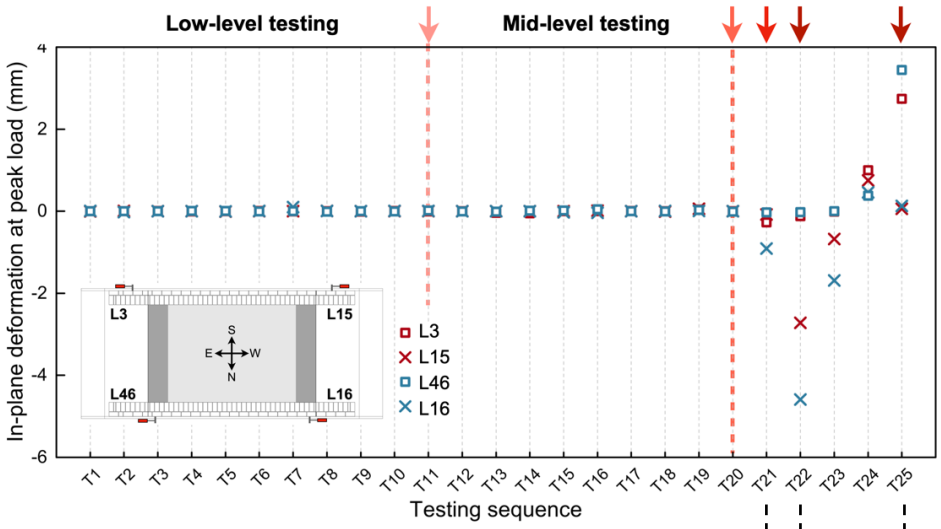
	C1	C2	C3	C4	C5	C6	C7
R1	0.31	0.9	0.8	2.82	5.27	3.95	4.68
R2	-	0.589	1.01	-	4.73	4.81	-

Out-of-plane deformation at the peak load (mm)

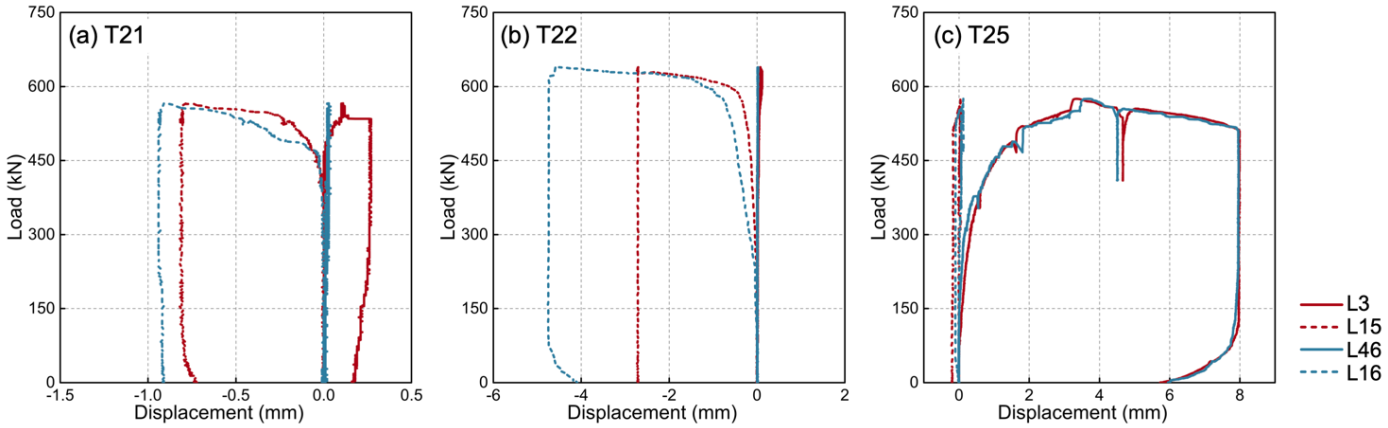
- When the load applied above the span of the arch, the spandrel walls moved outwards
- Failure mechanism: **combined effects of tilting and sliding**.
- The location closest to the loading had the most significant out-of-plane deformation, as it was subjected to the greatest lateral soil pressure under patch loading.
- Maximum out of plane deformation was approx **1 mm for the high level** test, **2.6 mm for the ultimate** 1 and **5.3 mm for the ultimate** 2

Results: In-plane deformation of spandrel walls

UNIVERSITY OF LEEDS



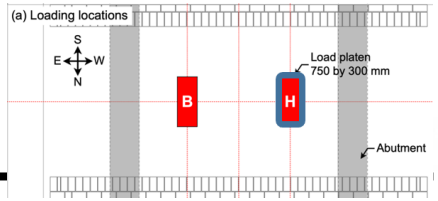
In-plane deformation at the peak load



- Almost no in-plane deformation was observed during the low- and mid-level testing;
- During the high-level and ultimate tests, in-plane deformation of the spandrel walls was observed;
- The deformation occurred away from the loaded side, due to sway of the arch barrel.
- The maximum in-plane deformation was obtained from the ultimate test 2 (T25), measuring 8 mm.

Displacement versus in-plane deformation curves for (a) T21, (b)T22, and (c) T25.

Results: Final crack width (after all tests)



- Damage on the north-side wall was more severe (max crack at hinge 5.46 mm)
- The south-side of wall didn't have any noticeable out-of-plane deformation

Out of plane deformation final

Conclusions

UNIVERSITY OF LEEDS

- A new full-scale testing platform for masonry arch bridges has been developed, incorporating a stiff U-shaped RC test bed.
- A 3m span brickwork arch bridge has been constructed, extensively instrumented and then subjected to a wide range of load tests, culminating in load tests to failure.
- The results obtained from the tests provide a rich dataset that can be used to validate numerical models.
- Specifically, it was found that separation of the spandrel wall and the arch ring before the formation of any visible hinges within the arch ring observed.
- Both fill and spandrel walls contributed to the strength of the bridge.
- Medium and higher magnitude point loads led to 3D modes of response being mobilised, but that when the bridge was loaded to failure, 2D modes of response were observed.
- Even if the bridge reached failure when testing it at quarter span, the bridge could sustain 90% of residual load as evidence when testing it from the opposite ¾ span.
- A future test will involve the application of cyclic loading regimes, to more faithfully replicate real-world traffic loads.

Acknowledgements

UNIVERSITY OF LEEDS

- Prof. Steve Garrity (Leeds University)
- Prof. Kostas Tsavdaridis (City University)
- Dr Dimitris Loverdos (Leeds University)
- Dr Imrose Muhit (Teesside University)
- Dr Anastasios Drougkas (UPC Barcelona)
- Laboratory technicians at Leeds (Ian Day, Mr Kamran, Mr Marvin William, Mr Rob Clarkson)

- Funding from: UKRI Engineering and Physical Sciences Research Council

Questions?