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CONSIGLIO NAZIONALE
DEGLI INGEGNERI

BRIDGE WATCH: ASSESSMENT AND MONITORING OF EXISTING INFRASTRUCTURES

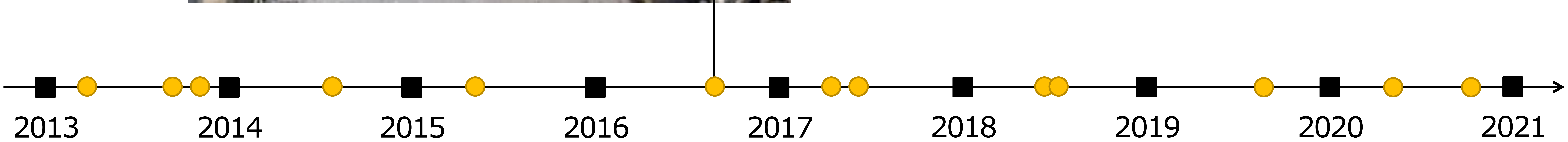
Giulio Zani
Politecnico di Milano
Department of Civil and Environmental Engineering

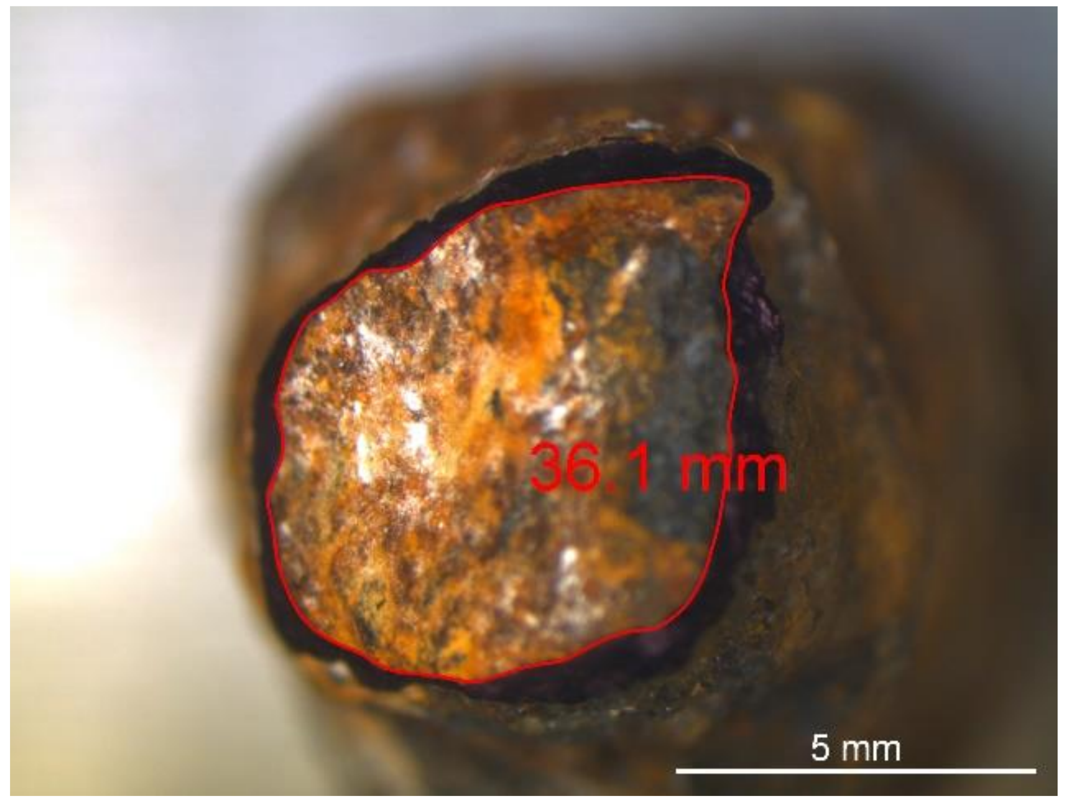
Co-funded by
the European Union

CONTEXT

1 FATALITY

Timeline of recent bridge collapses in Italy





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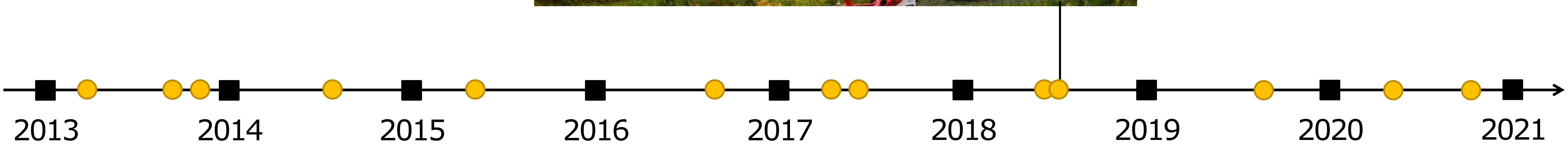
CONTEXT

43 FATALITIES



The majority of recent structural failures have occurred in RC/PC bridges

>50% of the Italian bridges is made of RC/PC

A large share (~80%) of the Italian bridges was build before the 1950s and 1960s

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CONTEXT

Is it just an Italian problem?

W. Phillip Yen, U.S. Department of Transportation - Federal Highway Administration (FHWA)

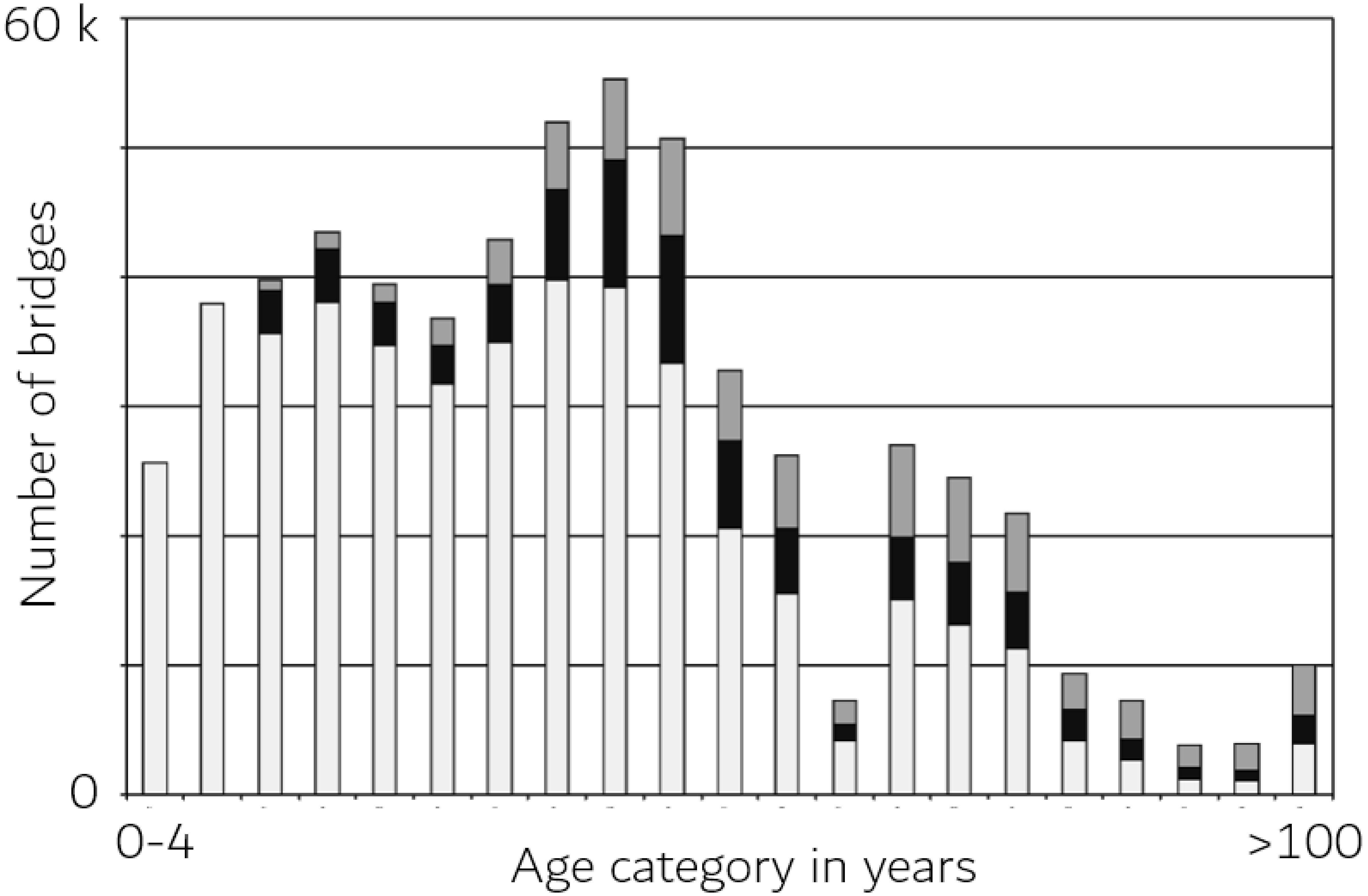
United States of America

>600 k highway bridges, 4.2 M miles of roads
1062 bridge failures (1980-2012)

U.S. highway bridges by age and condition

- No deficiencies
- Functionally obsolete
- Structurally deficient

Nearly **30%** rated as substandard in 2001



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Is it just an Italian problem?

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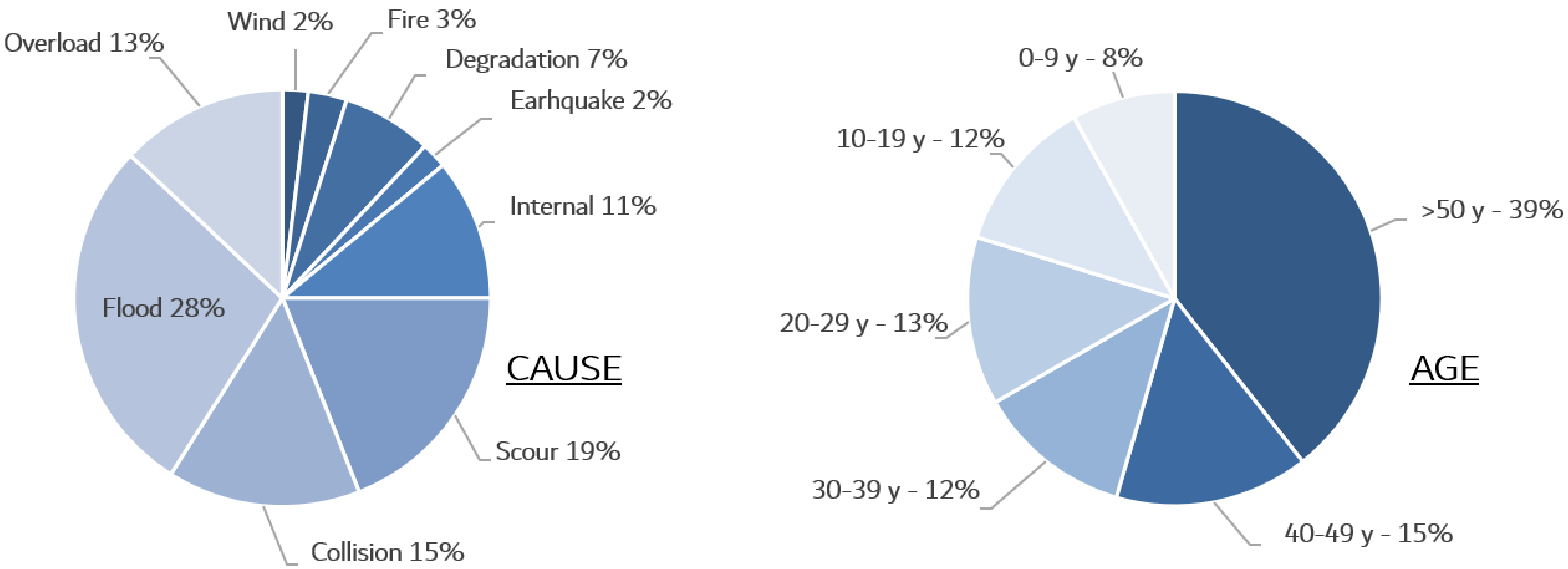

K. Wardhana, F. C. Hadipriono, Analysis of Recent Bridge Failures in the United States, Journal of Performance of Constructed Facilities, 17(3), 2003

Sample of 503 bridges of various types failed in 1989-2000 in the U.S.
~50% of total bridge failures are associated to steel beam/girder and steel truss structures
~10% associated to concrete beam/girder and concrete slab structures

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CONTEXT

Post-failure actions

From original RC/PC structures to steel structures

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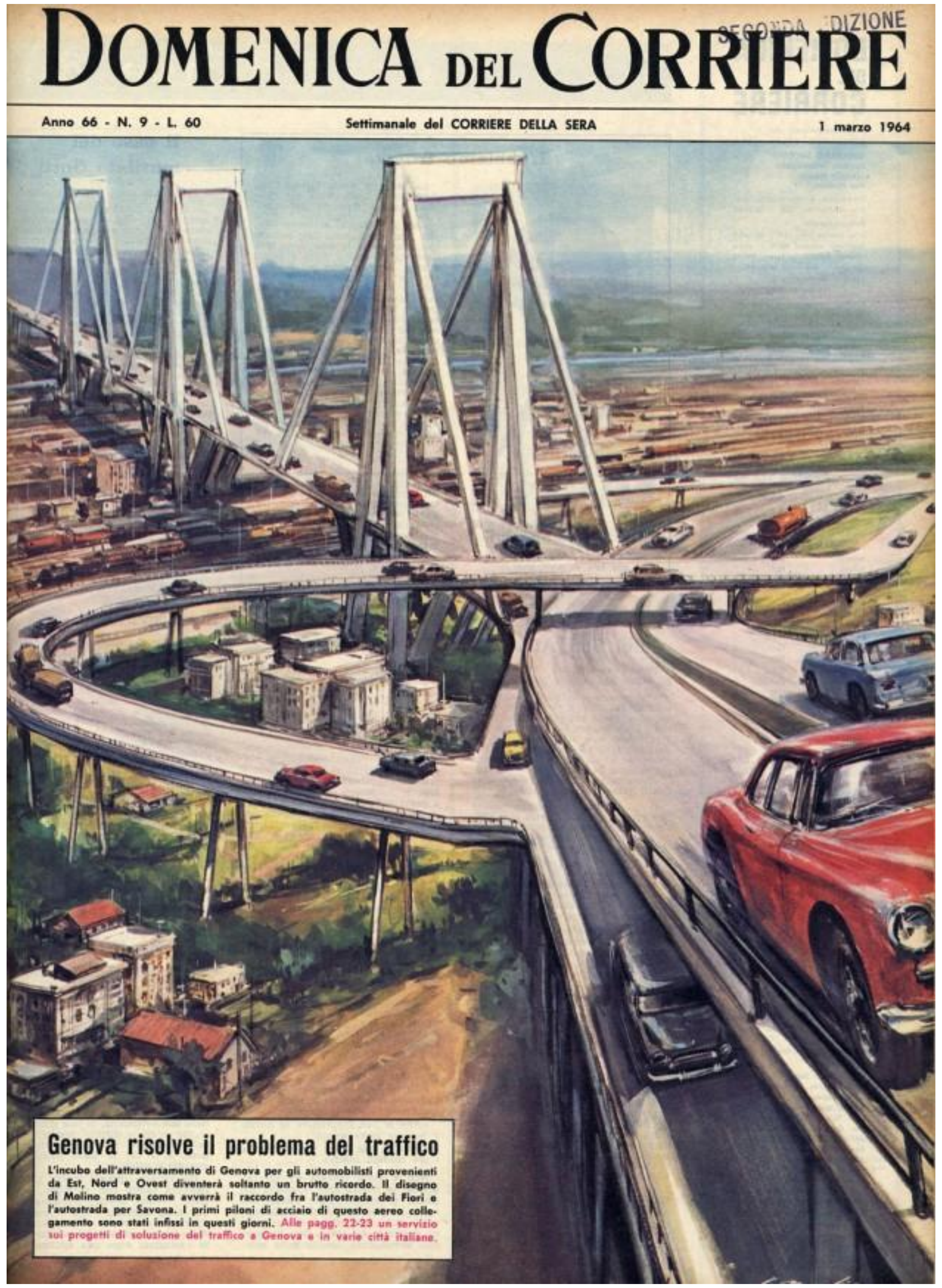
CONTEXT

Viadotto Polcevera (1963-1967), Riccardo Morandi



Demolished in August 2019
Masterpiece of Italian engineering
Pioneer application of PC technology
Significant creep effects and corrosion since the 1970s
Role of the level of knowledge and technology at the time of construction

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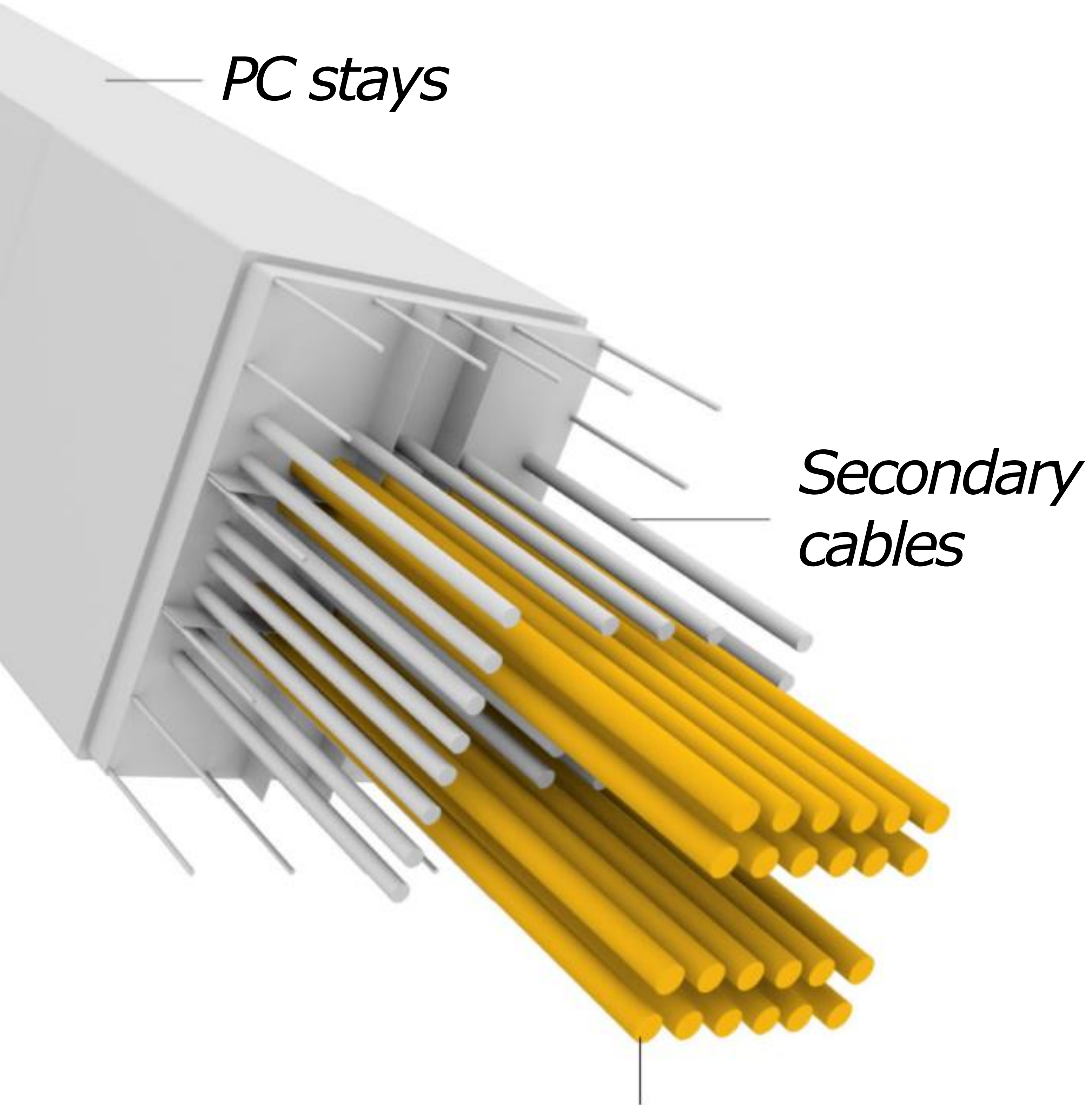
CONTEXT

Viadotto Polcevera (1963-1967), Riccardo Morandi



Corrosion

CARBONATION	**CHLORIDES**
ACID RAIN	**SULFATES**

Initiation parameters

CARBONATION

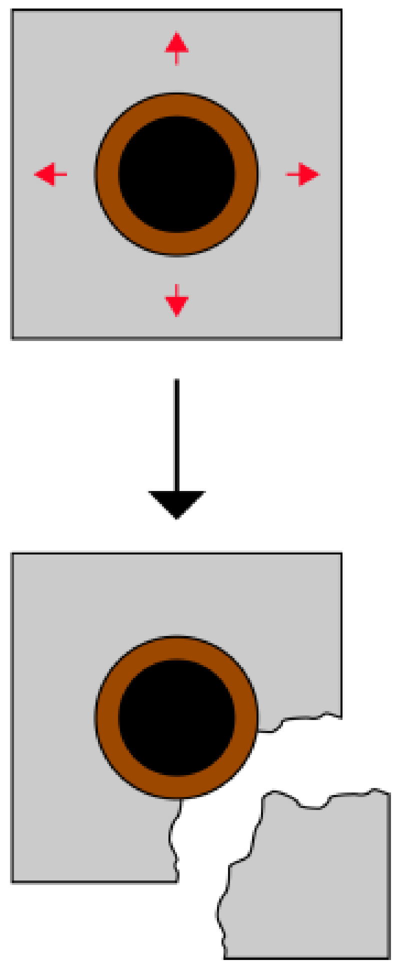
CHLORIDES

↓

DEPASSIVATION

+ MOISTURE

+ OXYGEN



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CONTEXT

Viadotto Polcevera (1963-1967), Riccardo Morandi

R. Morandi, The long-term behaviour of viaducts subjected to heavy traffic and situated in an aggressive environment: The viaduct on the Polcevera in Genoa, IABSE Reports of the Working Commissions, 32 (1979), pp. 170-180

As it is well-known, a reinforced concrete bridge, apart from possible troubles due to specific static deficienses, is subject to a slow deterioration because of :
- the effect of movable loads and of the environmental action, especially on the paving, on the supporting structures, on the joints and on the finishes,
- the chemical and mechanical effects due to the metereological action on the concrete and also on the reinforcement.

From all the above, which is quite well-known, the necessity arises which is felt more and more as the technique and technology for reinforced and prestressed concrete becomes more sophisticated, to keep the structures under careful observation as time goes on, to decide about possible remedial works which, in any case, must be carried out quickly and properly.

On the other hand, the atmospheric aggressiveness is what represents a definitely negative environmental condition for this structure.

We must think about what would have been the maintenance costs if, instead of a structure made entirely of concrete, a steel solution had been adopted or at least if the solution of the stay-cables embedded in a concrete shell under compression, and therefore not subject to cracking, had not been adopted.

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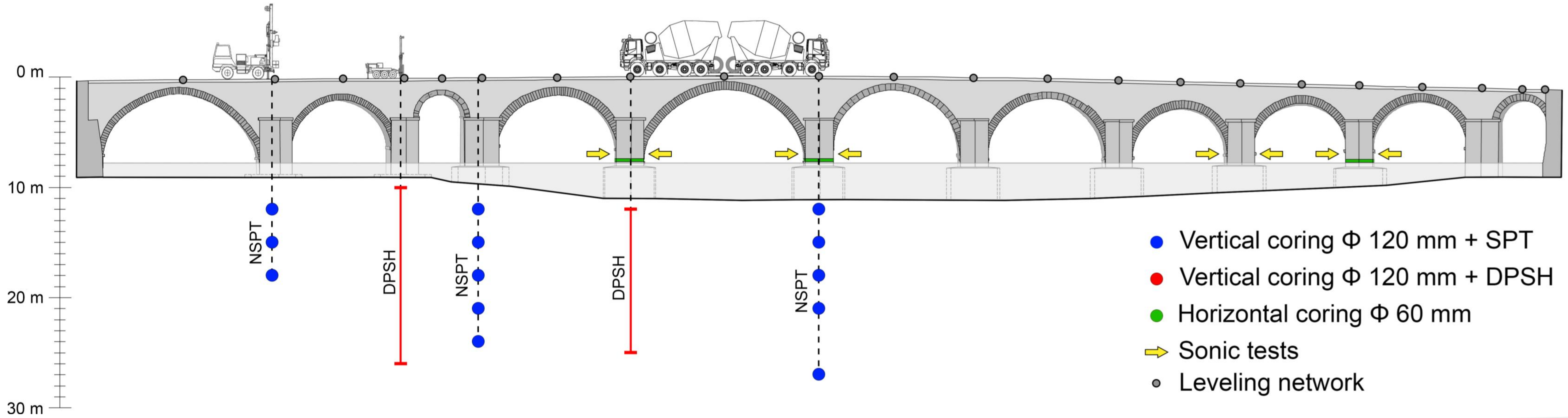
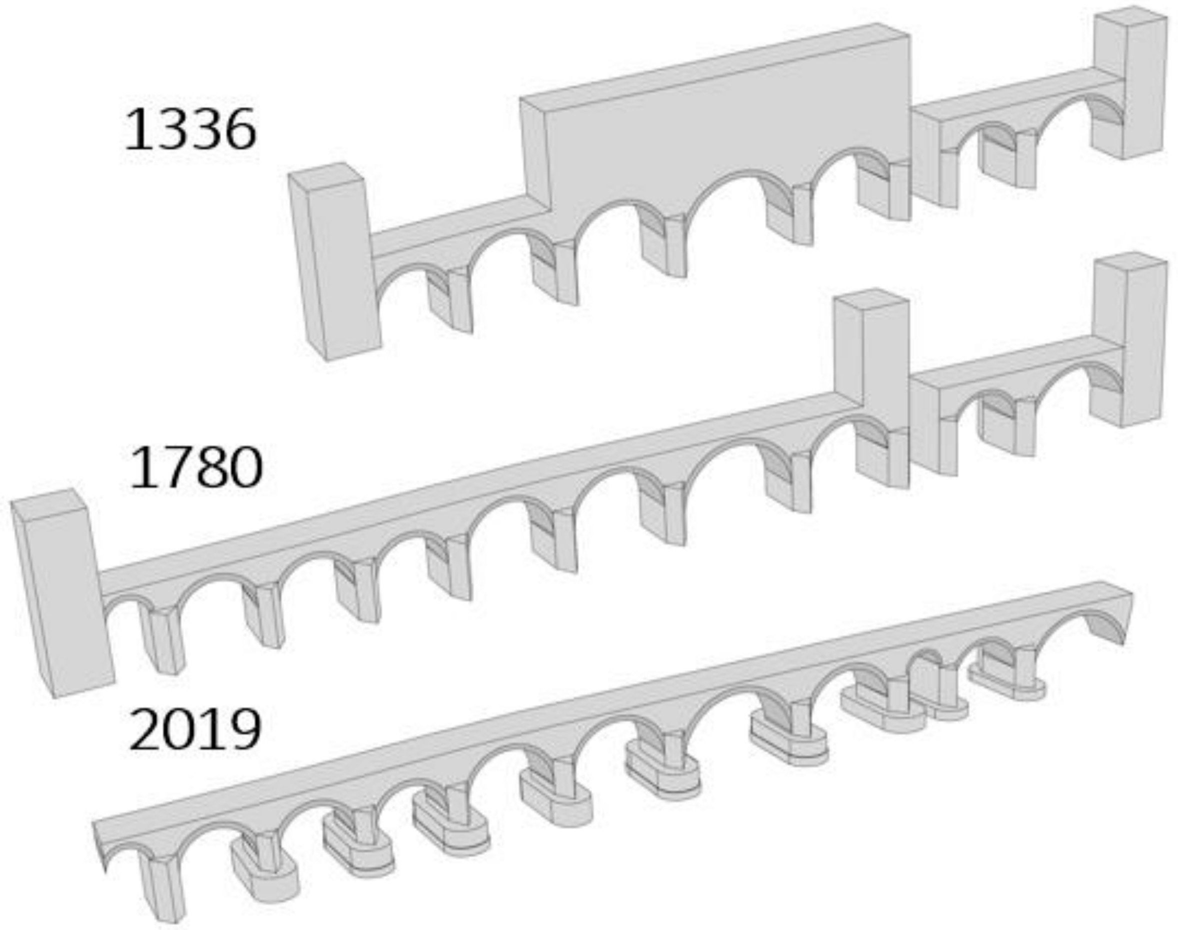
CONTEXT

Ponte Azzone Visconti (1336-1338)





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CONTEXT

Ponte del Risorgimento (1963-1968), Pier Luigi Nervi

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CONTEXT

Ponte sul Basento (1971-1976), Sergio Musmeci

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CONTEXT

2018: agreement on the **definition of criteria and guidelines for the maintenance and management of road infrastructures**

Population: **~10 M** (about 1/6 of the Italian population) Regione Lombardia

Estimated number of strategic bridges: **>10 k**

>20 Professors, Post-Docs and PhD Students POLITECNICO MILANO 1863

Dept of Civil and Environmental Engineering (DICA)
Dept of Architecture, Built Environment and Construction Engineering (DABC)
Dept of Mechanical Engineering (DMEC)
Dept of Management, Economics and Industrial Engineering (DIG)

Sample of ~400 bridges

Management and monitoring guidelines

Classification and intervention priorities

Demo cases

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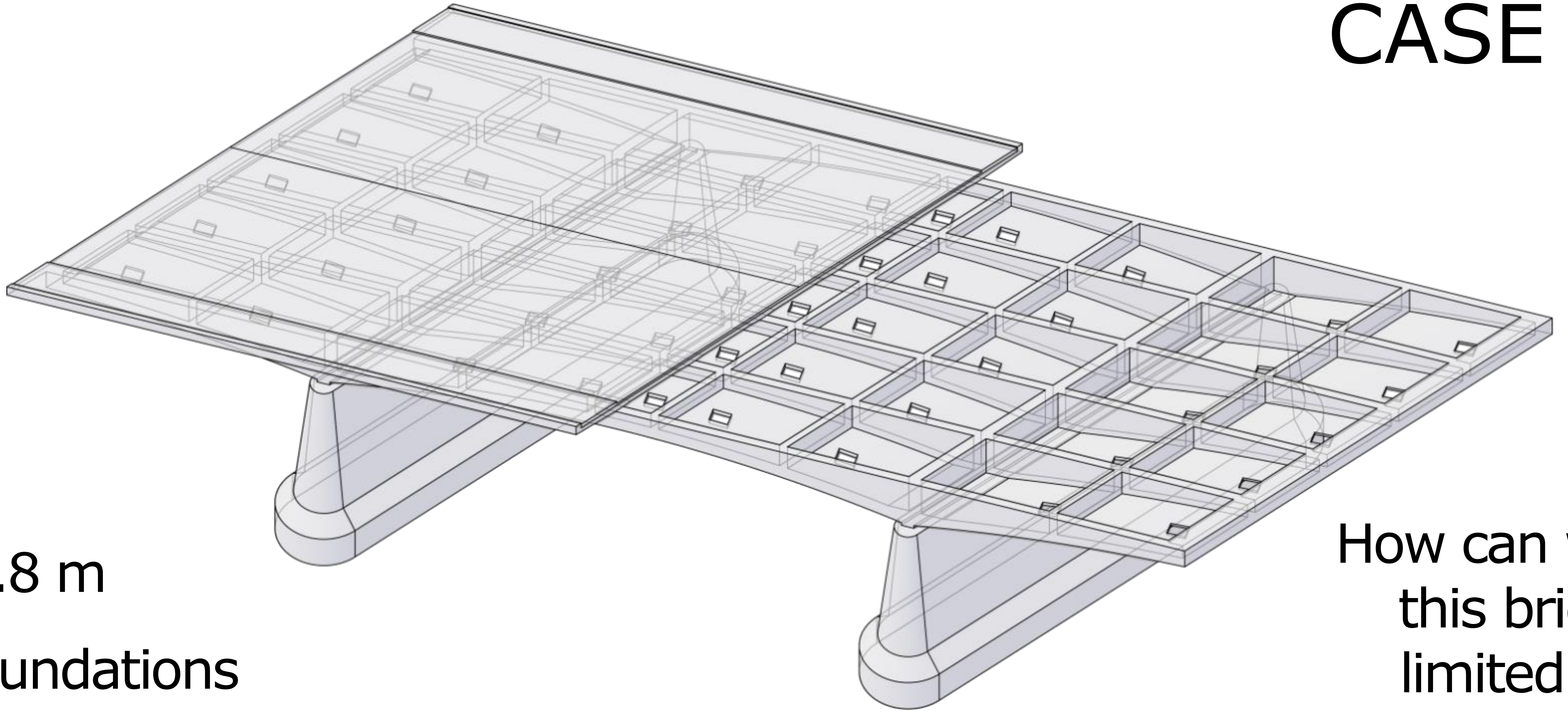
CASE STUDY



Multicellular RC bridge

Built in the 1950s

Total length 42.8 m

3 spans

Variable depth 1.4 - 2.8 m

2 piers on deep pile foundations

How can we monitor this bridge on a limited budget?

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METHODOLOGY

1.0 Archival Research & Documentation

2.0 Inspection and Condition Survey

3.0 Design and installation of a monitoring system

4.0 Load testing and validation

5.0 Observation

6.0 Modelling

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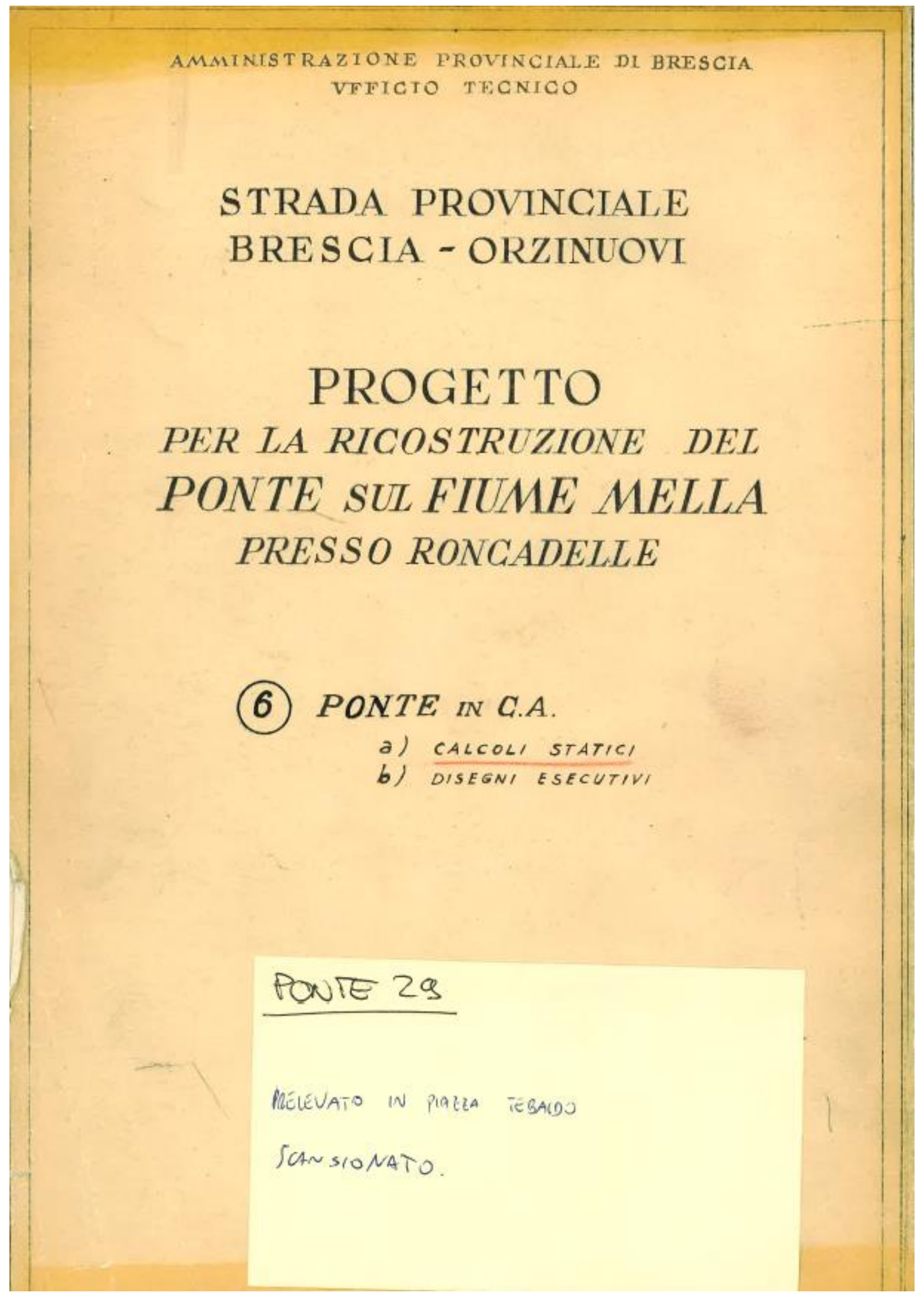
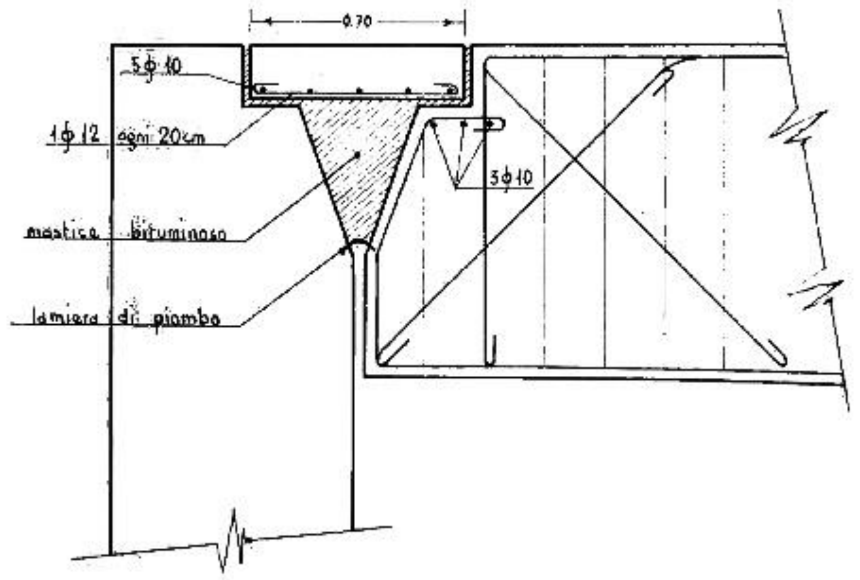
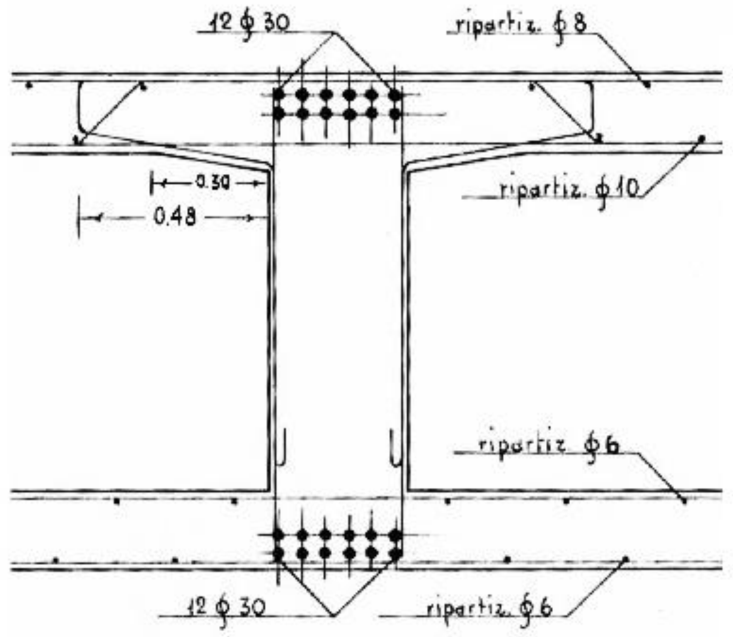
PROJECT PHASE

1.0 Archival Research & Documentation

- Original design report ✓
- Original technical drawings ✓
- Photos ✓
- Inspection report ✓
- Last inspection ≤ 10 years ✓







<table>
<tr><th rowspan="2"></th><th rowspan="2">Design reports</th><th rowspan="2">Technical drawings</th><th rowspan="2">Photos</th><th rowspan="2">Inspection reports</th><th colspan="2">Date of the last inspection</th><th rowspan="2">Bridges per case</th><th rowspan="2">Bridges per level of completeness</th></tr>
<tr><th>≤ 10 y</th><th>> 10 y</th></tr>
<tr><td rowspan="3">LC-I</td><td>✓</td><td>✓</td><td></td><td></td><td>✓</td><td></td><td>48</td><td rowspan="3">67 (23.2%)</td></tr>
<tr><td>✓</td><td>✗</td><td></td><td></td><td>✓</td><td></td><td>5</td></tr>
<tr><td>✗</td><td>✓</td><td></td><td></td><td>✓</td><td></td><td>14</td></tr>
<tr><td rowspan="5">LC-II</td><td>✓</td><td>✓</td><td></td><td></td><td></td><td>✓</td><td>12</td><td rowspan="5">162 (56%)</td></tr>
<tr><td>✓</td><td>✗</td><td></td><td></td><td></td><td>✓</td><td>2</td></tr>
<tr><td>✗</td><td>✓</td><td></td><td></td><td></td><td>✓</td><td>13</td></tr>
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<tr><td>✗</td><td>✗</td><td>✗</td><td>✓</td><td colspan="2">✓</td><td>20</td></tr>
<tr><td rowspan="2">LC-III</td><td>✗</td><td>✗</td><td></td><td>✗</td><td></td><td>✓</td><td>13</td><td rowspan="2">60 (20.8%)</td></tr>
<tr><td>✗</td><td>✗</td><td></td><td>✗</td><td colspan="2">✗</td><td>47</td></tr>
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Levels of completeness (sample of 289 RL bridges)

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PROJECT PHASE

2.0 Inspection and Condition Survey

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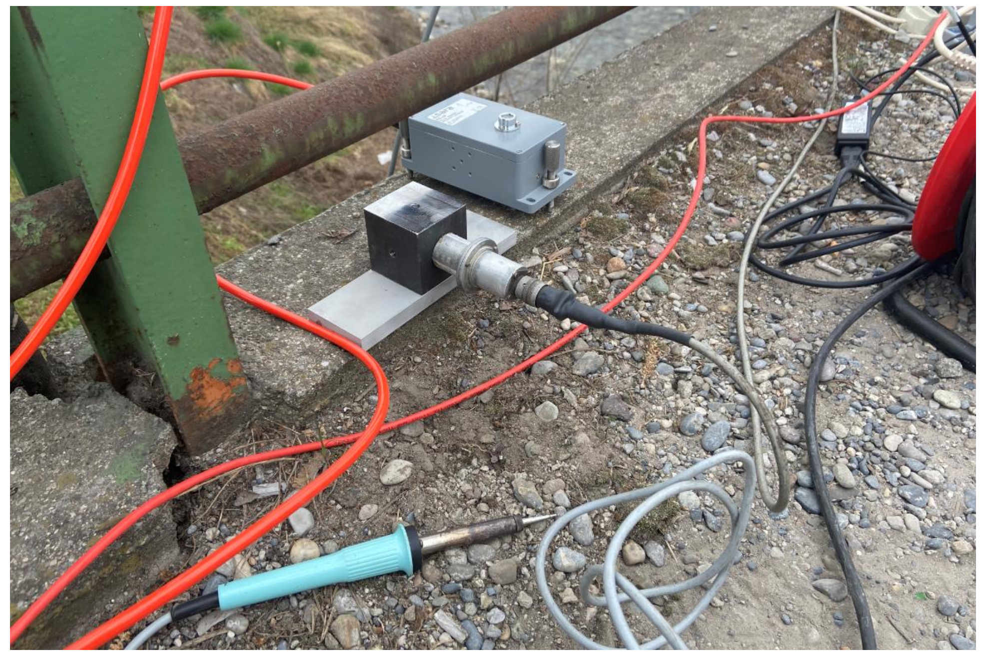
PROJECT PHASE

2.0 Inspection and Condition Survey

- Laser scanner survey
- Photogrammetric survey
- Ambient vibration test (AVT)
- Concrete coring (UPV, carbonation, uniaxial compression tests)
- Carbon tests (right bank pier)
- Radar scans (piers and deck)
- Direct sonic pulse velocity tests (SPV, piers)
- Indirect ultra-sonic pulse velocity tests (deck)
- Rebound hammer tests
- Measurement of exposed rebars



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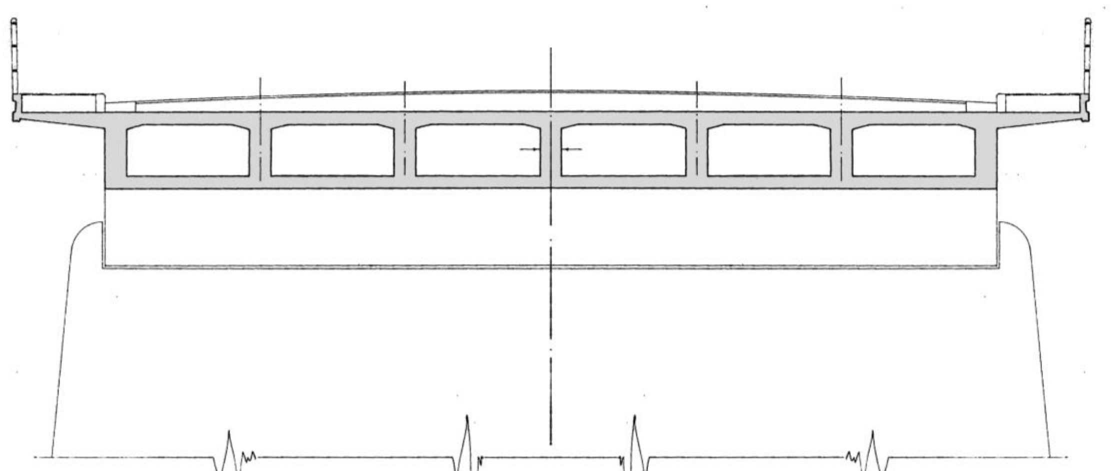
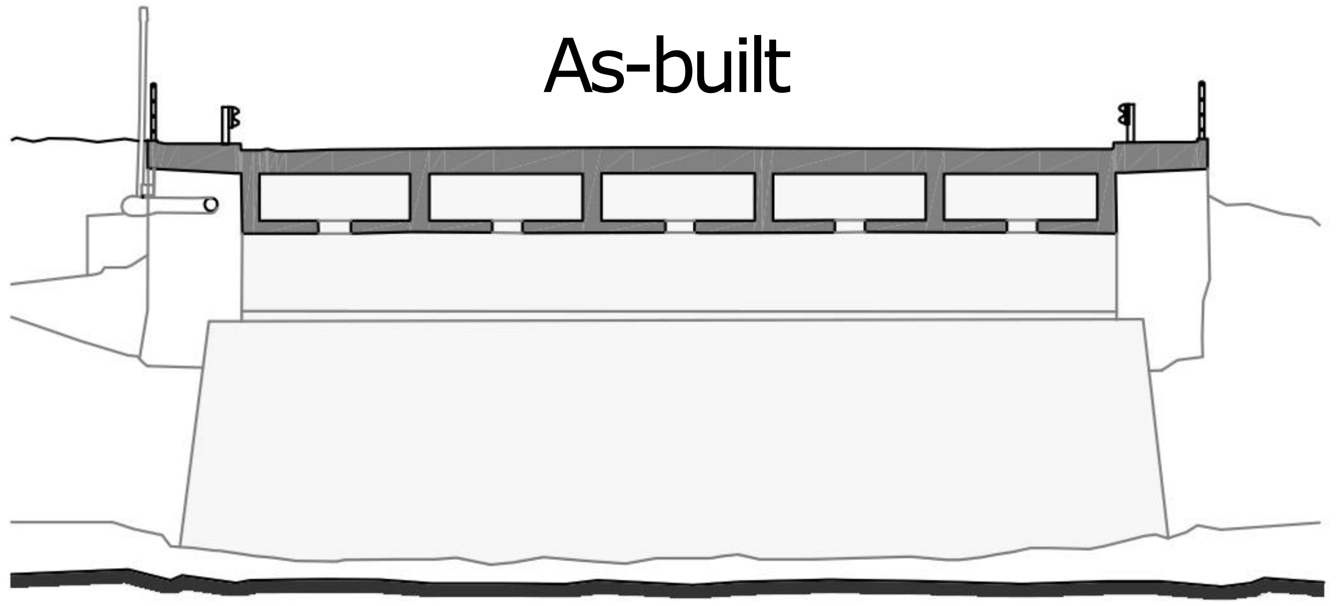
PROJECT PHASE

2.0 Inspection and Condition Survey

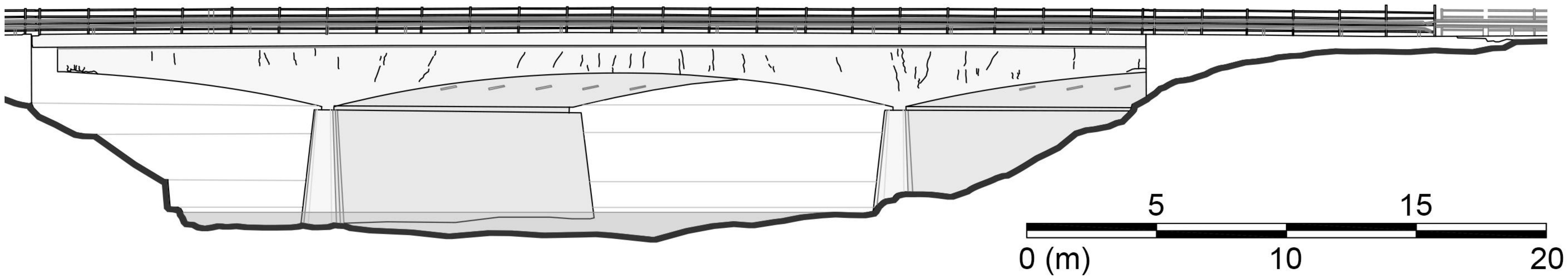
Original



As-built

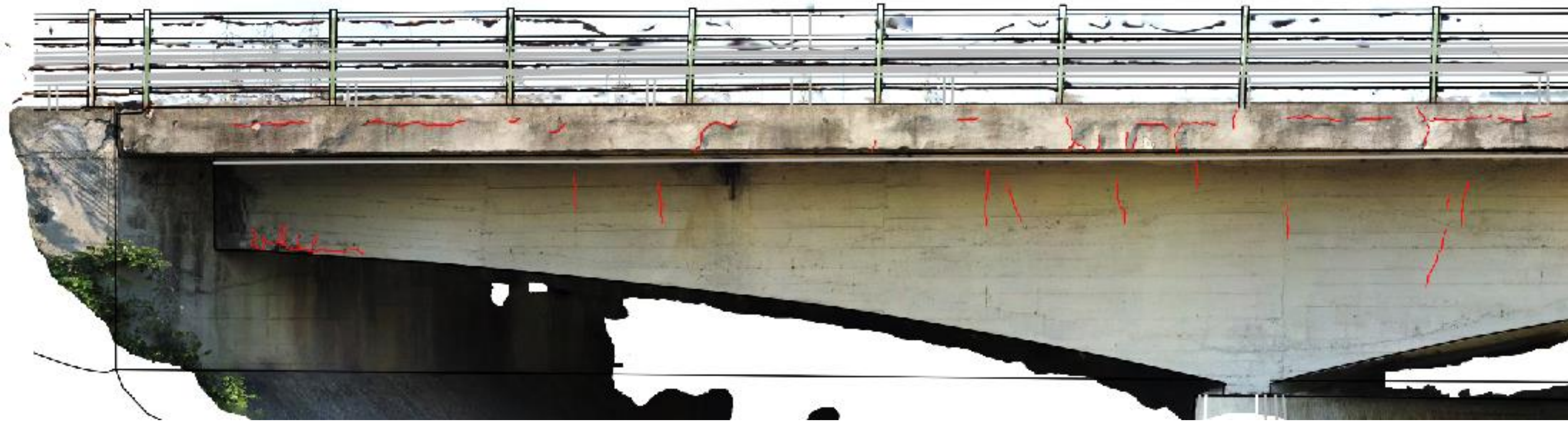


3D laser scanner



5 TRANSVERSE CELLS, NOT 6!

Reconstruction of the cracking pattern



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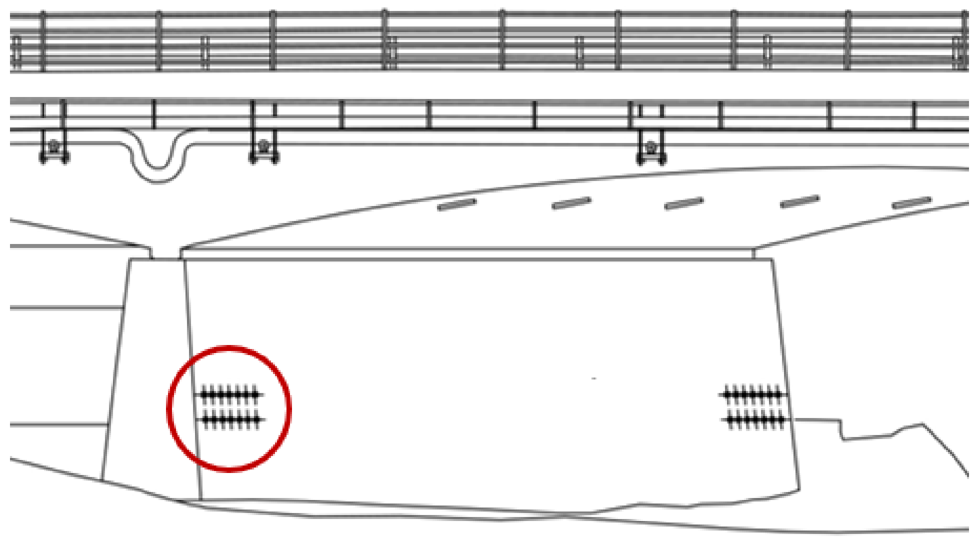
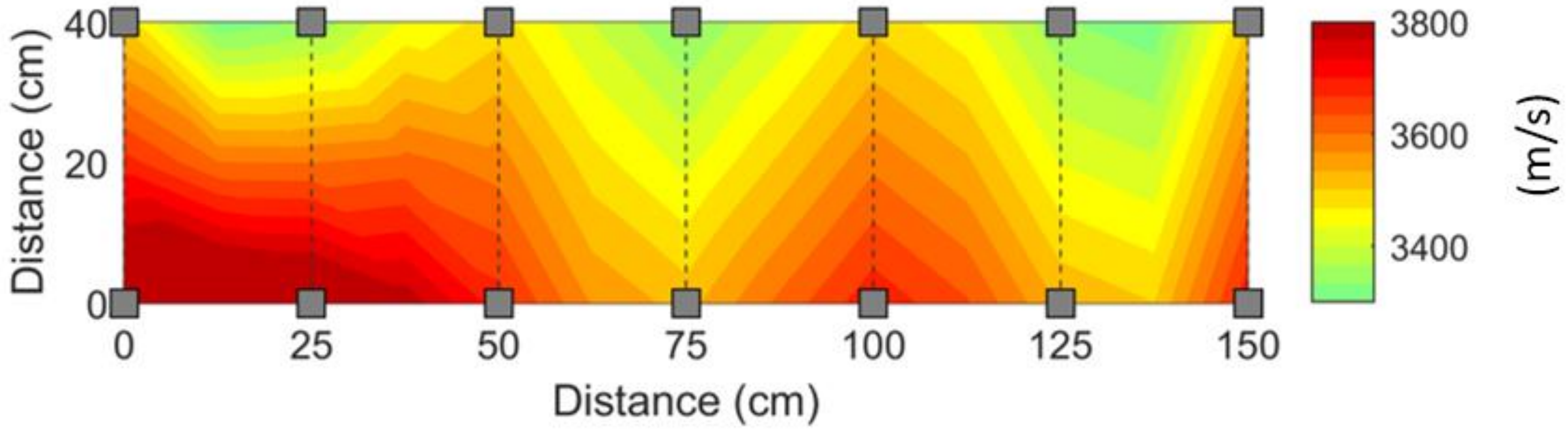
Mechanical characterization of concrete

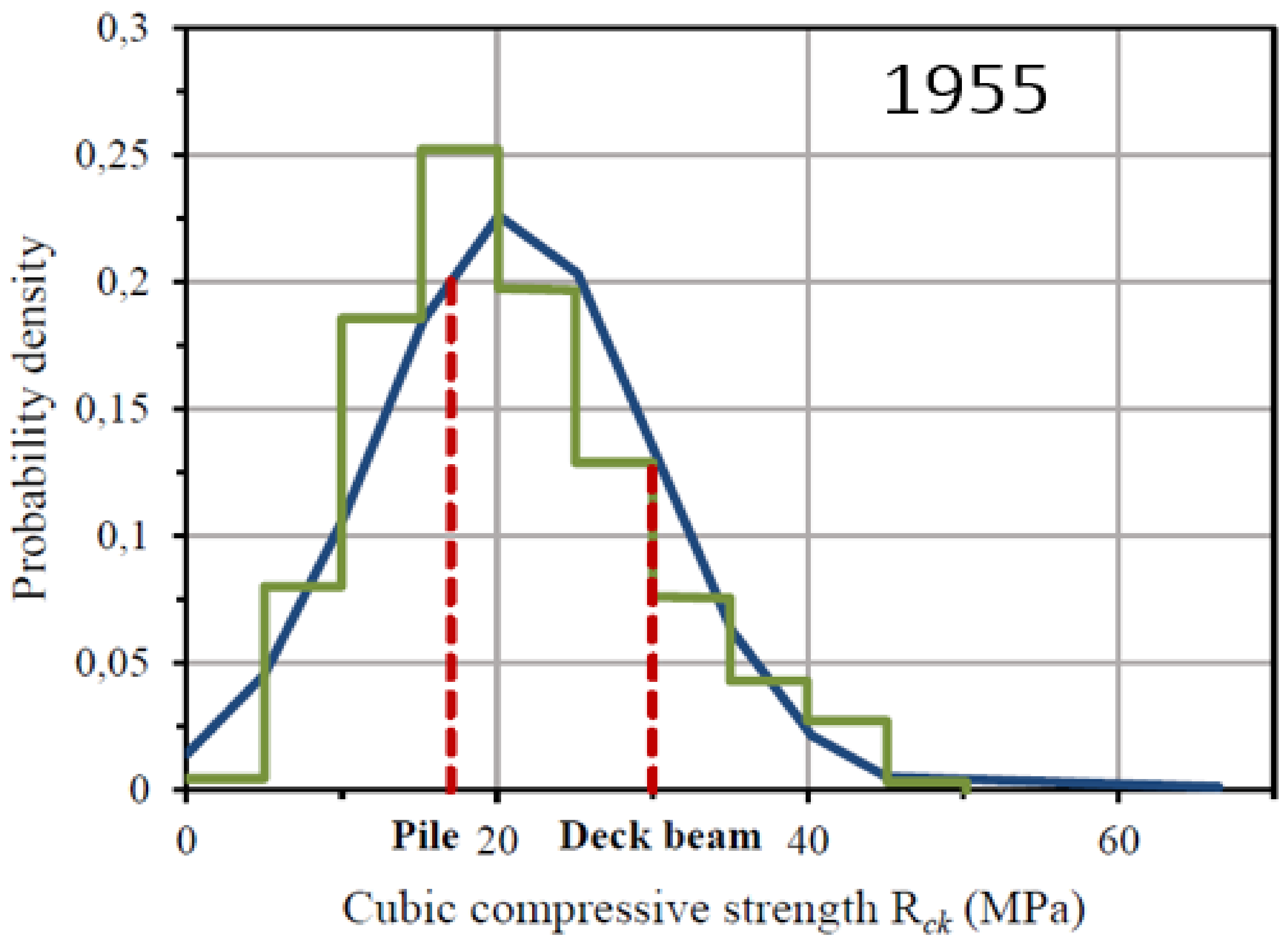
Concrete coring (UPV, carbonation, UCT); Carbon tests (right bank pier);
Direct sonic pulse velocity tests; *SonReb* approach



Specimen	UPV	Carbonation
	v_{avg} (m/s)	Depth (mm)
B1A	4088.0	60
B1B	4162.4	
B2A	3683.2	40
B2B	4323.6	
B3	4455.0	35



Element	$f_{cm}(t)$ (MPa)	f_{cm} (MPa)
Pier	21.4	14.8
Deck	37.1	25.7
	70 years	28 days



Fantilli, A.P., Chiaia, B., Ferraro, E. (2018). La resistenza dei calcestruzzi dei ponti storici in cemento armato (in Italian), in Ingenio Magazine n.67.

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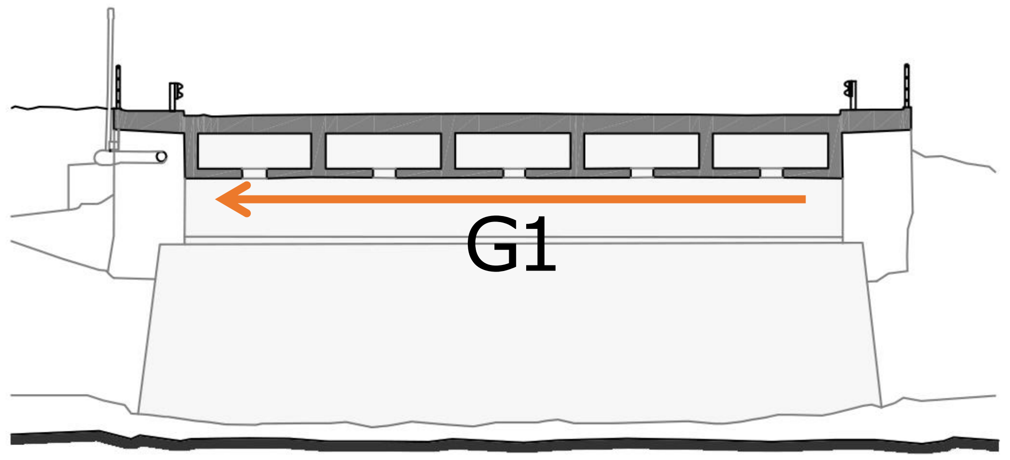
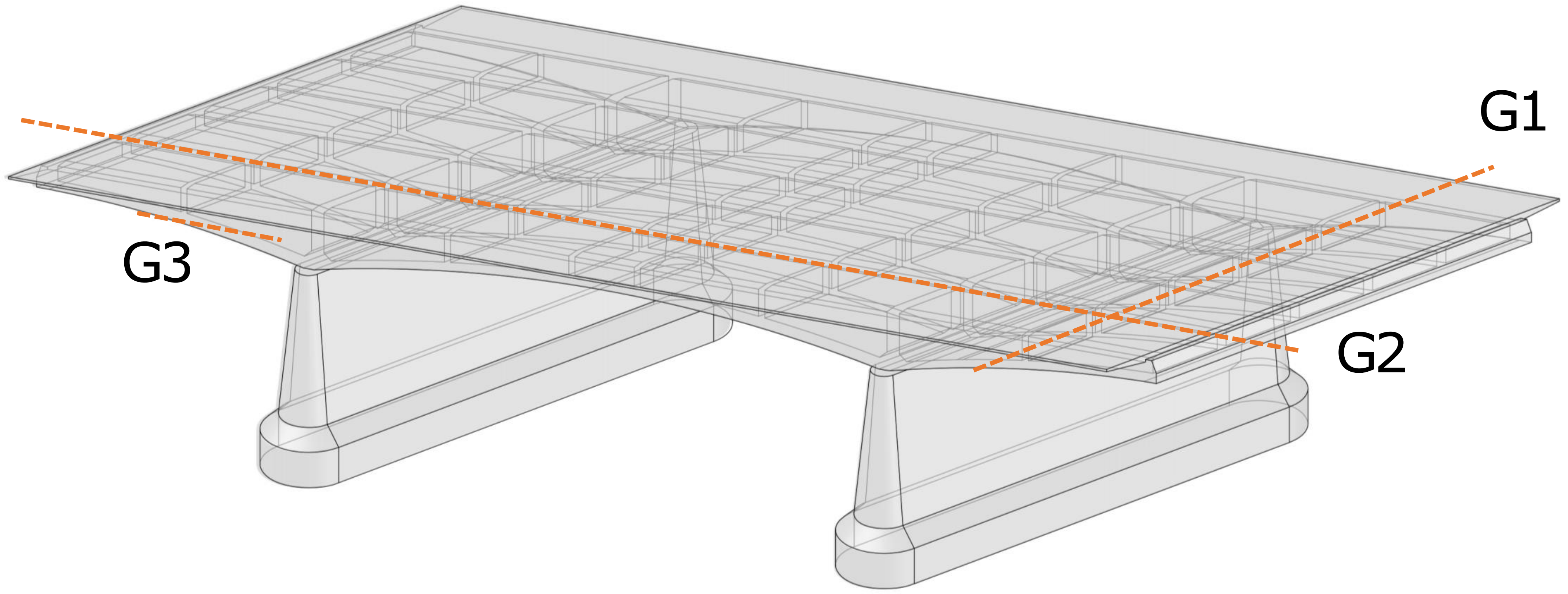
PROJECT PHASE

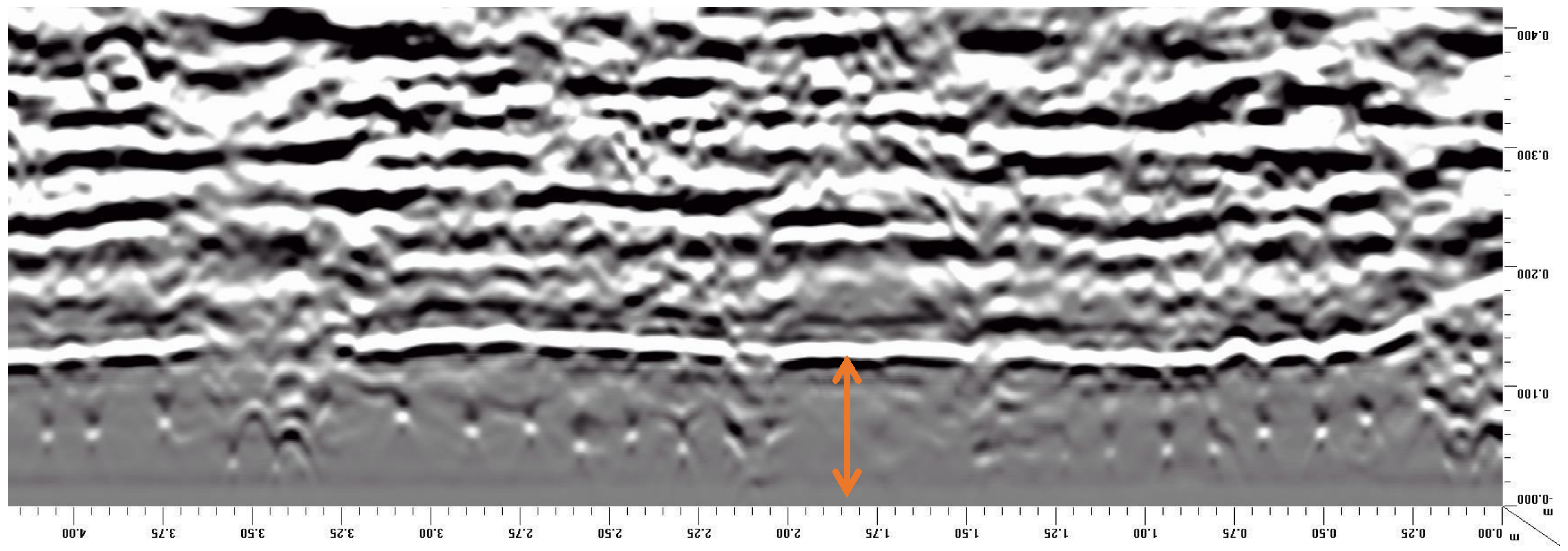
2.0 Inspection and Condition Survey

Radar scans

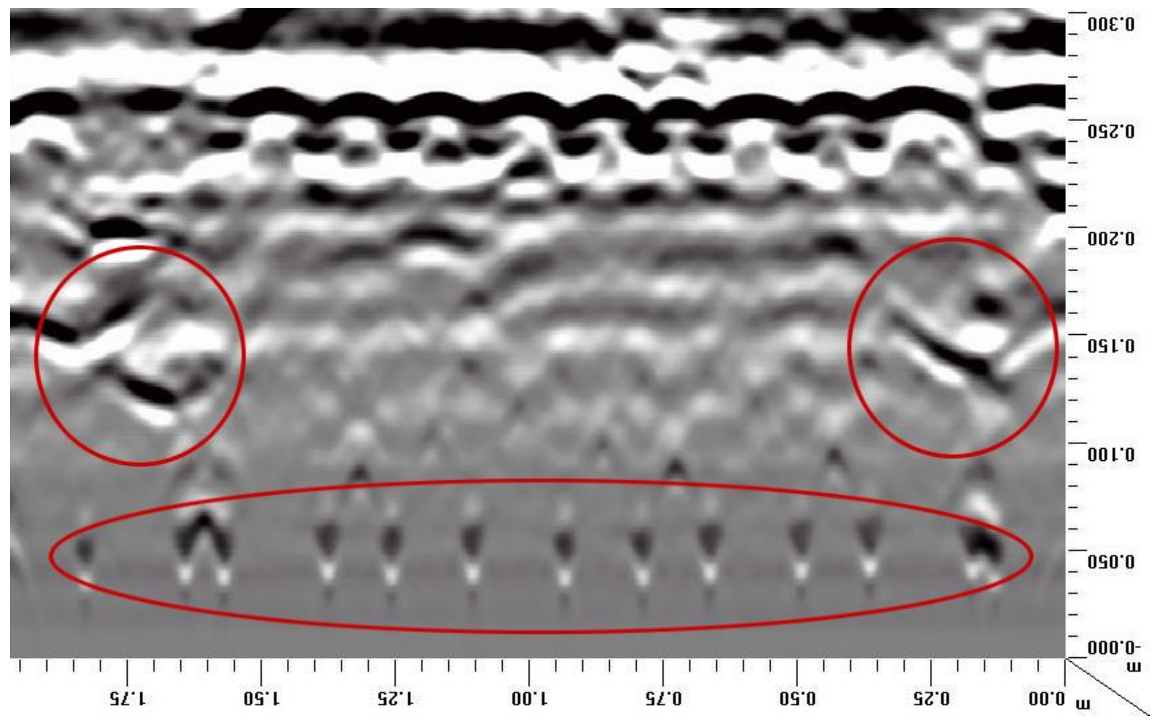




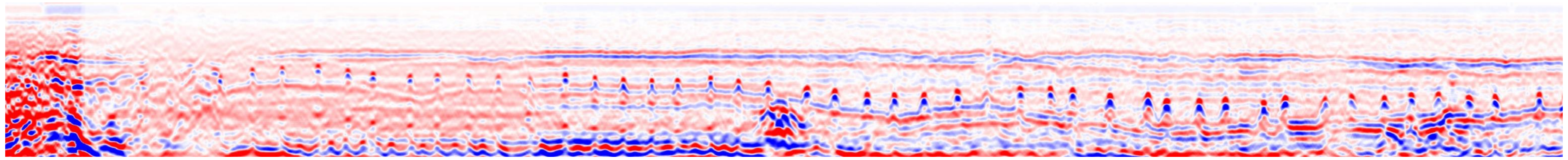
G1 - intrados slab thickness and reinforcement layout



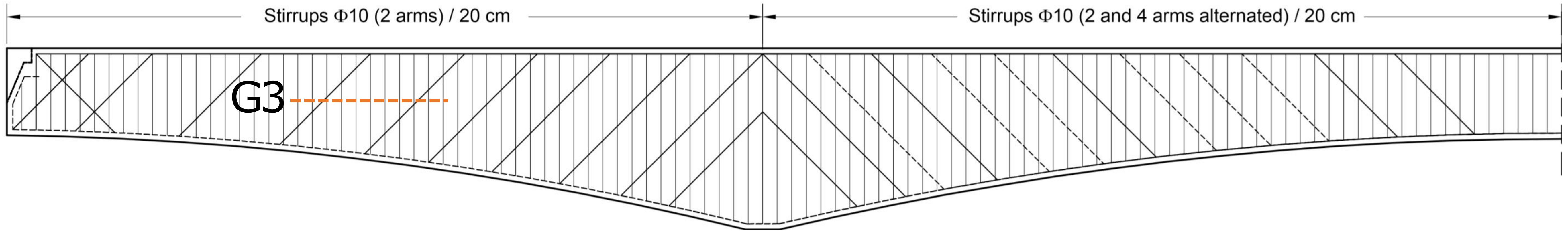
G3 - identification of the shear reinforcement



G2 - transverse reinforcement in the extrados slab



Reproduction of the original 1950s drawings



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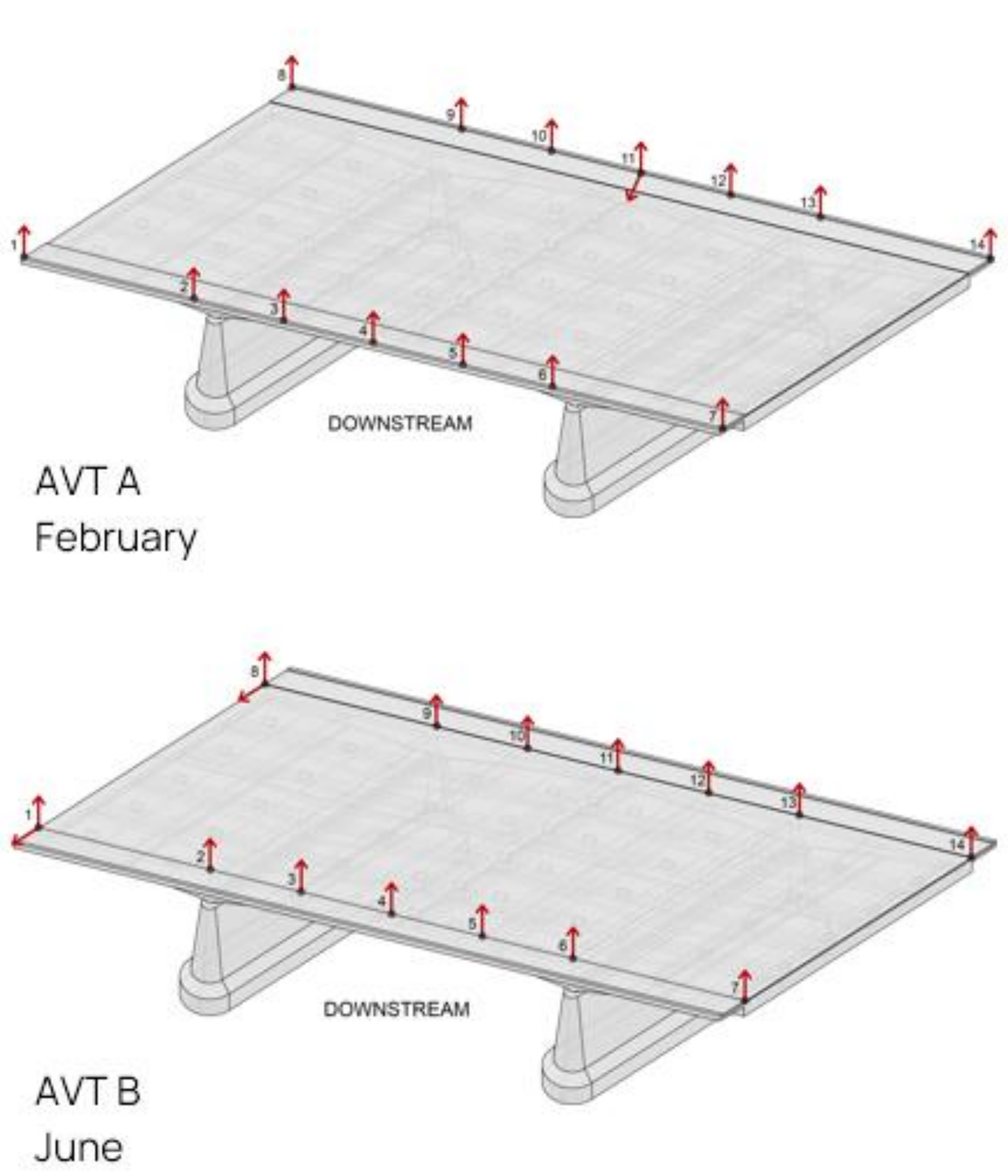
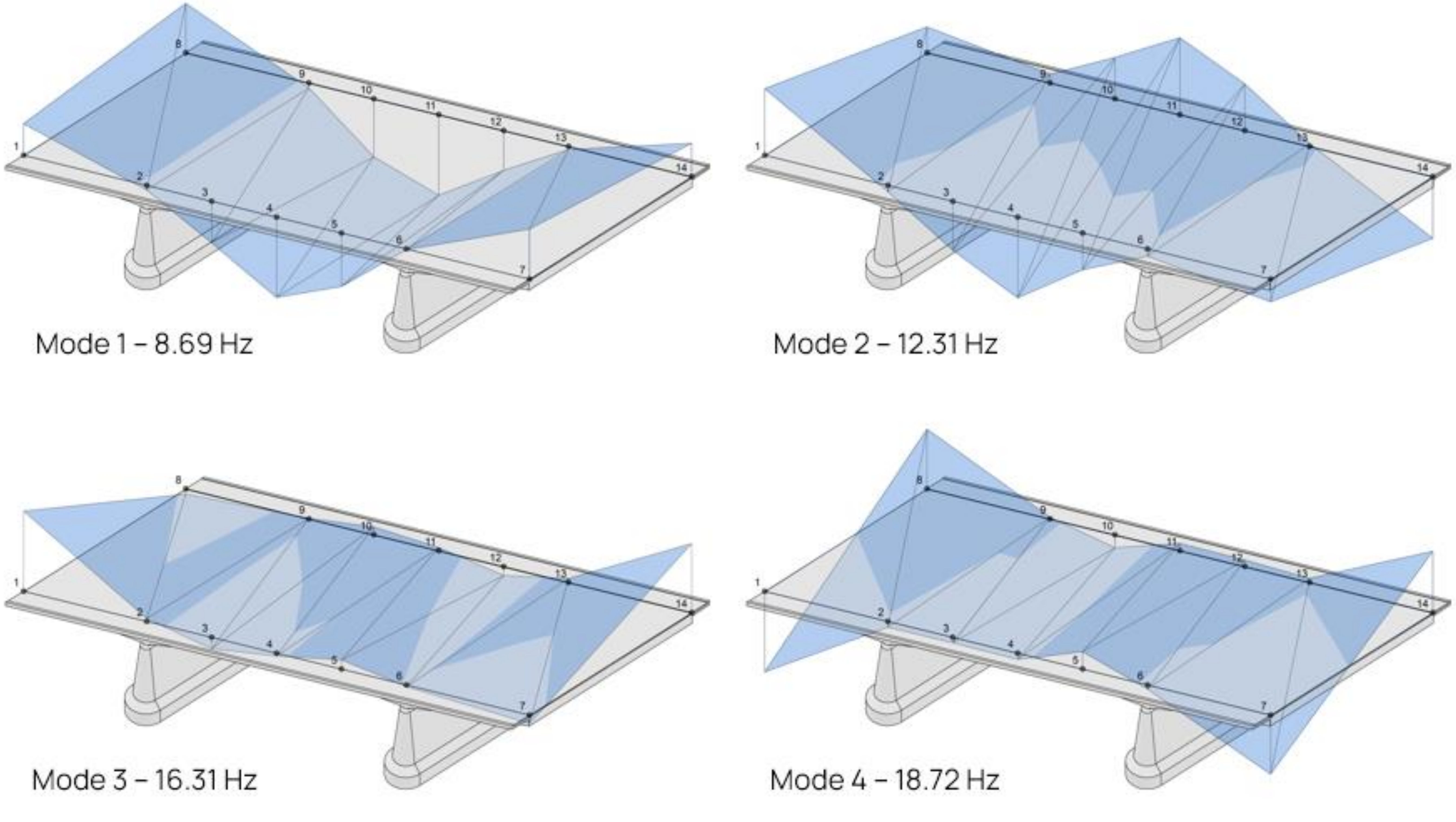
Dynamic characterization



AVT experimental setups



AVT B experimental mode shapes

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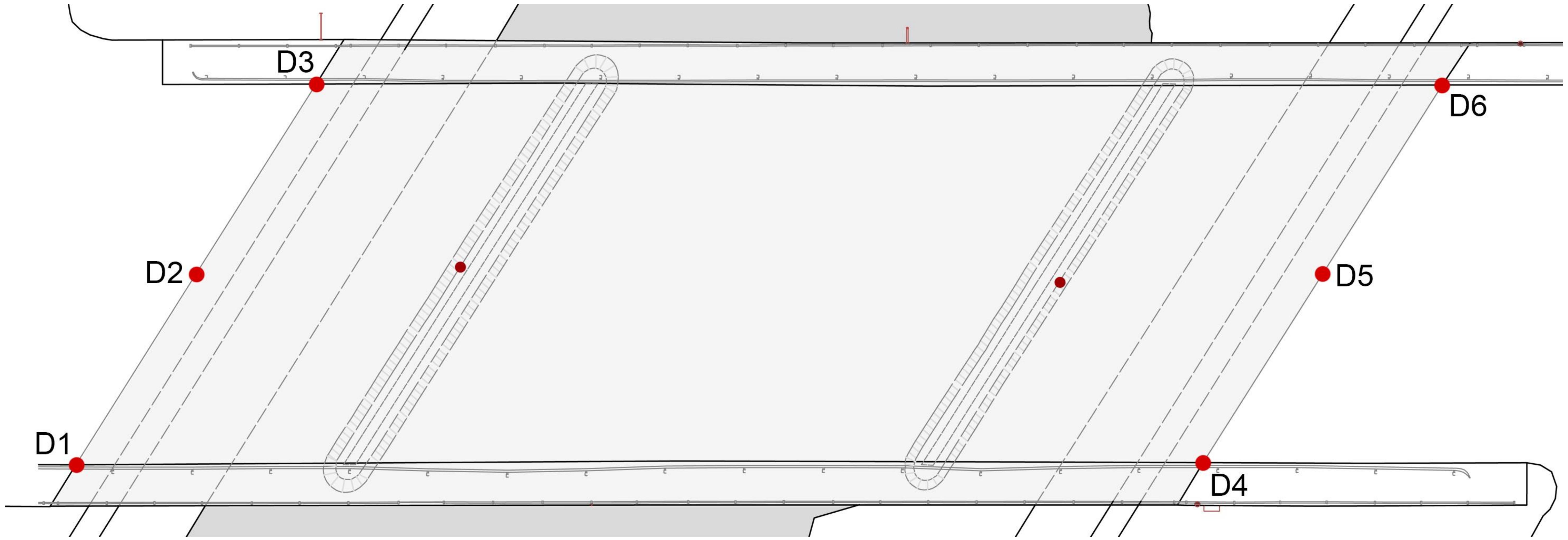
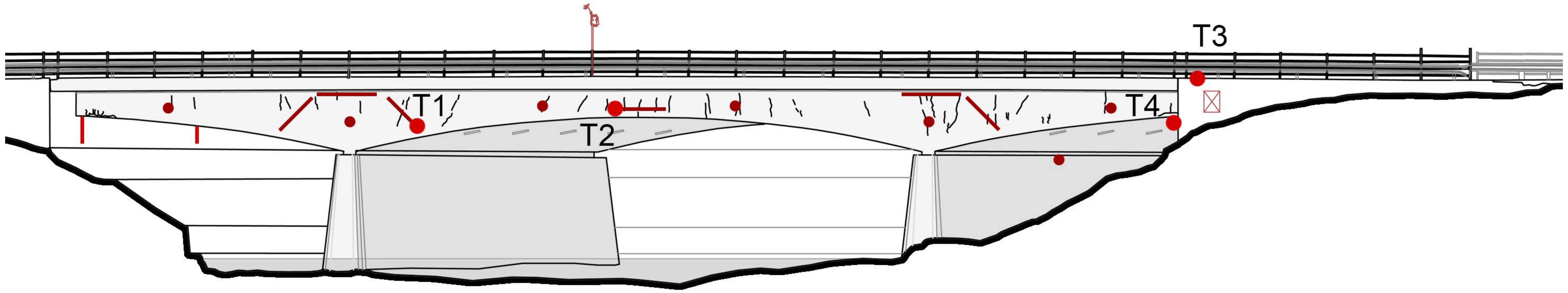
PROJECT PHASE

3.0 Design and installation of a monitoring system

- 8 biaxial MEMS tiltmeters on the deck and at the top of the piers
- 12 electrical deformometers with potentiometer wire transducers
- 4 surface temperature sensors (2 integrated thermistors and 2 thermocouples)
- 1 weather station, 1 hydrometer, 1 digital camera





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PROJECT PHASE

3.0 Design and installation of a monitoring system

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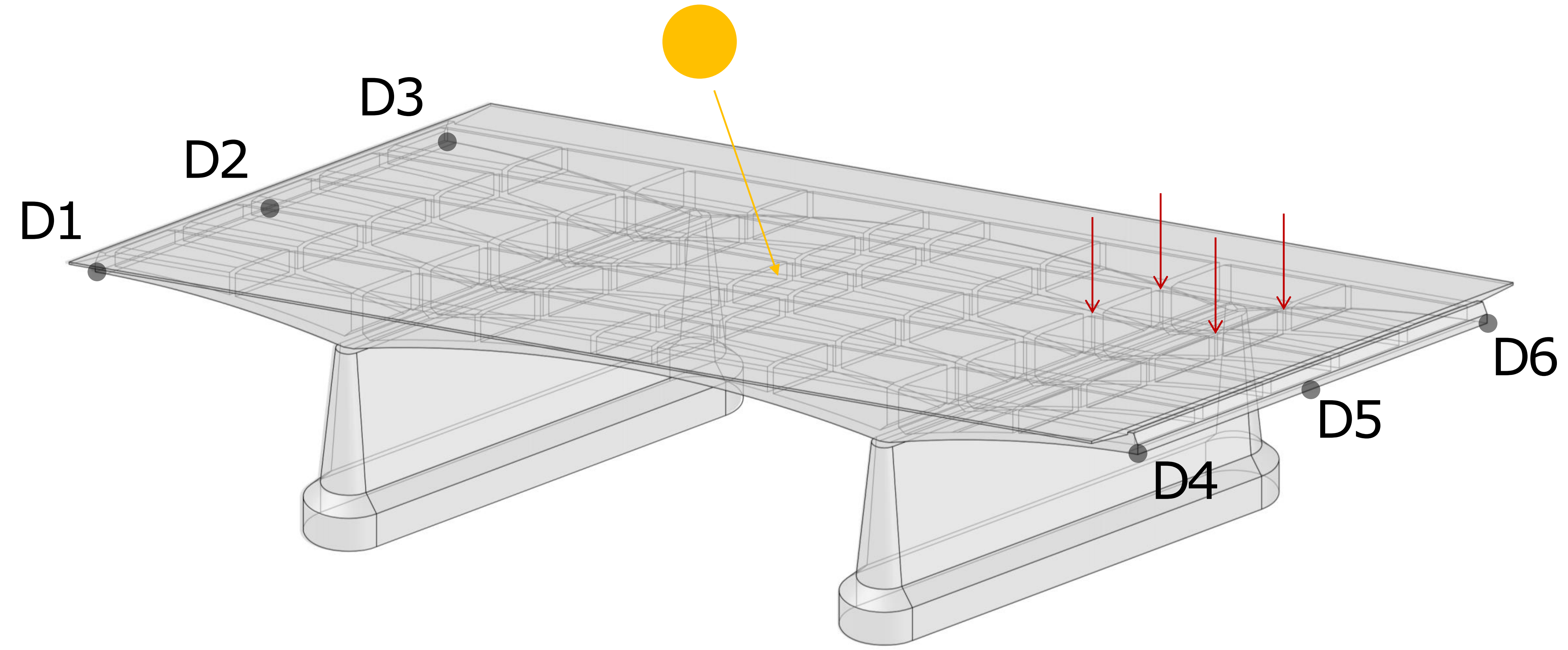

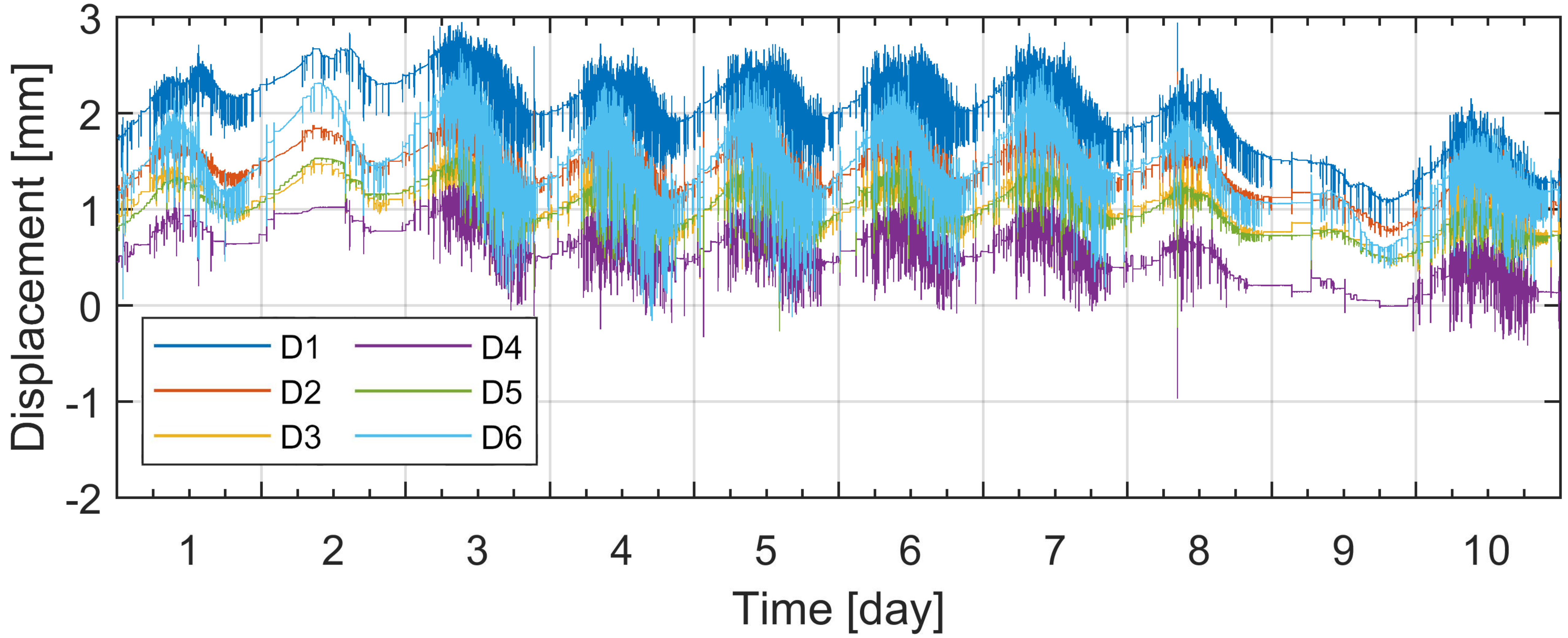

Potentiometer wire transducers D1-D6

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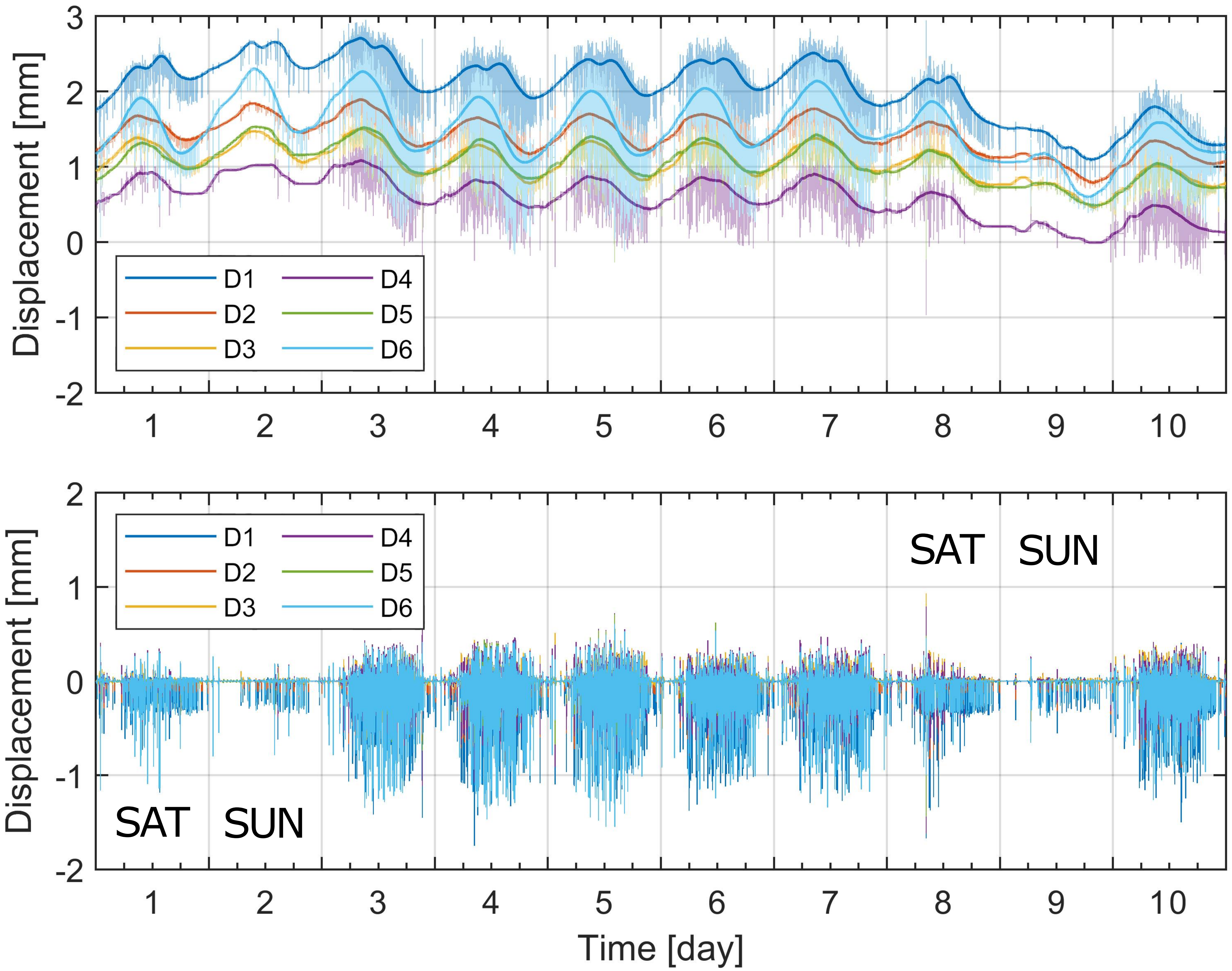
PROJECT PHASE

3.0 Design and installation of a monitoring system



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PROJECT PHASE

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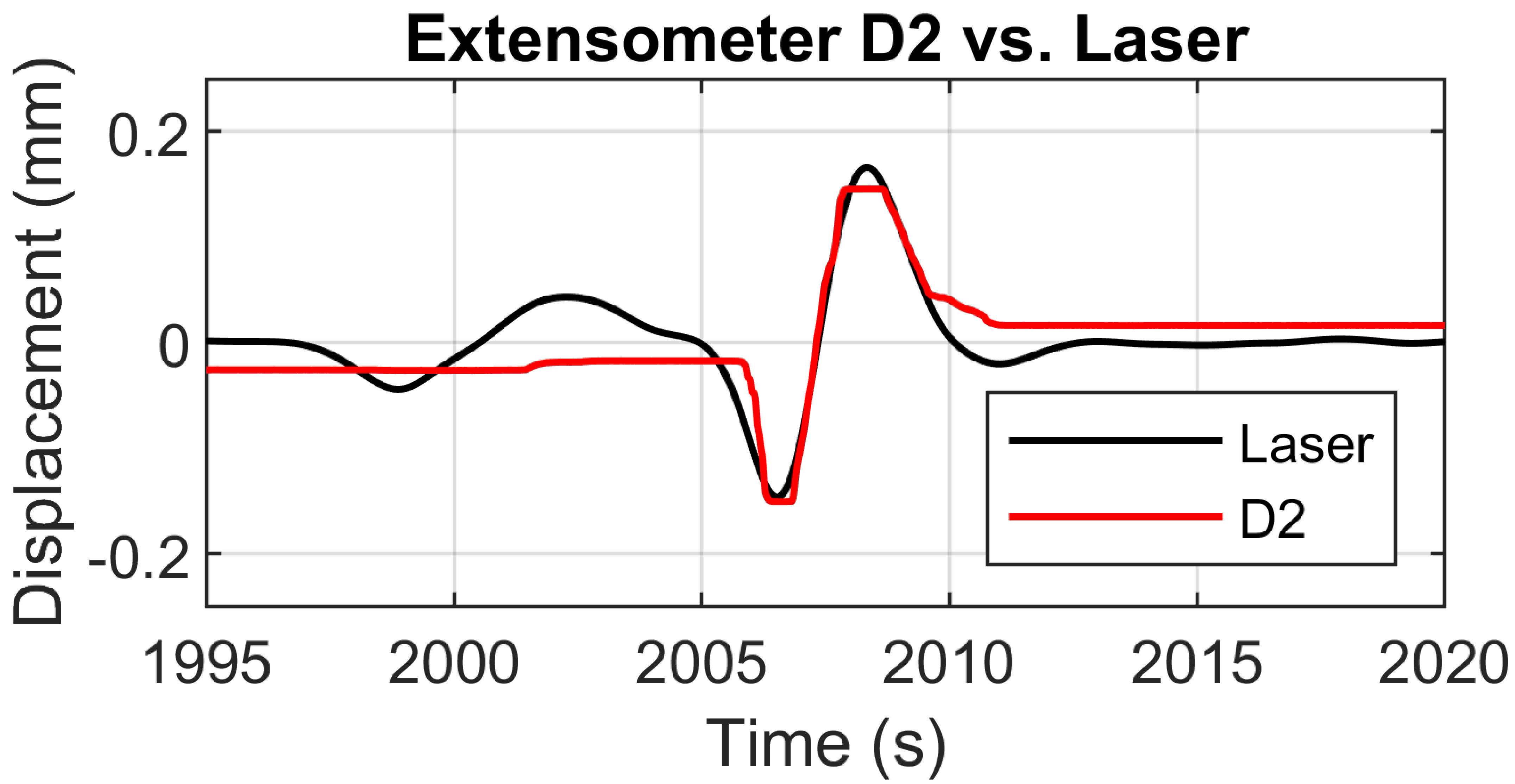

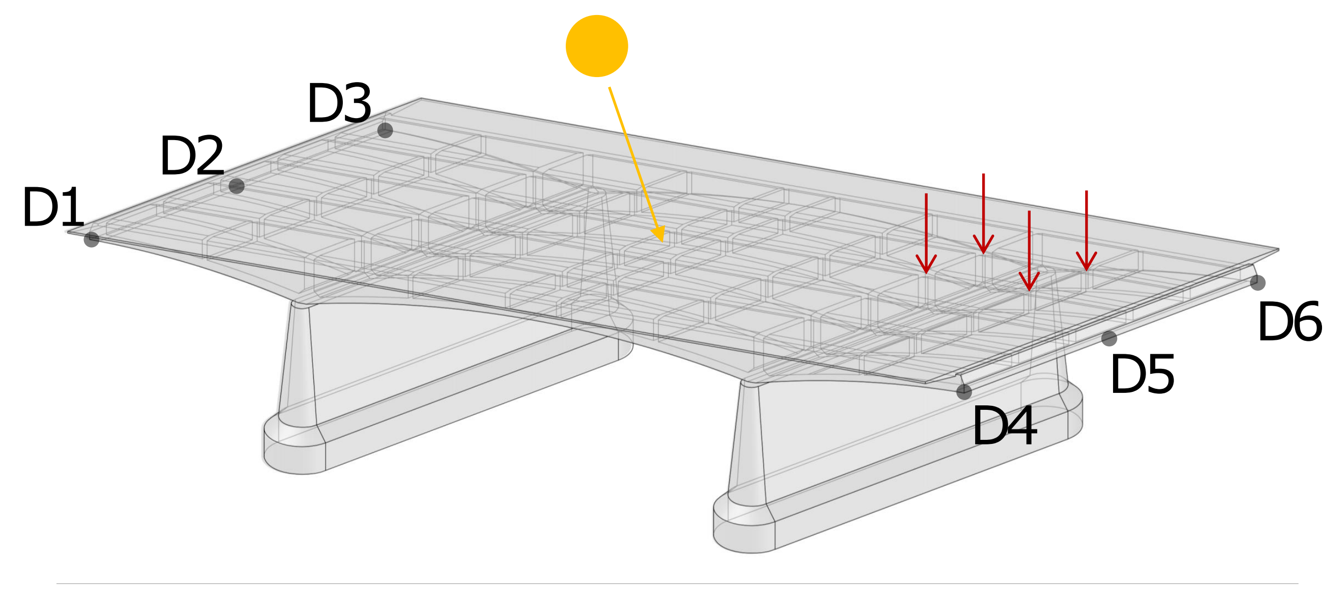

Ordinary traffic induces vertical displacements that can occasionally be larger than 2 mm

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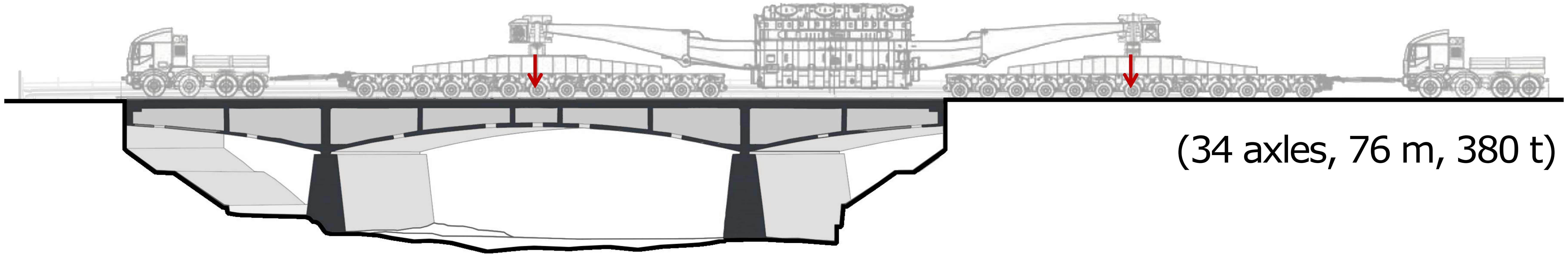
PROJECT PHASE

4.0 Load testing and validation

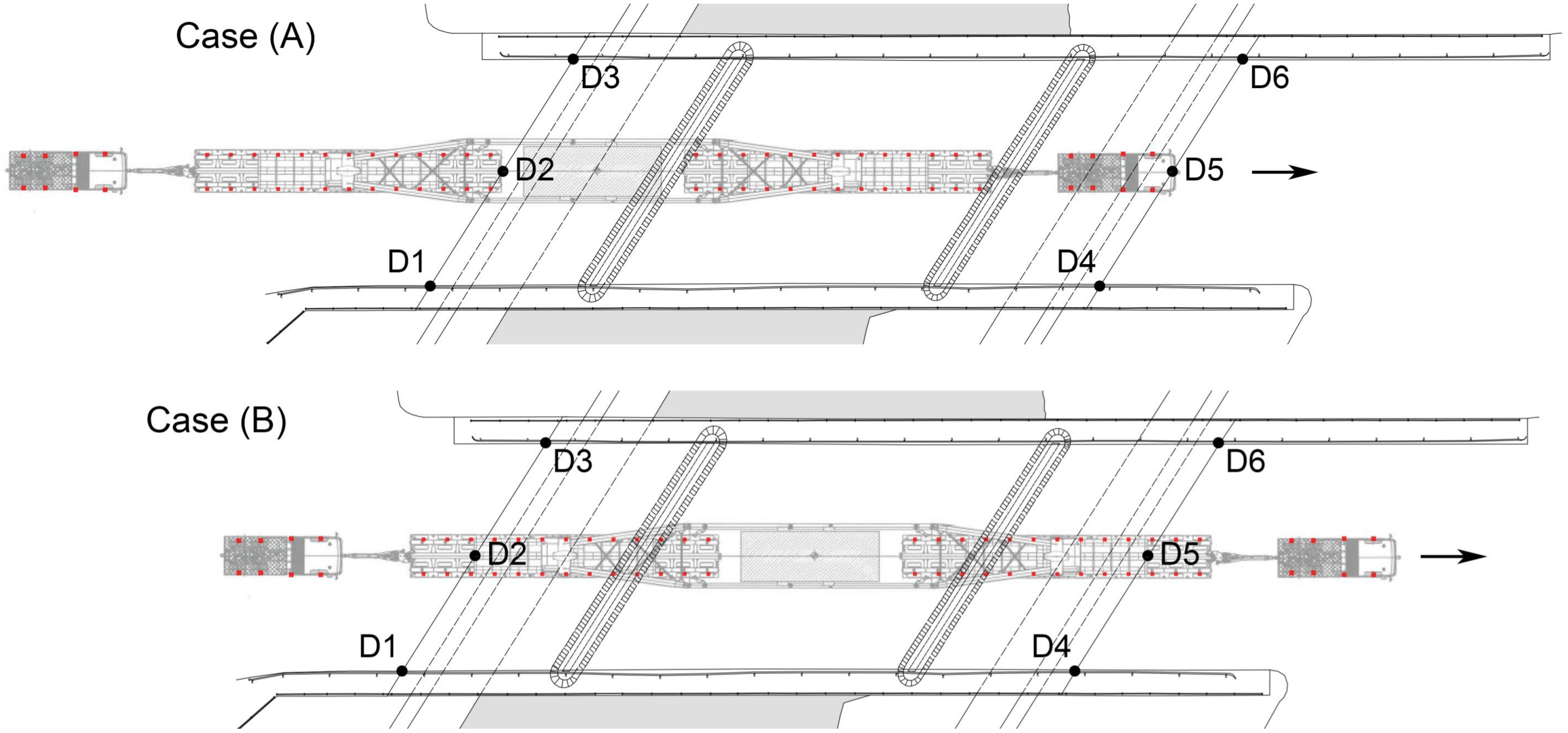
Passage of a heavy goods vehicle (HGV) transporting a massive transformer
Train of two 4-axle trucks and two 13-axle trailers

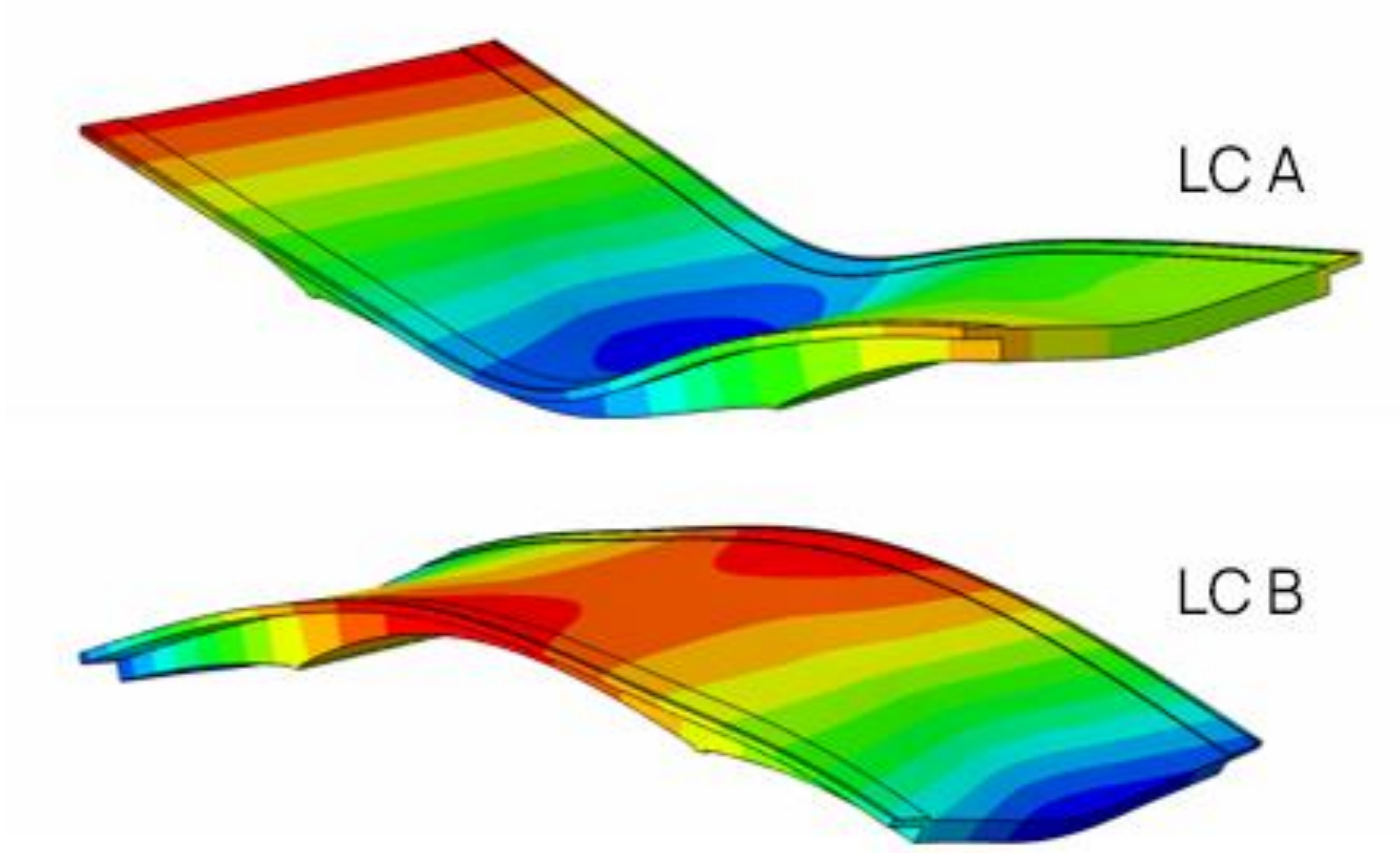


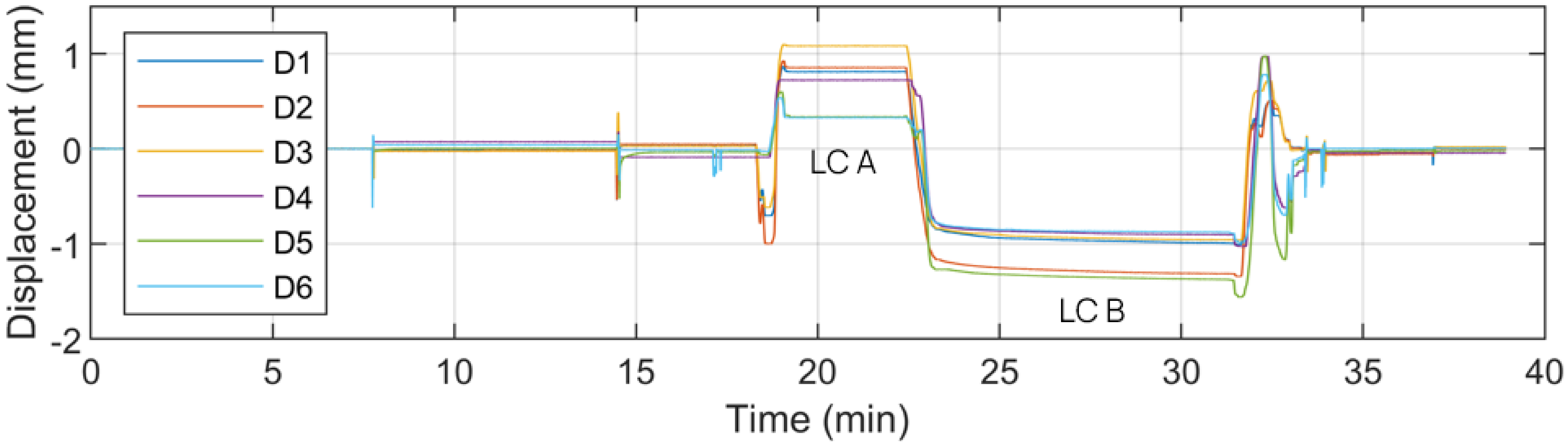
(34 axles, 76 m, 380 t)

PROJECT PHASE

4.0 Load testing and validation







The HGV induced vertical displacements < 2 mm

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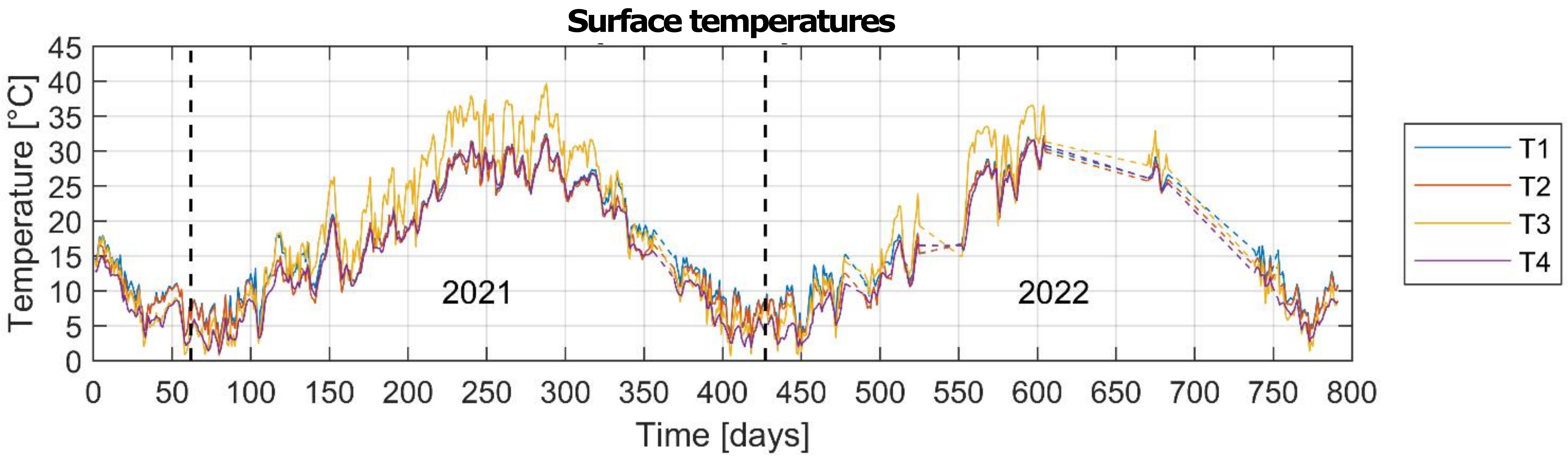
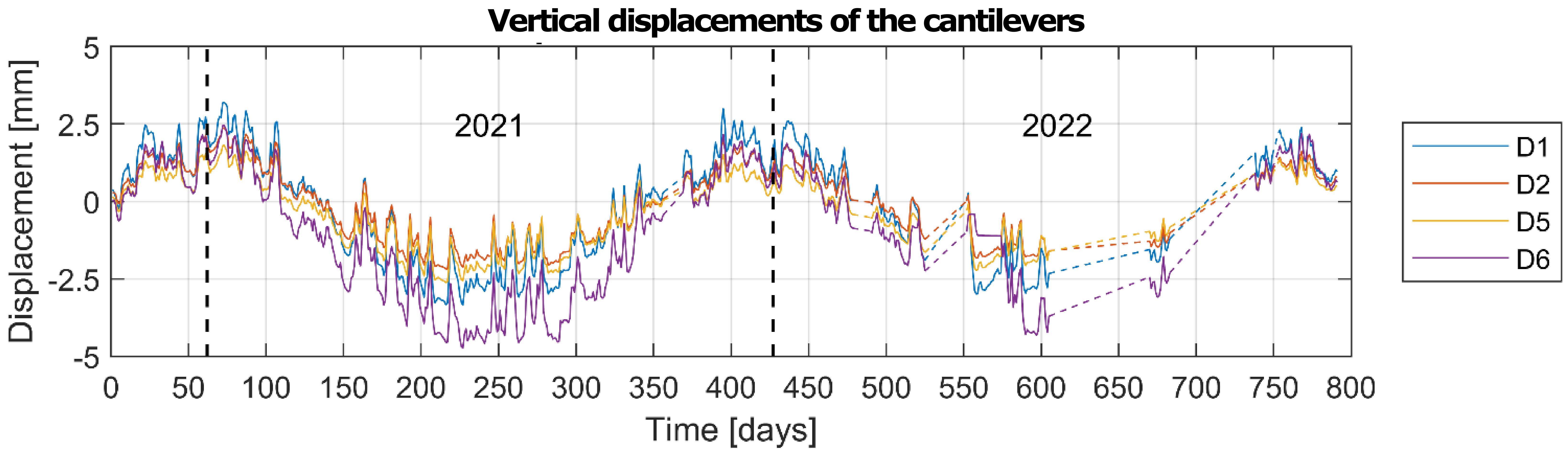
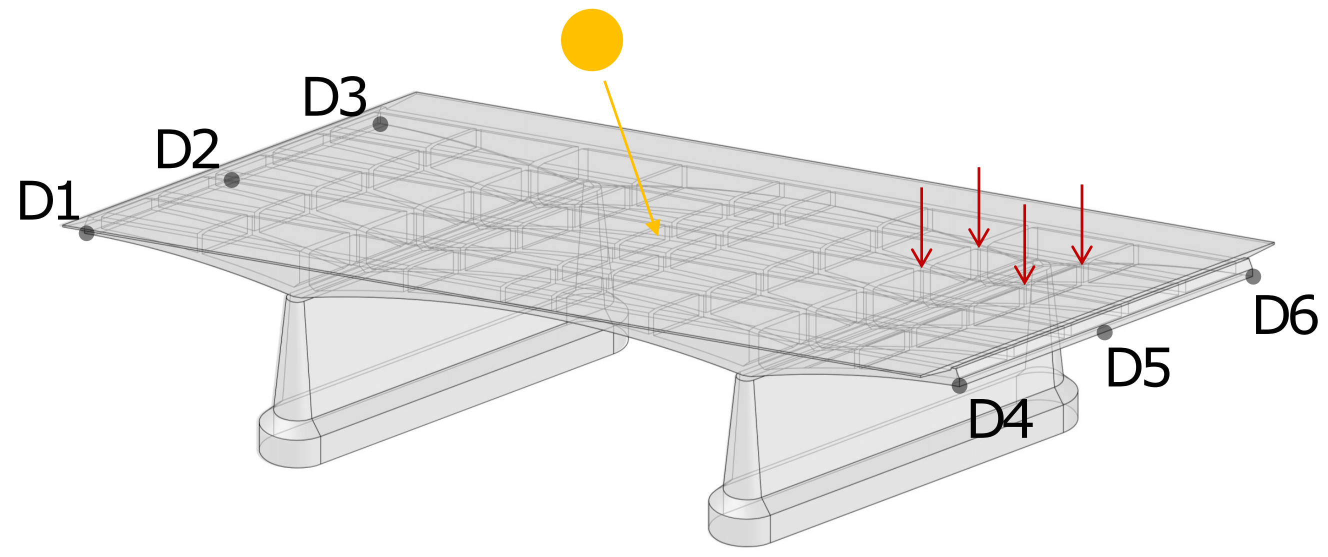
PROJECT PHASE

5.0 Observation







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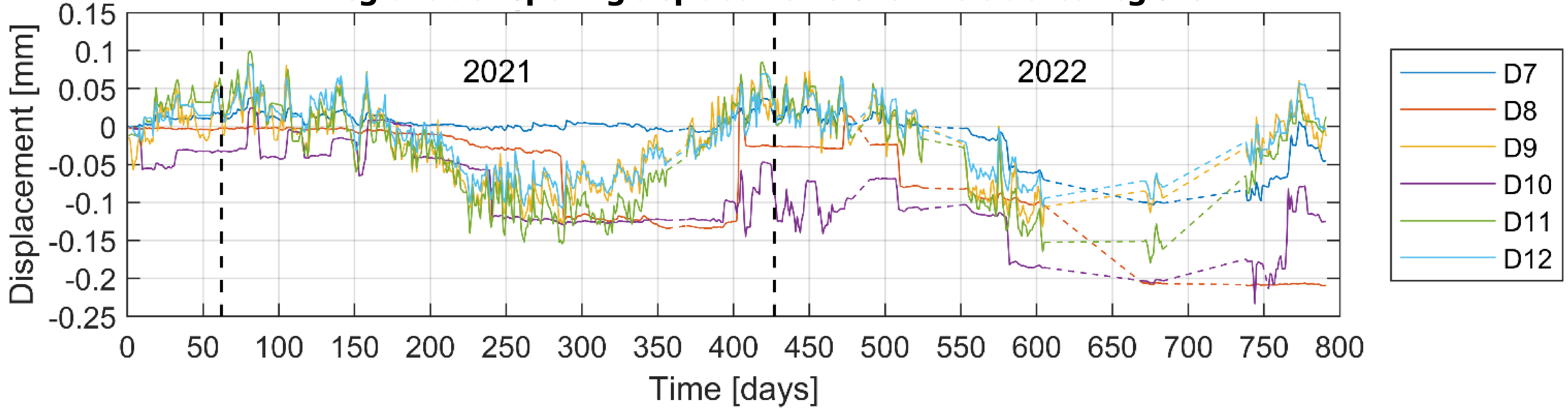
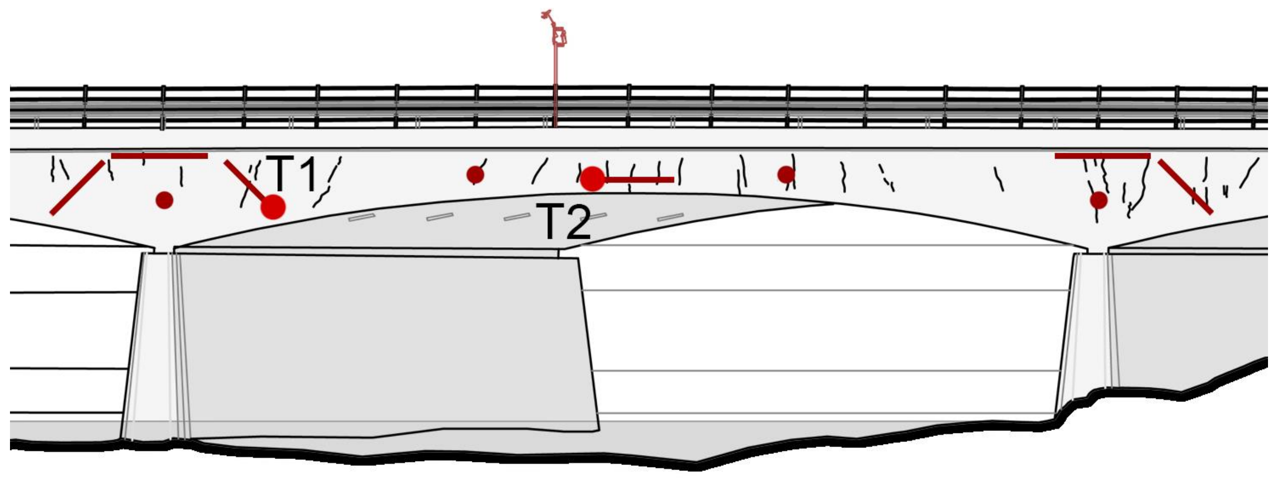
PROJECT PHASE

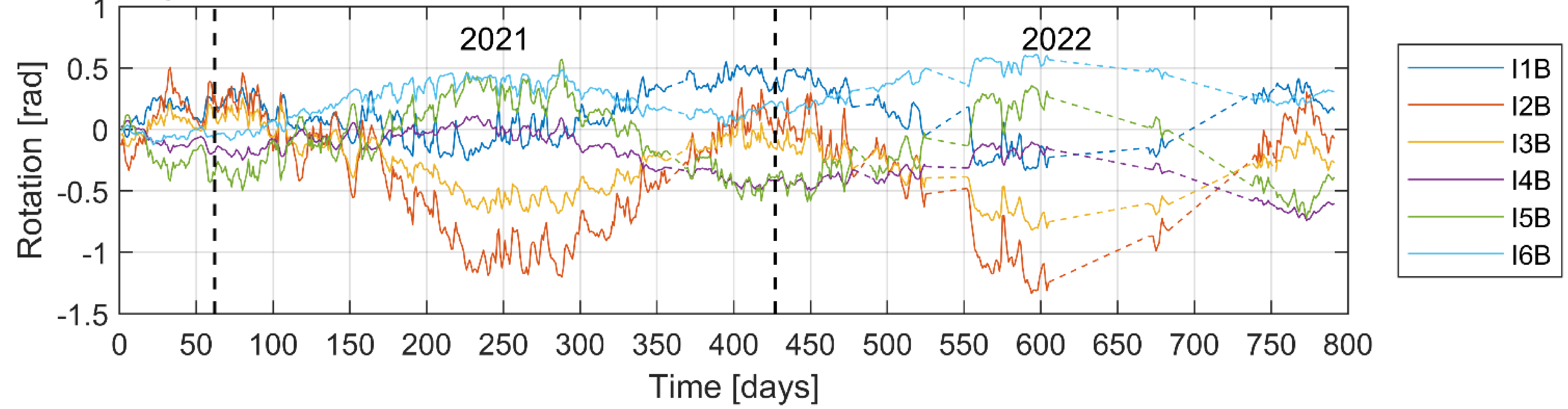
5.0 Observation

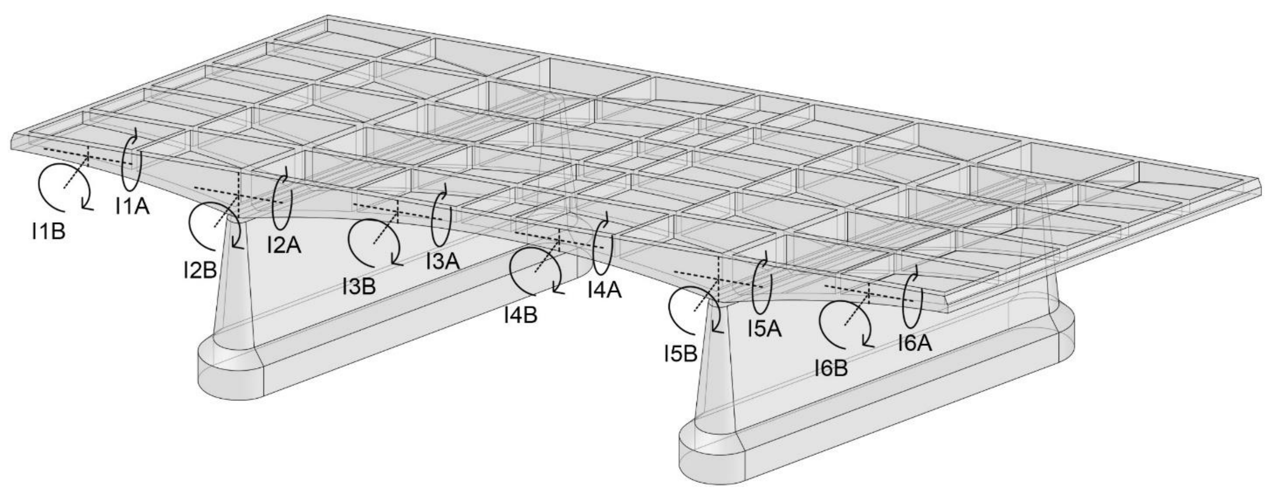
Integral crack opening displacements over the cracked regions





Deck flexural rotations





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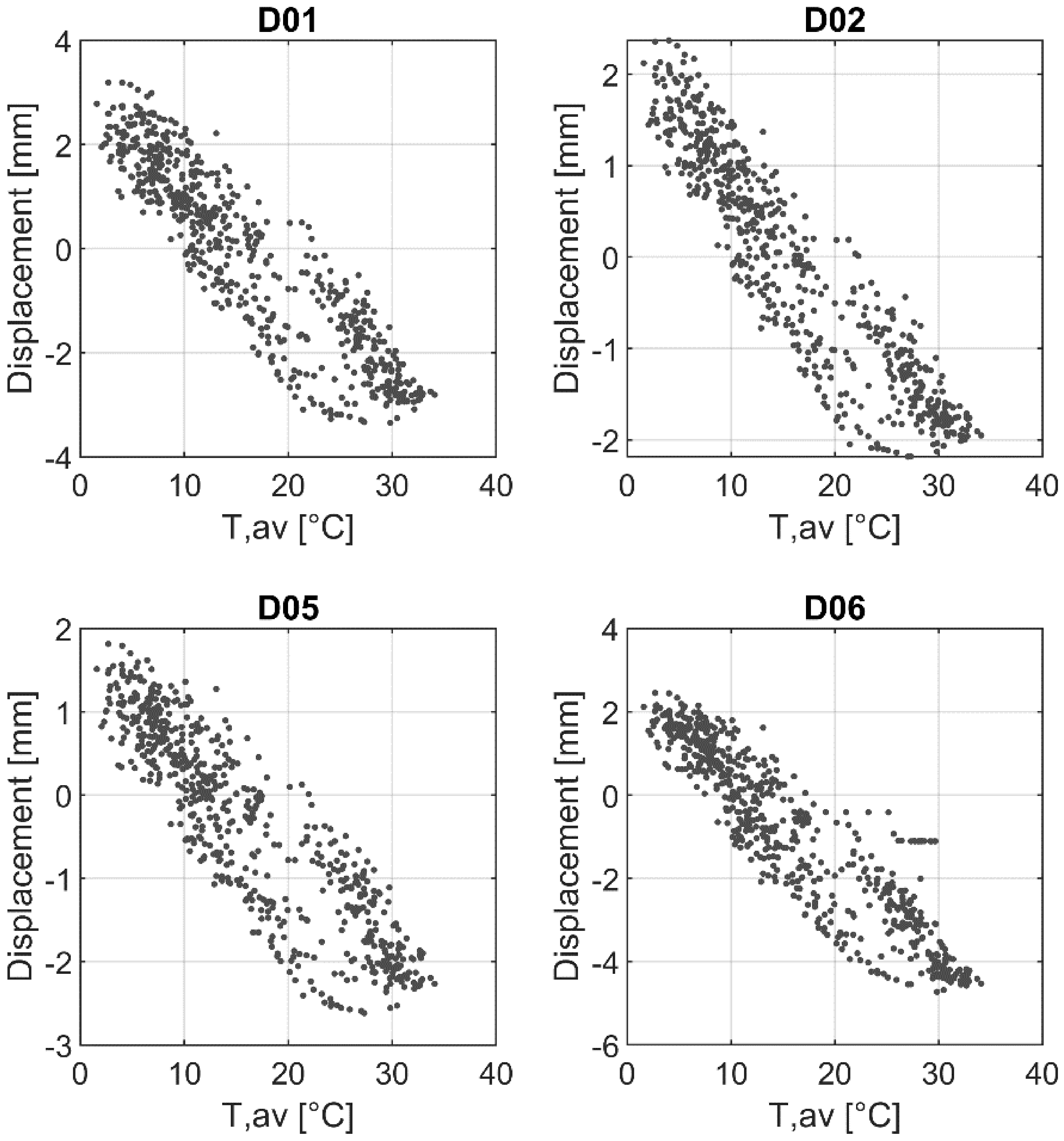
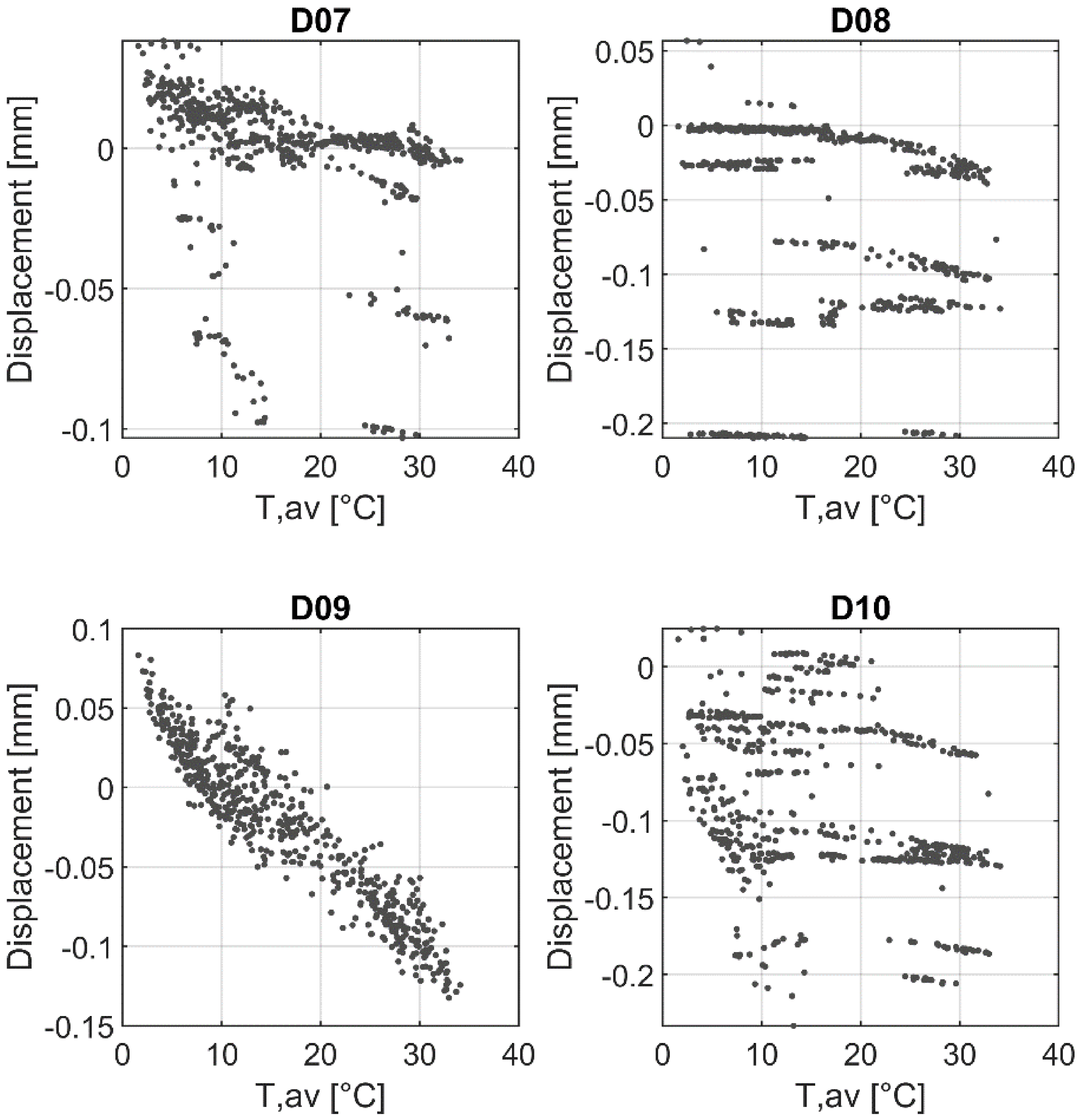
CONCRETO ACADEMY

PROJECT PHASE
5.0 Observation

Vertical displacements vs. temperature



Crack openings/closures vs. temperature



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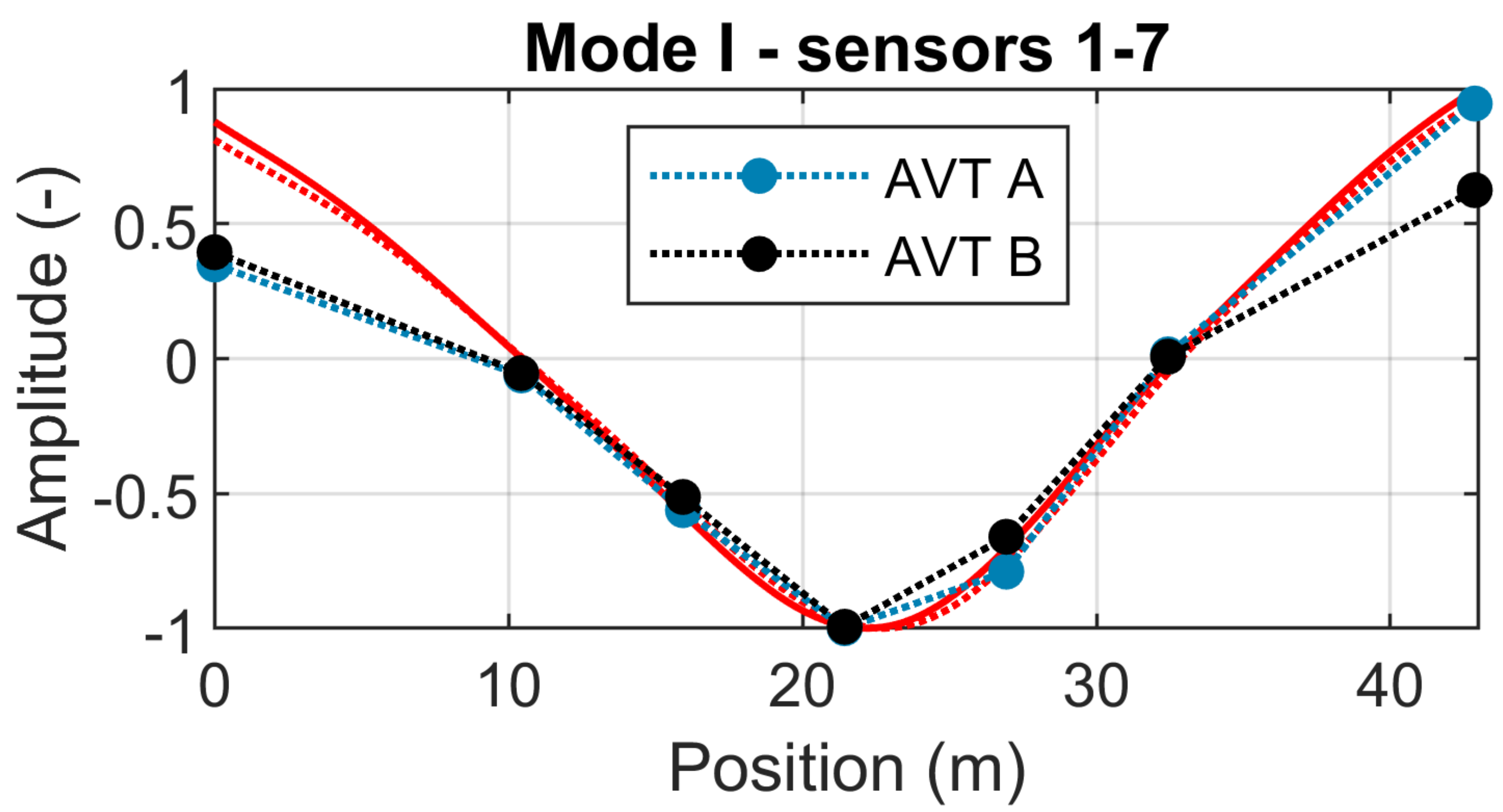
PROJECT PHASE

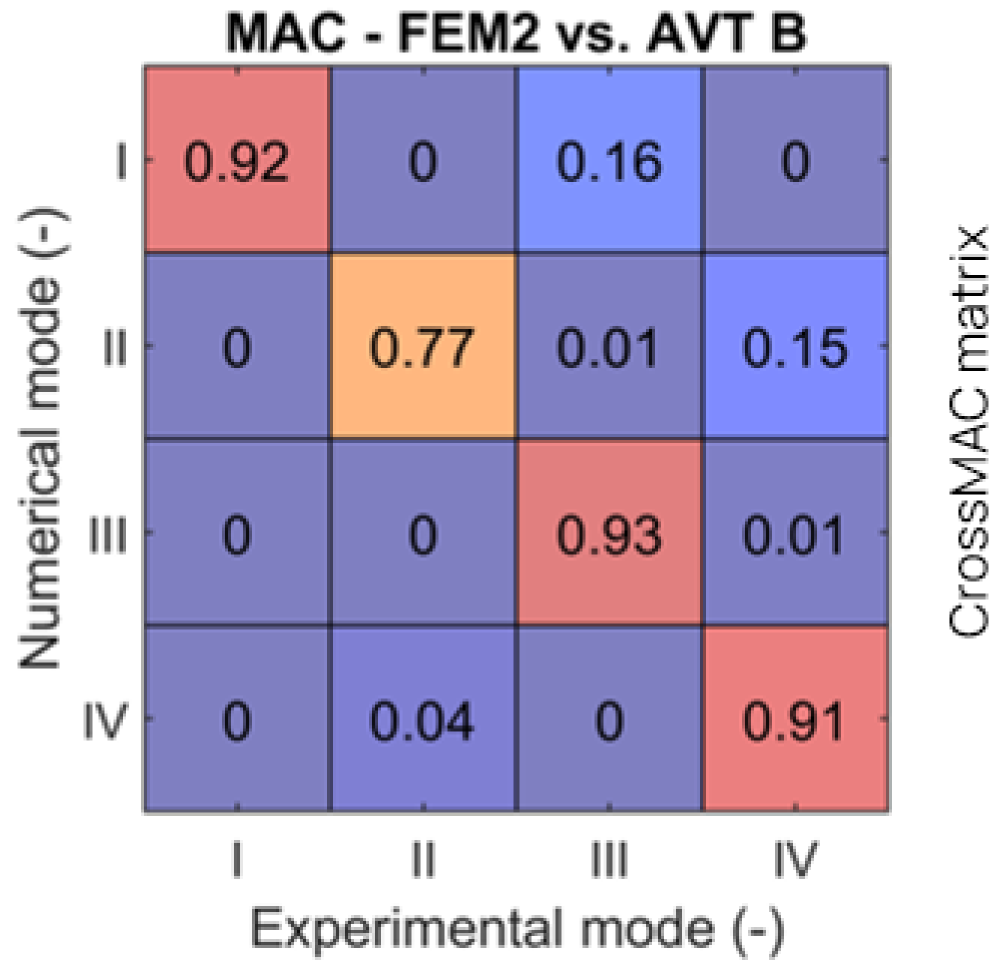
6.0 Modelling

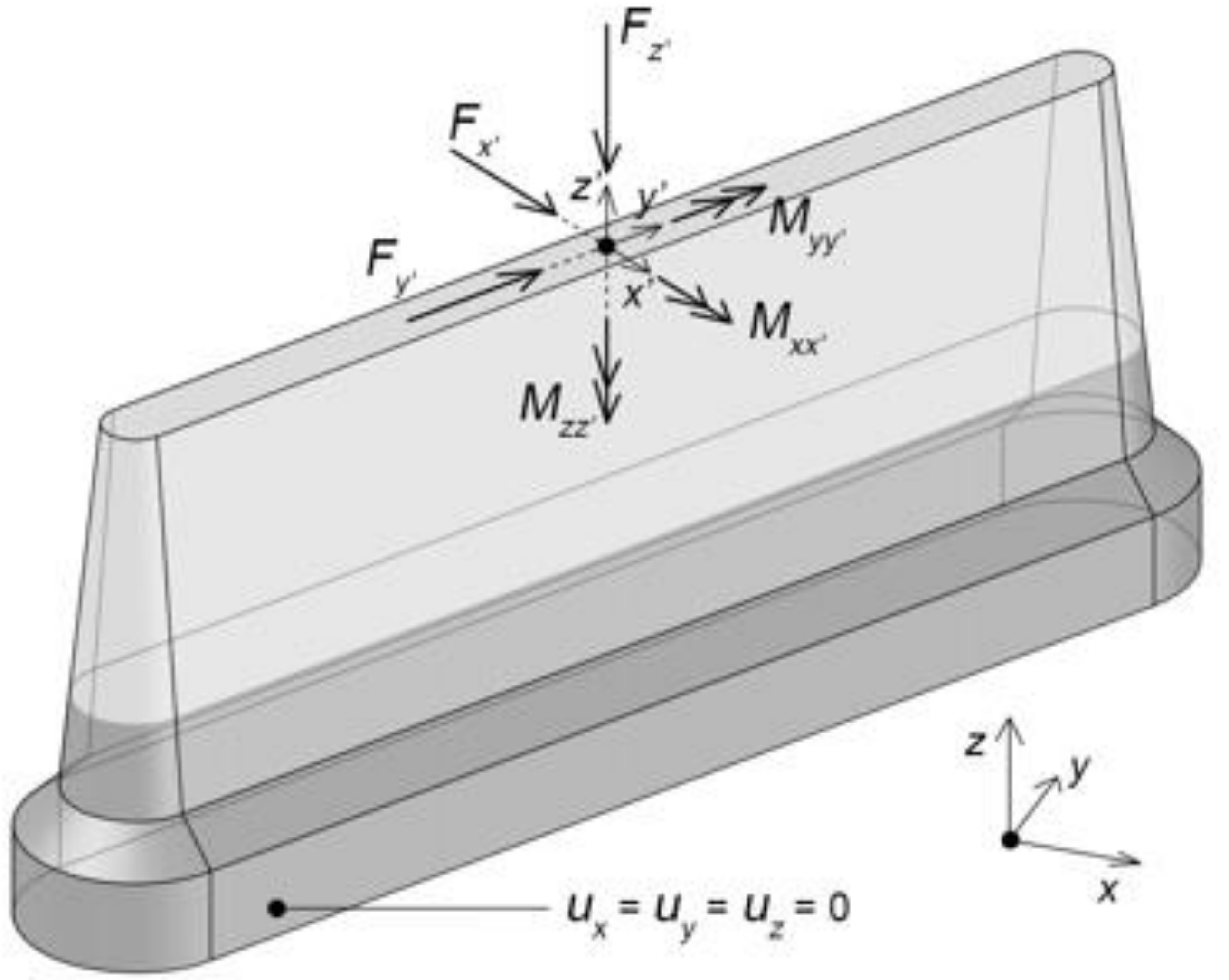
Model updating

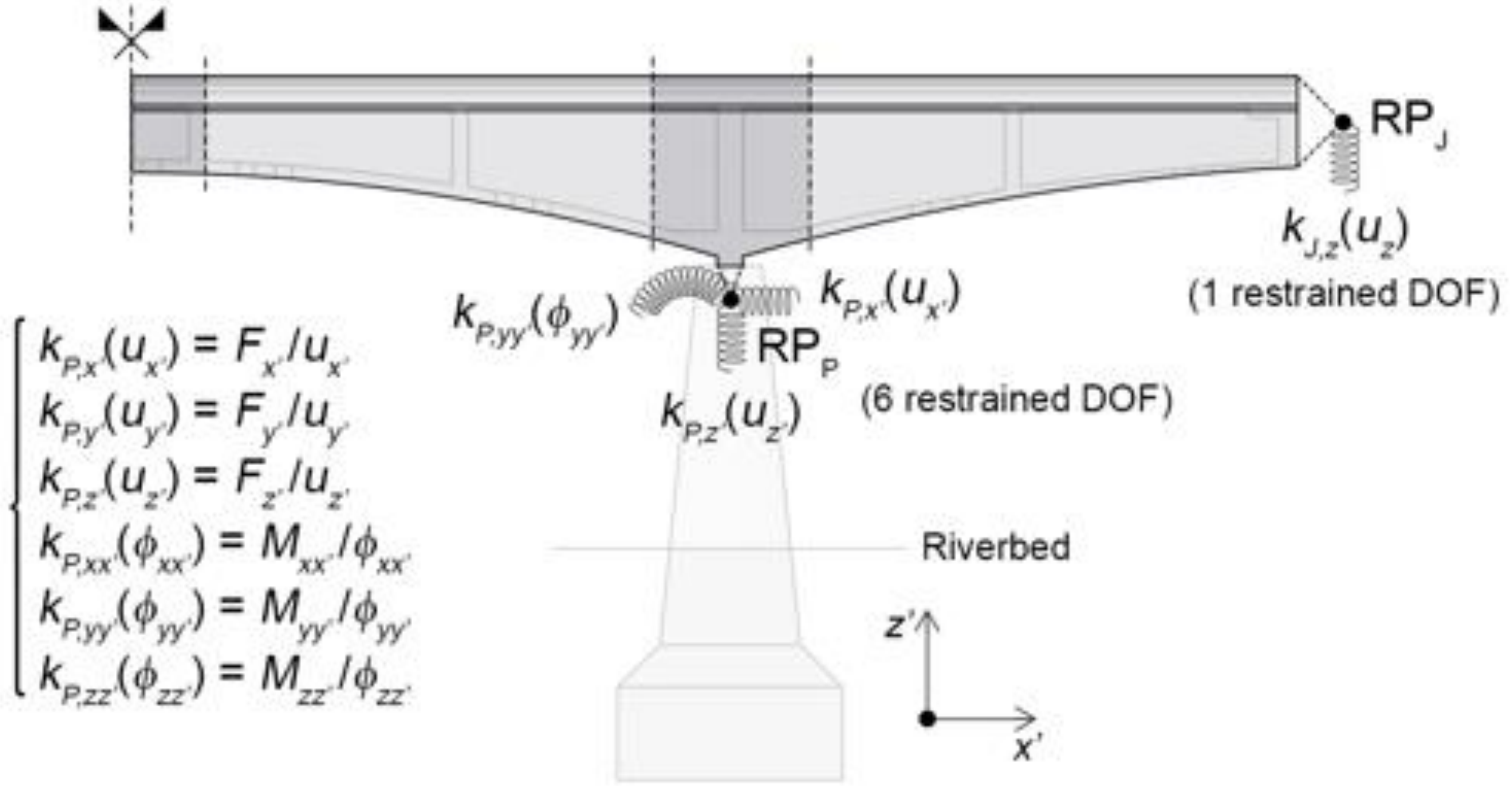
1. Calibration on AVTs
2. Modelling of the static response

Largest uncertainties found at the bearings and joints → lumped elastic springs

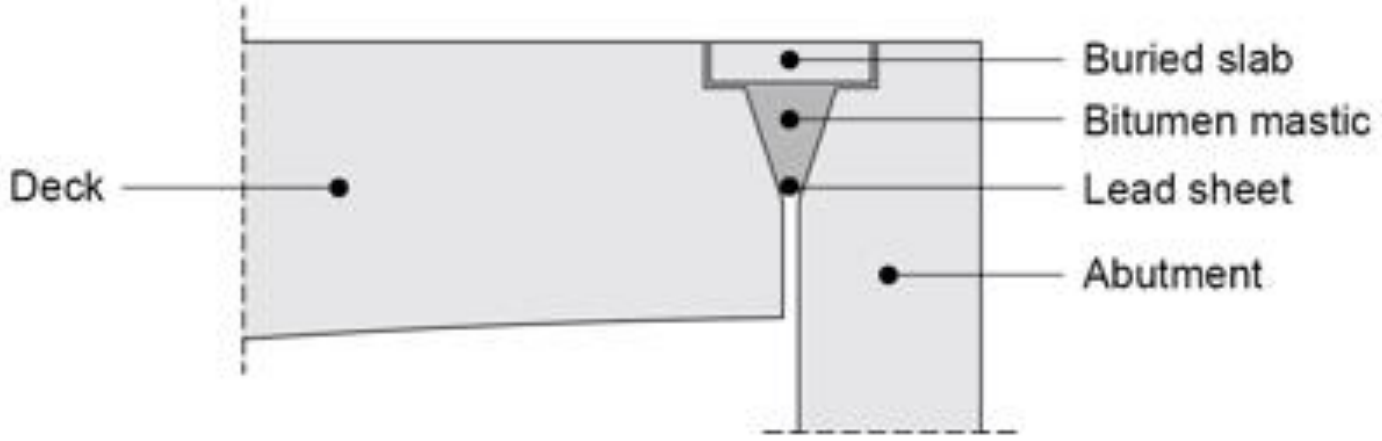








Displacement	Load case A	FEM2
D1 (mm)	0.81	0.34 (-58.02%)
D2 (mm)	0.85	0.48 (-43.53%)
D3 (mm)	1.08	0.61 (-43.52%)
D4 (mm)	0.72	0.31 (-56.94%)
D5 (mm)	0.33	0.12 (-63.64%)
D6 (mm)	0.33	0.02 (-93.94%)



Detail of the under-slab joint

The model calibrated on AVTs fails to reproduce the displacements observed under static loads

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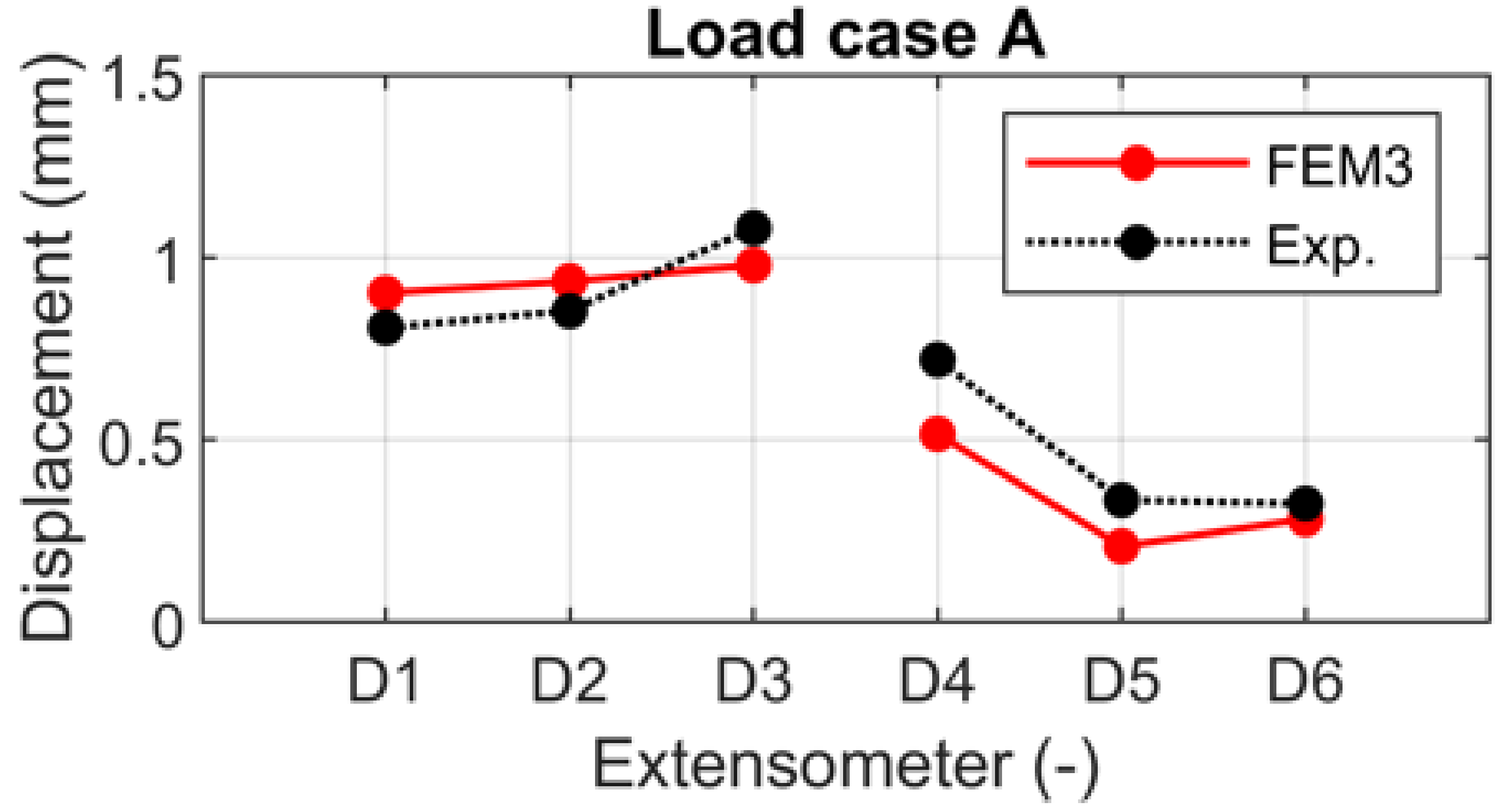
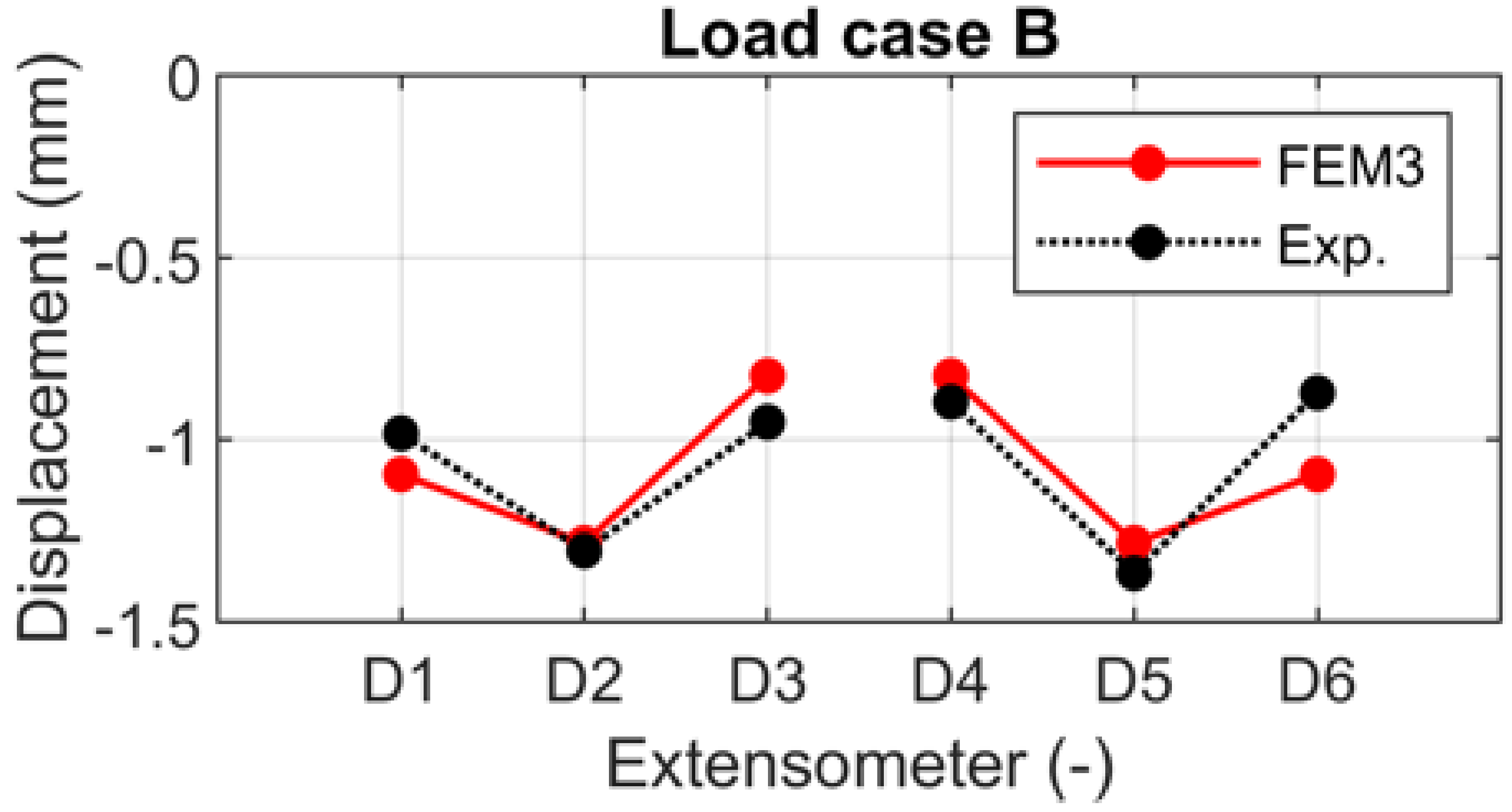
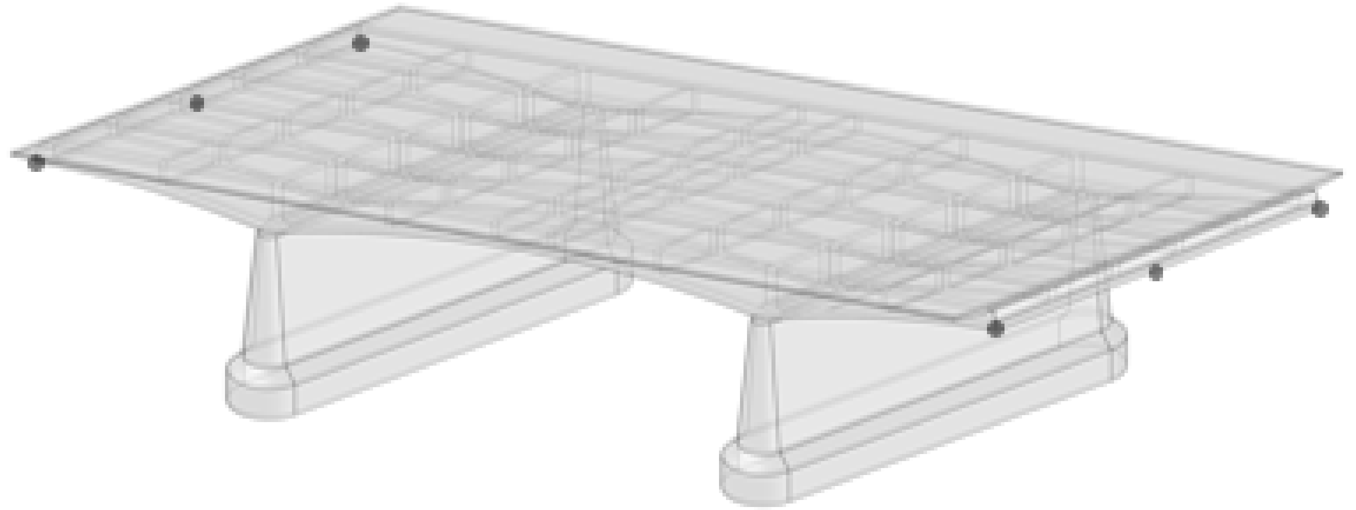
Modelling of the static response

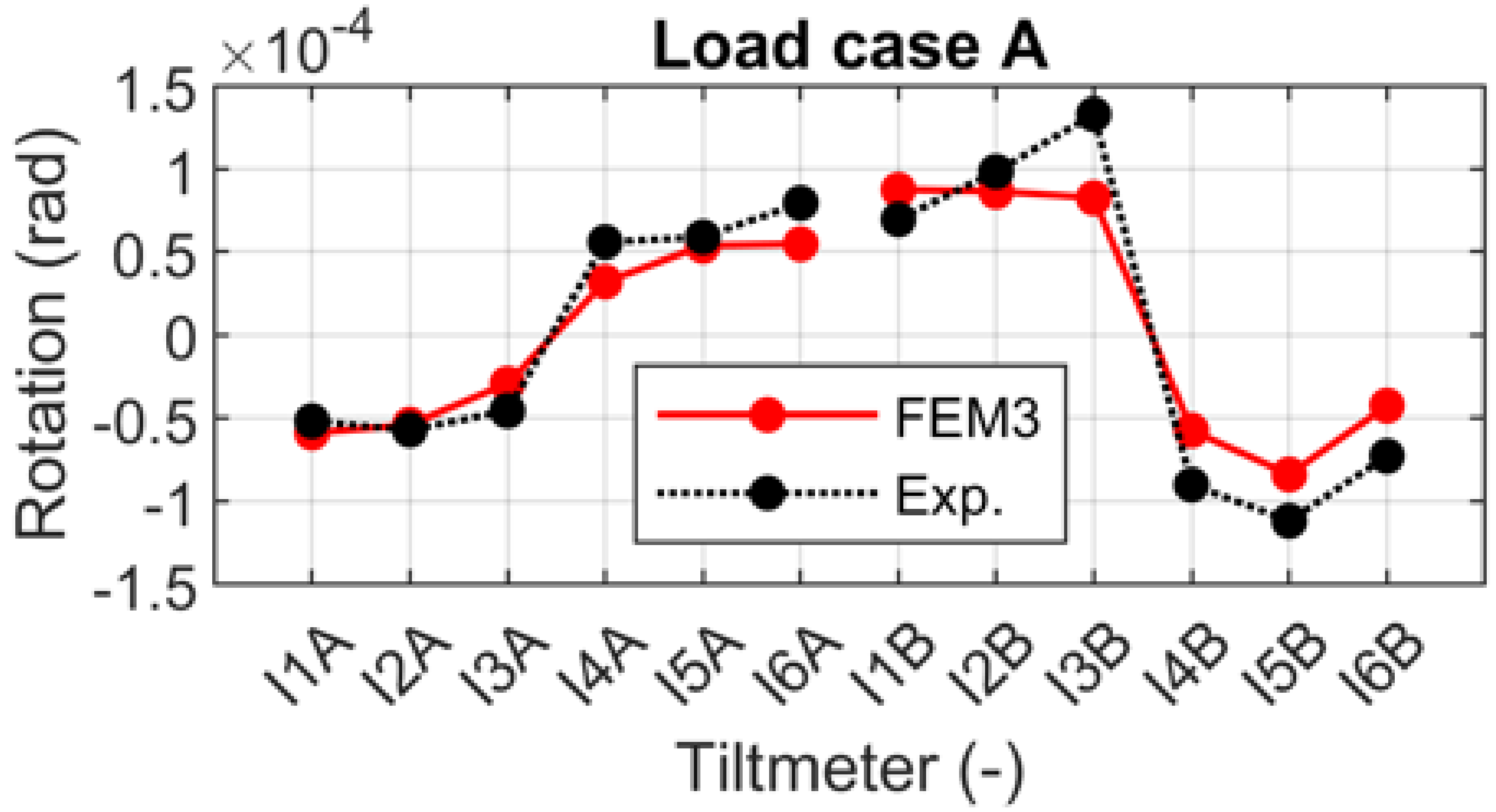
Bearings and end joints exhibit nonlinear behavior and are affected by frictional effects

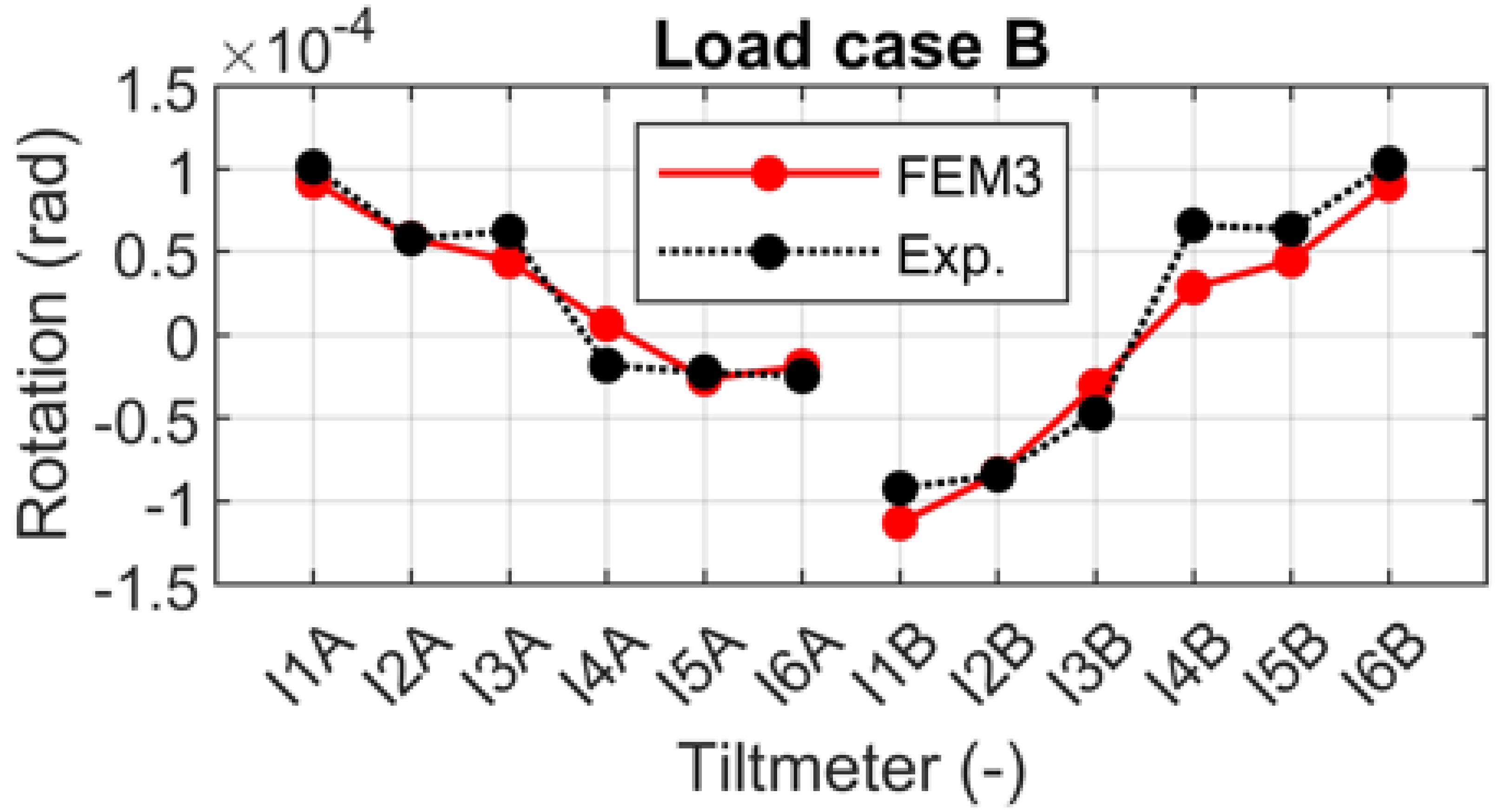


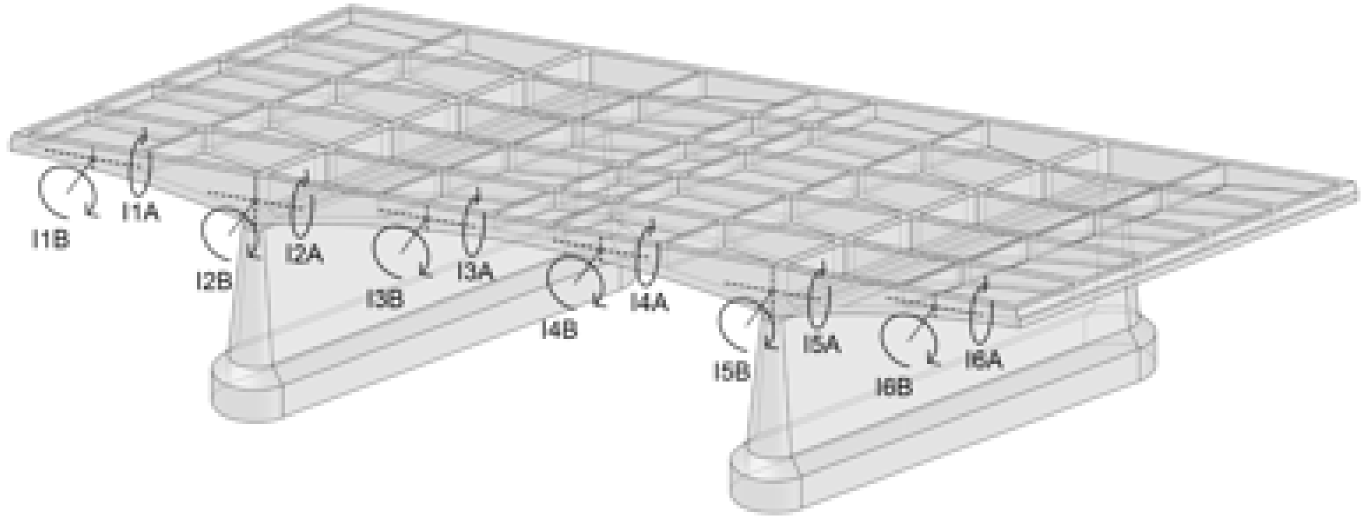




Vertical displacements







Flexural and torsional rotations

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CONCLUSIONS

Future & Maintenance

- Monitoring of a **70-year-old RC bridge, still operating on a heavy traffic network**
- The diagnostic campaign revealed **significant discrepancies with design documents** (e.g., number of girders), confirming the need for on-site validation in safety assessments
- Tests highlighted **degradation risks**, such as carbonation-induced corrosion, while confirming material properties typical of 1950s RC construction
- Crack pattern mapping enabled **targeted sensor placement**; fluctuations in crack openings point to the **need for continued monitoring**
- Despite limited instrumentation, the static monitoring system captured deck displacements and rotations, **including those due to traffic loads**
- The 380-ton load caused displacements similar to everyday traffic, showing that **exceptional loads are not always more critical**

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CONCLUSIONS

Future & Maintenance

- The discrepancies observed between dynamic and static responses underscore the **need for tailored modelling strategies**. While dynamic analyses are suitable for small-amplitude vibrations, they may oversimplify **frictional effects and nonlinearities** that become significant under large static loads, such as those induced by exceptional transports
- The knowledge produced is being used in the **upcoming maintenance and retrofitting works**, demonstrating the effectiveness of integrated strategies in supporting structural intervention planning.

> I think that sooner or later, may be in a few years, it will be necessary to resort to a treatment consisting of the removal of all traces of rust on the exposure of the reinforcements, to fill the patches, with epoxidic type resins and finally to cover everything up with elastomers of a very high chemical resistance.

R. Morandi, The long-term behaviour of viaducts subjected to heavy traffic and situated in an aggressive environment: The viaduct on the Polcevera in Genoa, IABSE Reports of the Working Commissions, 32 (1979), pp. 170-180

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CONCLUSIONS

Future & Maintenance

According to the so-called **rule of five**, the cost of repairing a defect increases roughly fivefold at each stage of deterioration — from preventive maintenance (1×) to minor repair (5×), major repair (25×), and full replacement (125×) — highlighting the economic value of early detection and timely intervention

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CONCLUSIONS

Future & Maintenance

- The first and most effective response to structural deterioration lies in **regular maintenance and continuous observation**, which allow early detection of damage and prevent costly interventions
- At the same time, it is essential to continue the development of **innovative cement-based materials**, which can provide efficient solutions for strengthening existing structures and for building new, more durable infrastructure

Butterfly bridge, A. Kasuga

Pont de la République, R. Ricciotti

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THANK YOU

giulio.zani@polimi.it

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