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SLOVENIAN NATIONAL BUILDING AND CIVIL ENGINEERING INSTITUTE
UNIVERSITY OF LJUBLJANA
FGG
Faculty of Civil and Geodetic Engineering

Using Bridge Weigh-in-Motion System for Structural Health Monitoring of Bridges

ISWIM Young Researcher Award Webinar

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- Literature review and terminology
- Theory background
- Case study
  - Calibration vehicle passages
  - Extraction of B-WIM influence line
  - Acceleration measurements
  - FEMU
  - Validation
- Conclusions

Ageing infrastructure

- Six European countries, 2011: 85% older than 35 years
- Slovenia, 2017: ≈ 60% older than 50 years (non highway roads)
- Germany, 2022: > 50% older than 40 years
- United States, 2021: average age of bridge is 44 years
- United States, 2025: average age of bridge is 47 years

ASCE (2021), ASCE (2025), Žnidarič et al. (2011), Casas (2015), Bundesministerium für Digitales und Verkehr, (2022)

Increasing traffic loads

- Total transport activity increase 2019 – 2050:

≈ 79 % Passenger transport

≈ 100 % Freight transport

OECD,(2023)

Increasing extreme weather events

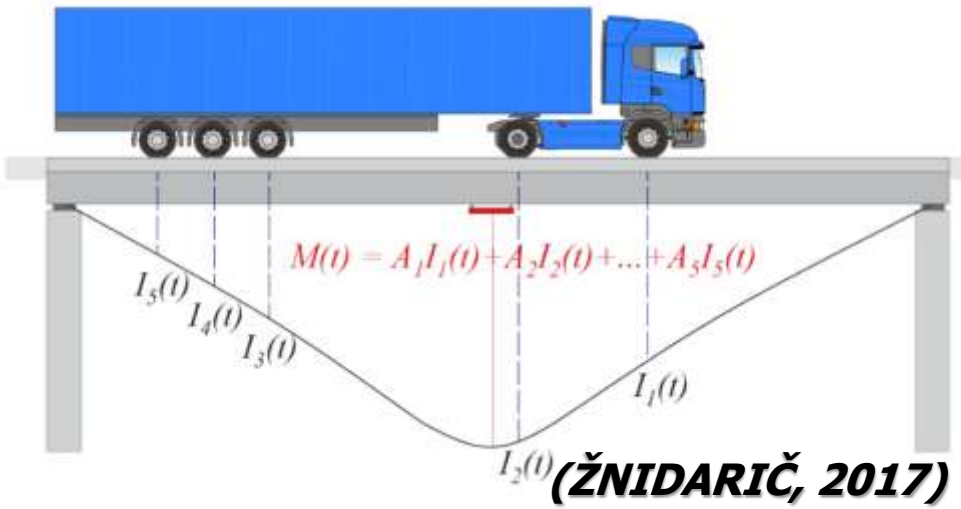
- Scour is the number one cause of bridge failures:
  - In most countries
  - Reported:
    - In United States (Briaud et al. (2014))
    - In Italy (D'Angelo et al. (2025))

Urgent need for more advanced and continuous monitoring techniques

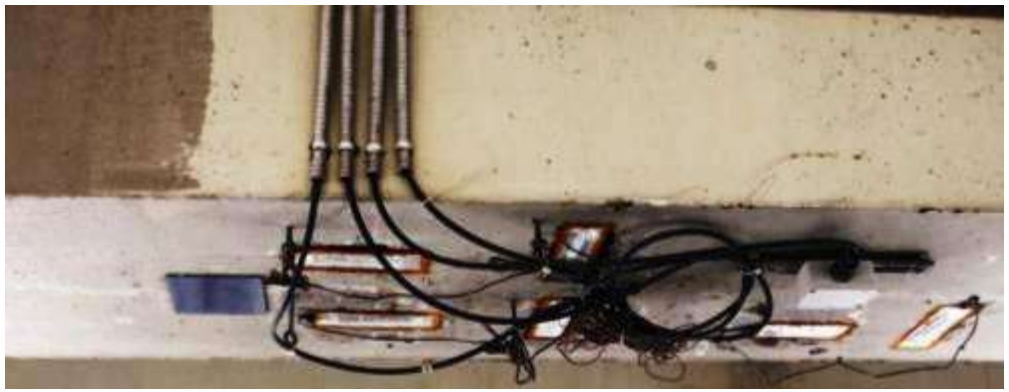
- Recognised more than 20 years ago (Chang et al. 2023)
- Traditional inspection/assessment techniques are irreplaceable, but are:
  - Expensive
  - Labour intensive
  - Rare (1 x every 3 years, every second inspection is principal inspection)
- Goal is to have a system that enables earlier detection of structural issues and more informed maintenance decisions

Literature review: terminology

- Bridge weigh-in-motion (B-WIM)
  - A specific weigh-in-motion technique that uses an instrumented bridge or culvert to weigh the passing vehicles at highway speed (Žnidarič, 2017)
- Structural health monitoring (SHM)
  - Integration of sensing and possibly also actuation devices to allow the loading and damaging conditions of a structure to be recorded, analyzed, localized, and predicted in a way that nondestructive testing (NDT) becomes an integral part of the structure and a material.” (Boller, 2009)
  - Process of implementation of a damage detection strategy (of civil engineering structures) (Farrar & Worden, 2012)



(ŽNIDARIČ, 2017)

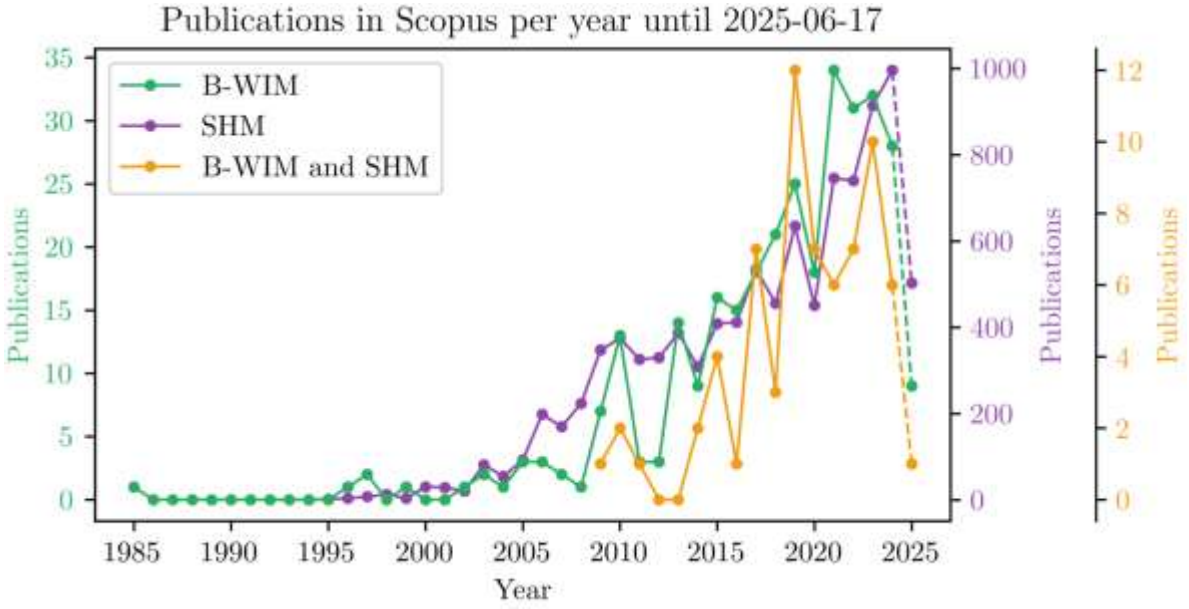


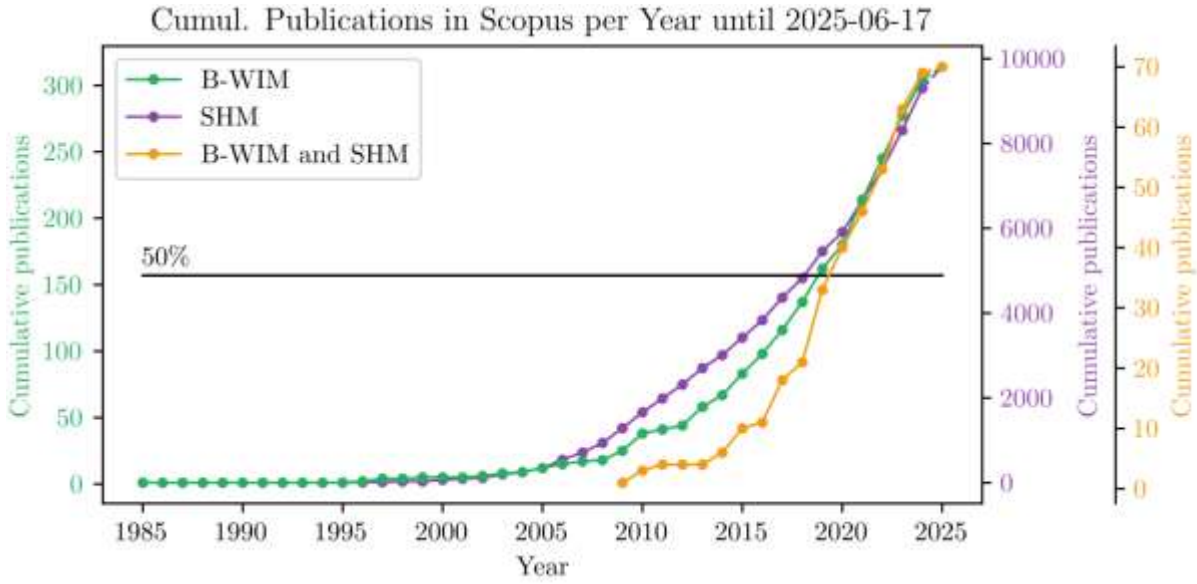
Finite element model updating (FEMU) - why?

- Finite element model updating (FEMU)
  - FEMU is a specific technique often used within SHM to update the FE model of a structure so that it accurately reflects the current (possibly damaged) state of the real structure (Ereiz et al. 2022).
- Safety analyses
  - When performing safety analyses of existing bridges it is crucial to have the realistic representation of the real structure (original design documentation is not enough)
- Damage detection
  - SHM → **model-driven** vs. data-driven approach

Literature review: Scopus database for B-WIM, SHM, B-WIM & SHM

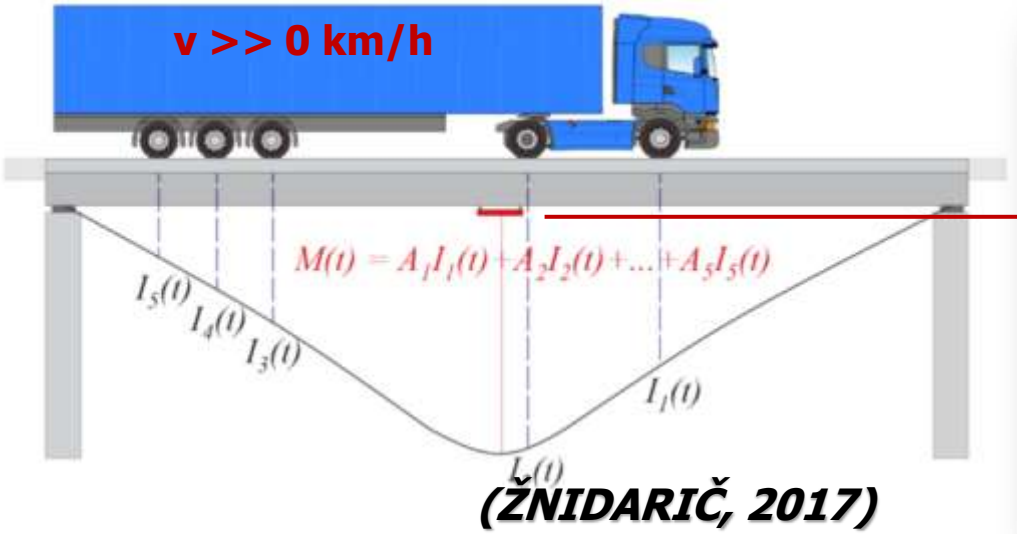
- Most of the B-WIM and SHM literature was published in last 6-7 years
- First B-WIM & SHM study was published (Scopus) in 2009





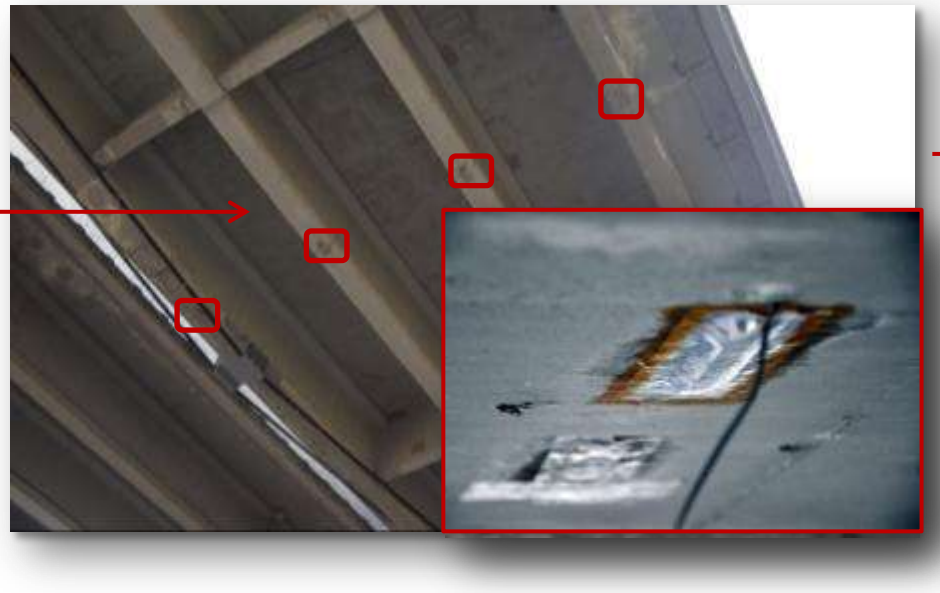
Theory background: B-WIM

- Core assumptions still valid from Moses (1979) : Bridge oscillates around a static equilibrium position during vehicle passage, Bernoulli's plane sections, linear stress-strain relationship
- Needs calibration with truck(s) of known weight

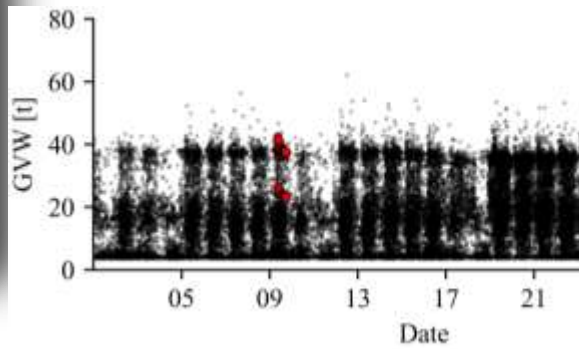


(ŽNIDARIČ, 2017)

$$M(t_j) = \sum_{i=1}^{N} A_i I(x) = \sum_{i=1}^{N} A_i I\left(v(t_j - t_i)\right);\ j = 1\ \ldots\ N_M$$

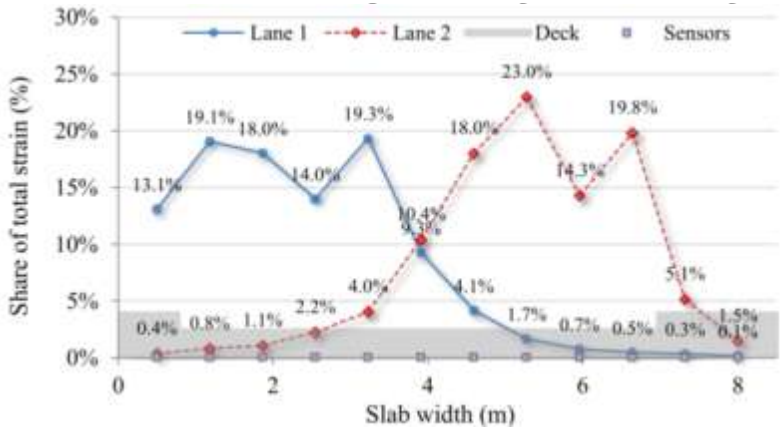


axle weights,
axle distances,
velocities

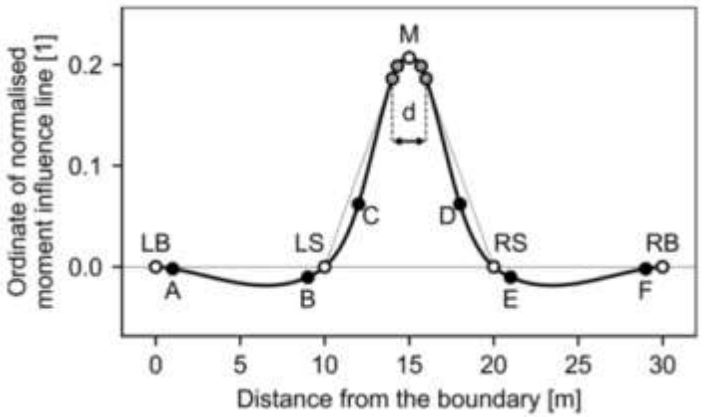


Theory background: B-WIM

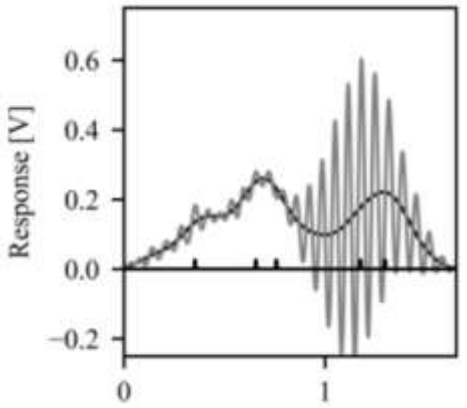
- Beside axle loads, other features can also be obtained from B-WIM system:
  - Load (girder) distribution factors
  - Influence Line
  - Dynamic Amplification Factor (DAF)



(ŽNIDARIČ, 2017)



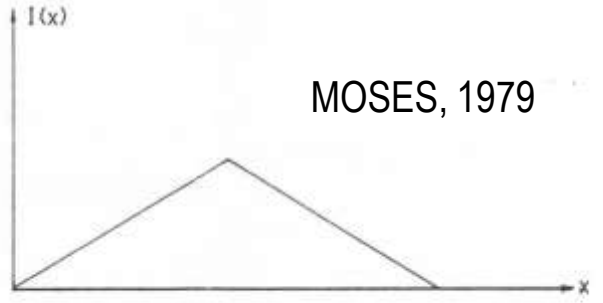
(ŽNIDARIČ & KALIN, 2020)



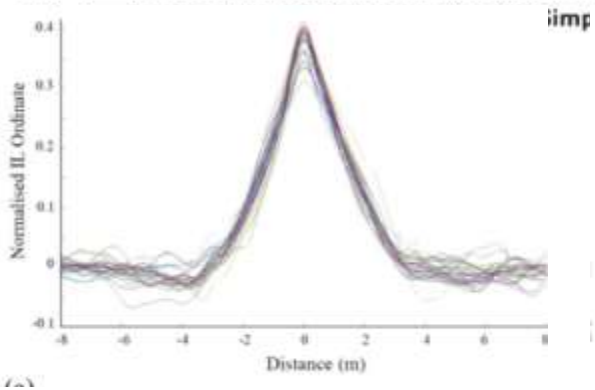
(KALIN ET AL., 2021)

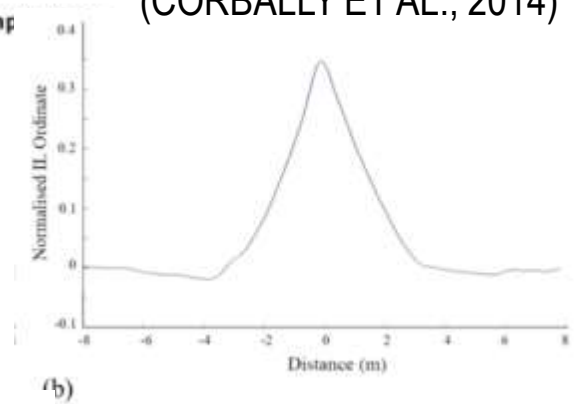
Theory background: B-WIM

- In the beginning of the B-WIM, the theoretical influence lines were used. Simply supported girder example → ideal triangular-shaped influence line.
- In 2000s, theoretical influence lines were replaced for measured ones (matrix method, ZAG method)
- In 2017, 2020 the parametrised ZAG method was introduced
- ZAG method employs non-linear optimisation and utilises a large number of randomly selected vehicles from regular traffic, whose axle loads are unknown, to estimate the influence line shape.
- To derive the ZAG influence line, same equation is used as for the weighing, with additional parameters that describe the shape of the influence line.
- Slight modification of the ZAG influence line had to be done, because the original ZAG methos normalises the influence line such that the area under influence line is 1

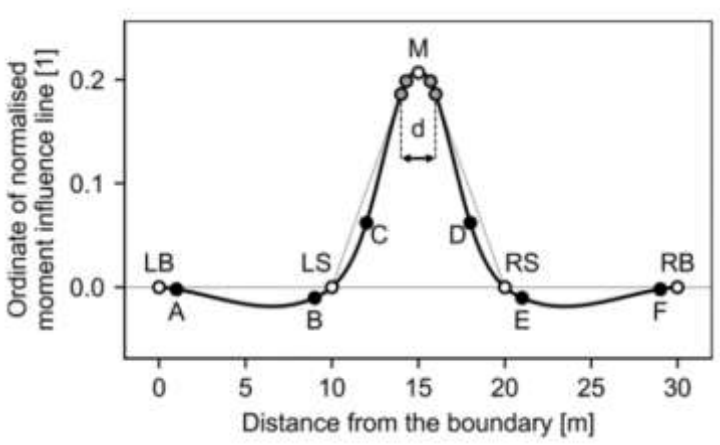


MOSES, 1979





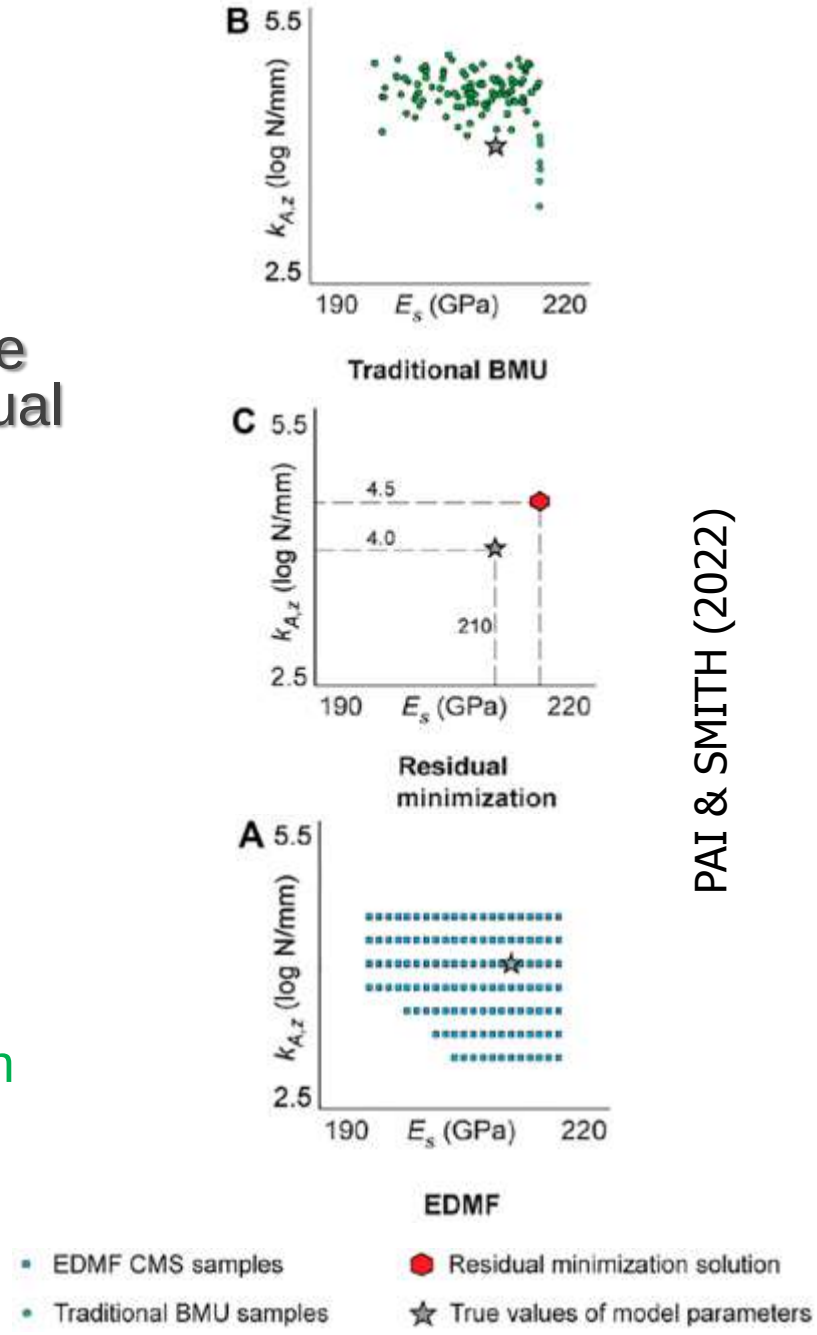
(MCNULTY ET AL., 1999)
(OBRIEN ET AL., 2005)
(CORBALLY ET AL., 2014)



(ŽNIDARIČ, 2017)
(ŽNIDARIČ & KALIN, 2020)

Theory background: FEMU

- The FEMU problem is defined as the difference between the structural behaviour predicted by the FE model and the actual (measured) behaviour.
  - Iterative stochastic FEMU → statistical problem
    - Bayesian interference
  - Iterative deterministic FEMU → optimisation problem)
    - FEMU is performed using the maximum likelihood method (MLM)
    - Single-objective (used in this PhD) and multi-objective optimisations
    - Manual FEMU → trial and error approach
    - Automatic FEMU → nonlinear optimisation using various algorithms:
      - Sequential least squares programming (SLSQP)
      - Particle swarm optimisation (PSO)
      - Genetic algorithm (GA)
  - Error-domain model falsification (EDMF) → gaining attention in recent years (used in the PhD)
    - Karl Popper's concept from 1930's
    - Models cannot be fully validated by data, they can only be falsified



PAI & SMITH (2022)

Theory background: FEMU

- Residual minimisation
  - Most authors minimise the difference of dynamic data:
    - **Natural frequencies** (most often)
    - **Mode shapes** through modal assurance criterion (MAC) (often)
    - **Combination** of natural frequencies and mode shapes (less often)
- Studies considering static data sets **(strains, displacements) are rare**
- Few studies combine static and dynamic data sets

$$J_f = \sum_{i=1}^{n} \left(f_{i,\mathrm{nu}}{}^{\mathrm{m}} - f_{i,\mathrm{ex}}{}^{\mathrm{p}}\right)^2 \quad J_f = \sum_{i=1}^{n} \left(\frac{f_{i,\mathrm{nu}}{}^{\mathrm{m}} - f_{i,\mathrm{ex}}{}^{\mathrm{p}}}{f_{i,\mathrm{ex}}{}^{\mathrm{p}}}\right)^2$$

$$\mathrm{MA}^{\mathrm{C}}(\psi_{ci}, \psi_{di}) = \frac{|\{\psi_{ci}\}^T \{\psi_{di}^*\}|^2}{\{\psi_{ci}\}^T \{\psi_{ci}^*\} \{\psi_{di}\}^T \{\psi_{di}^*\}}$$

$$J_{\mathrm{MA}}{}^{\mathrm{C}} = \sum_{i=1}^{n} (1 - \mathrm{MA}^{\mathrm{C}}{}_i)^2$$

$$J_{f,\mathrm{MA}}{}^{\mathrm{C}} = w_f \cdot J_f + w_{\mathrm{MA}}{}^{\mathrm{C}} \cdot J_{\mathrm{MA}}{}^{\mathrm{C}}.$$

$$J_\varepsilon = \sum_{v=1}^{n_v} \sum_{g=1}^{n_g} \frac{\left(\mathrm{z}_{\mathrm{nu}}{}^{\mathrm{m}}{}_{,v,g} - \mathrm{z}_{\mathrm{ex}}{}^{\mathrm{p}}{}_{,v,g}\right)^2}{\mathrm{ST}^{\mathrm{D}}{}_{\mathrm{ex}}{}^{\mathrm{p}}{}_{,v,g}{}^2}$$

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CESTEL

DEWESoft measurement innovation

Model updating of bridges using measured influence lines

Goal:

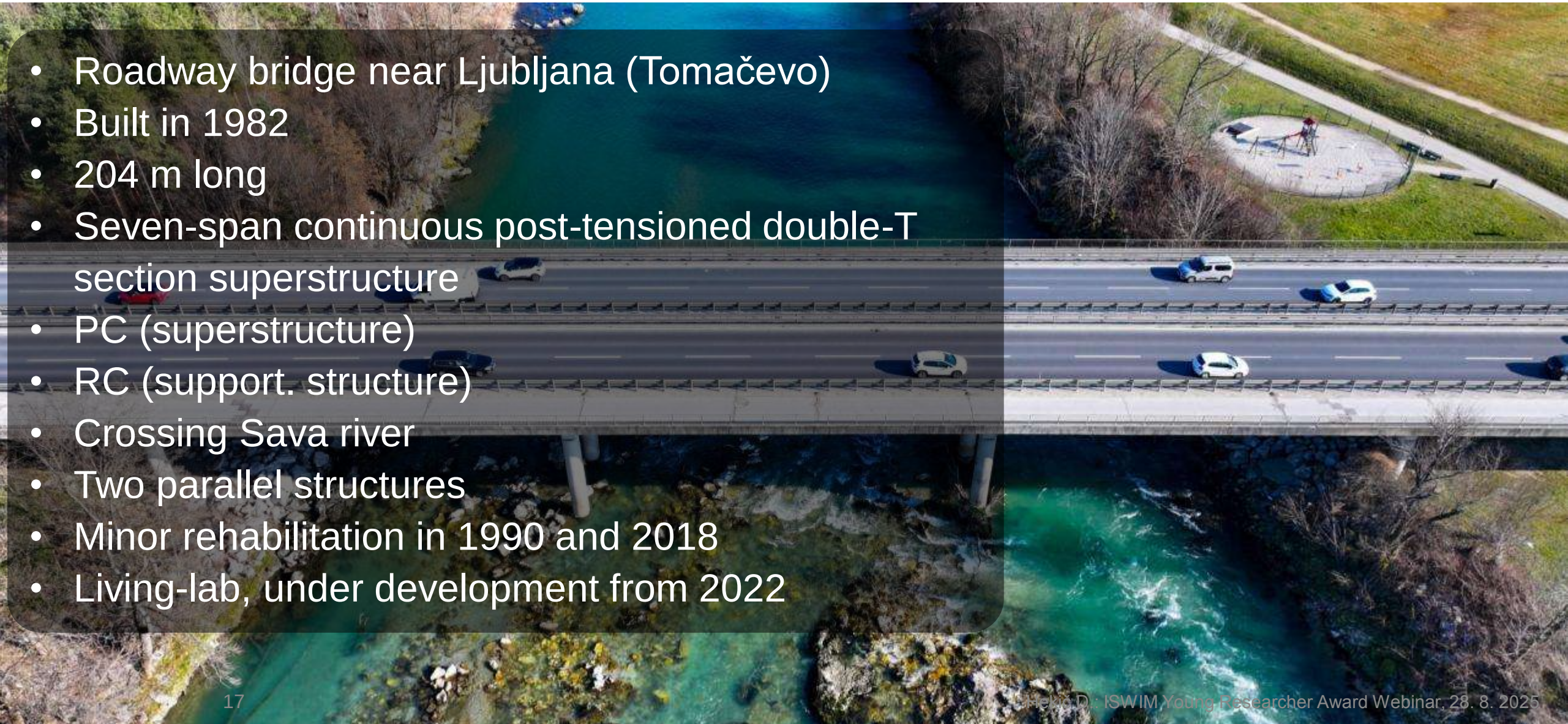
1) Find out if it is possible to use B-WIM derived strain IL for FEMU and

2) how it performs compared to other, traditonal (acceleration-based) FEMU

Aim:

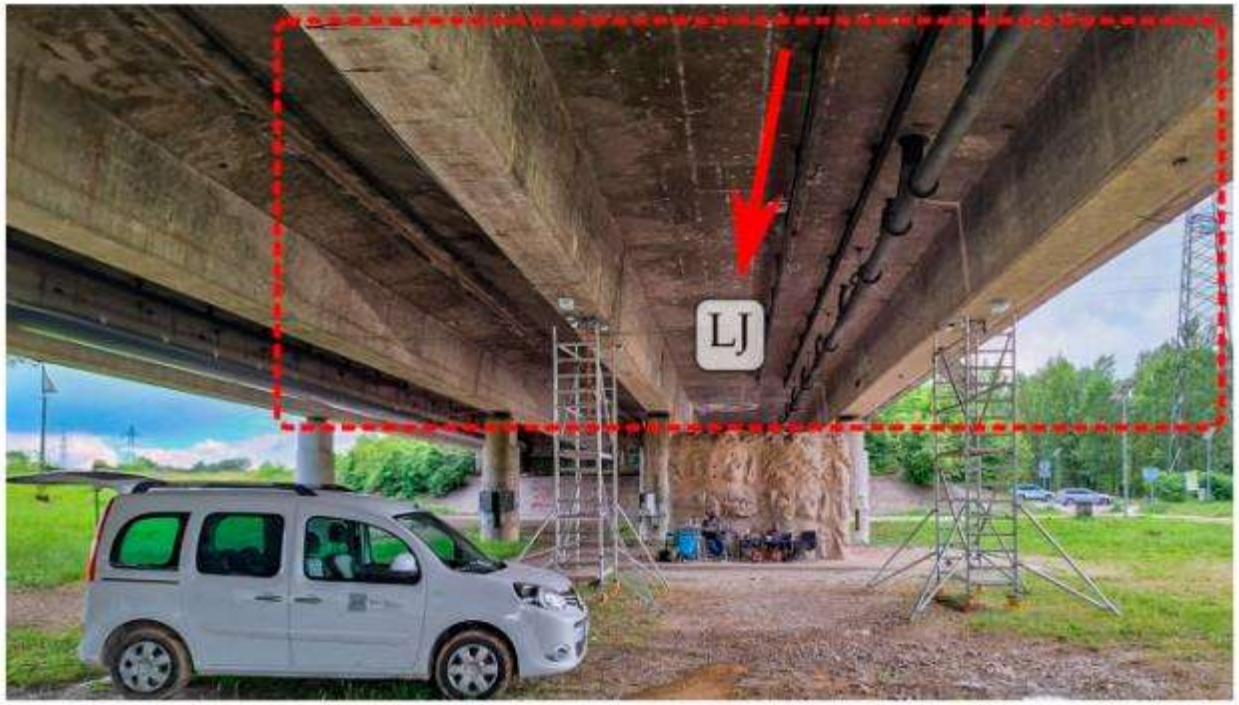
Extending B-WIM towards SHM through usage of the B-WIM derived influence line for the FEMU

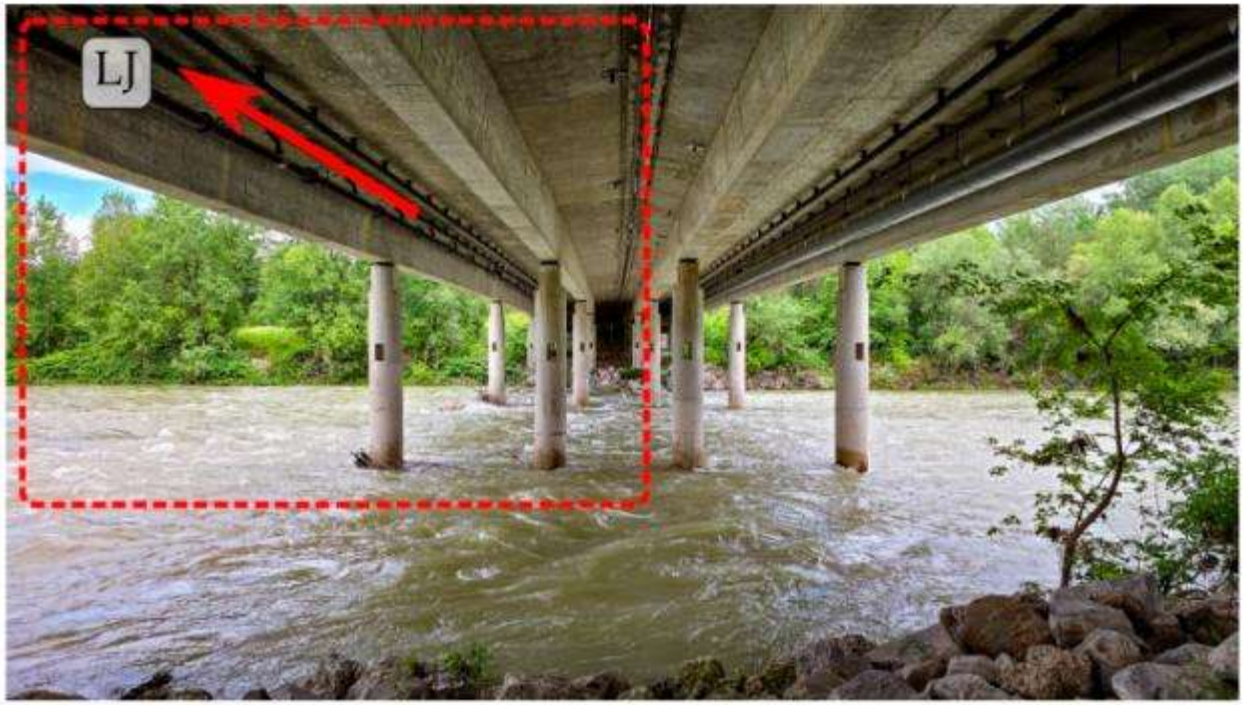
Case study viaduct

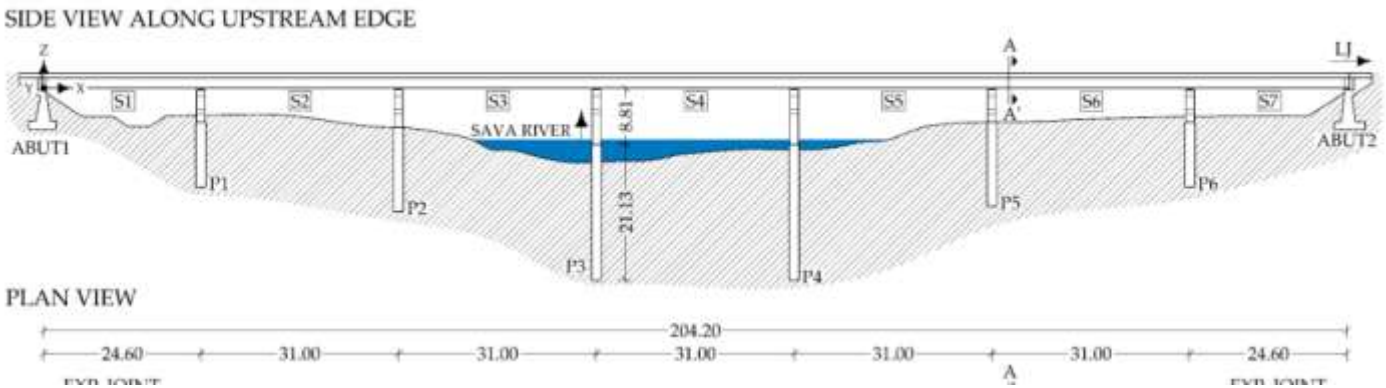


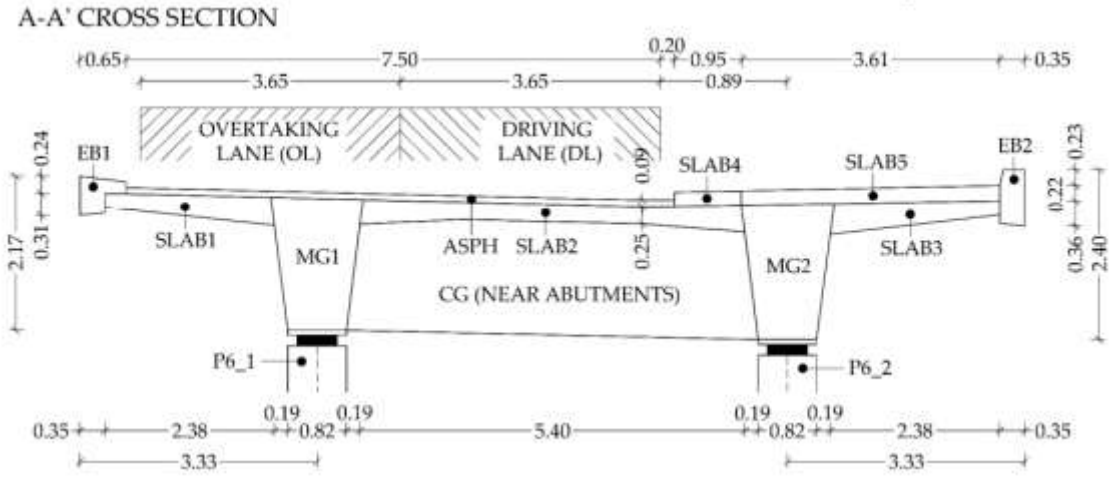
- Roadway bridge near Ljubljana (Tomačevo)
- Built in 1982
- 204 m long
- Seven-span continuous post-tensioned double-T section superstructure
- PC (superstructure)
- RC (support. structure)
- Crossing Sava river
- Two parallel structures
- Minor rehabilitation in 1990 and 2018
- Living-lab, under development from 2022

Case study viaduct



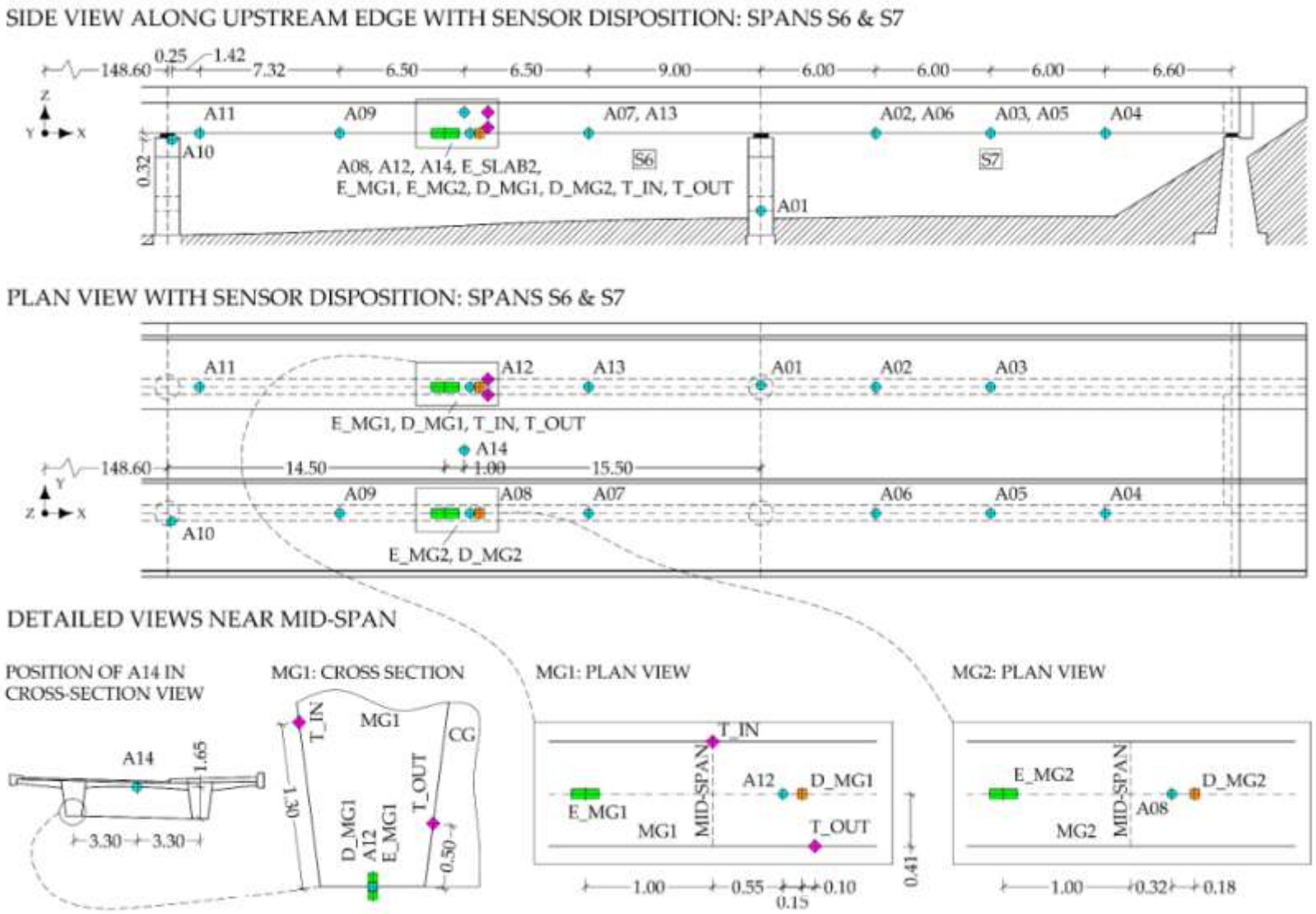






Measurements

- Sensors are installed in last two spans
- Sensors used for this study:
  - 14 accelerometers
  - 2 strain sensors (used for B-WIM), one on each girder's mid-span
  - 4 strain-based axle detectors (for B-WIM)
  - 2 displacement sensors
  - 2 temperature sensors
- 1st source of data: traffic induced strains and displacements
- 2nd source of data: modal parameters from ambient and traffic induced vibrations



Experimental campaign

Calibration vehicle passages

- 2 different calibration vehicles
- Full on the 1st night, empty on the 2nd
- Overall 72 passages

(a) (b)

Figure 7. Calibration vehicles: V1 (**a**) and V2 (**b**).

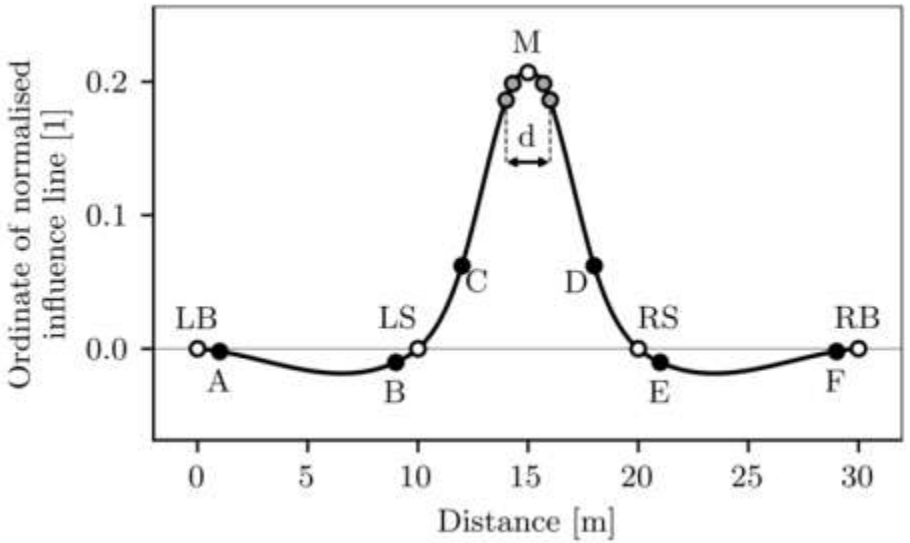
Table 1. Axle loads, axle spacing, and gross vehicle weights (GVW) of the calibration vehicles.

	1st Axle		2nd Axle		3rd Axle		4th Axle		5th Axle	
Vehicle [1]	Load (kN)	Spacing (m)	Load (kN)	Spacing (m)	Load (kN)	Spacing (m)	Load (kN)	Spacing (m)	Load (kN)	GVW (kN)
V1_F	68.67	3.42	73.58	1.37	71.61	/	/	/	/	213.86
V1_E	57.88	3.42	37.28	1.37	36.30	/	/	/	/	131.45
V2_F	69.65	3.60	90.25	2.82	64.75	1.31	61.80	1.31	59.84	346.29
V2_E	56.90	3.60	29.43	2.82	14.72	1.31	15.70	1.31	14.72	131.45

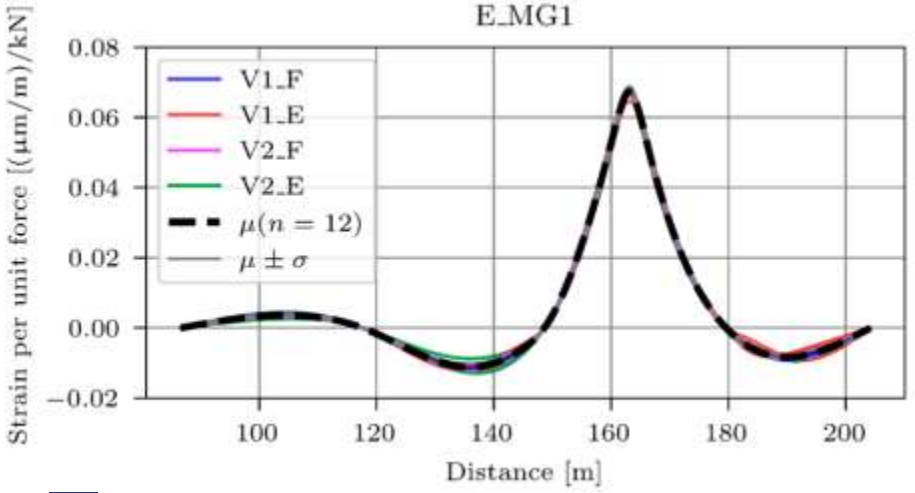
[1] F represents a fully loaded truck, and E an empty truck.

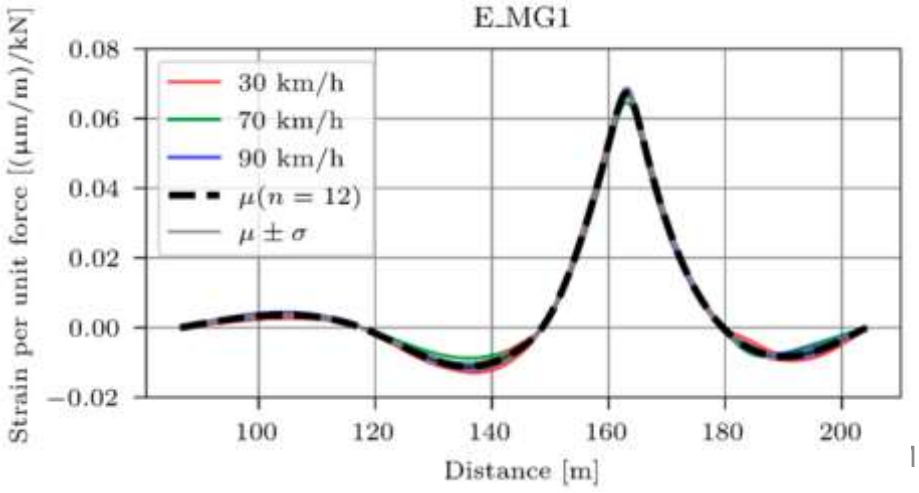
Extraction of the B-WIM influence line

- ZAG's method was used to extract the B-WIM influence line from the vehicle-induced mid-span strains.
- Modification was performed to replace normalised influence line for absolute.
- Influence of the following parameters on the influence line was investigated:
  - vehicle type (rigid vs. tractor with a semi-trailer)
  - load (loaded vs unloaded vehicles)
  - different speeds (30, 70, 90 km/h)



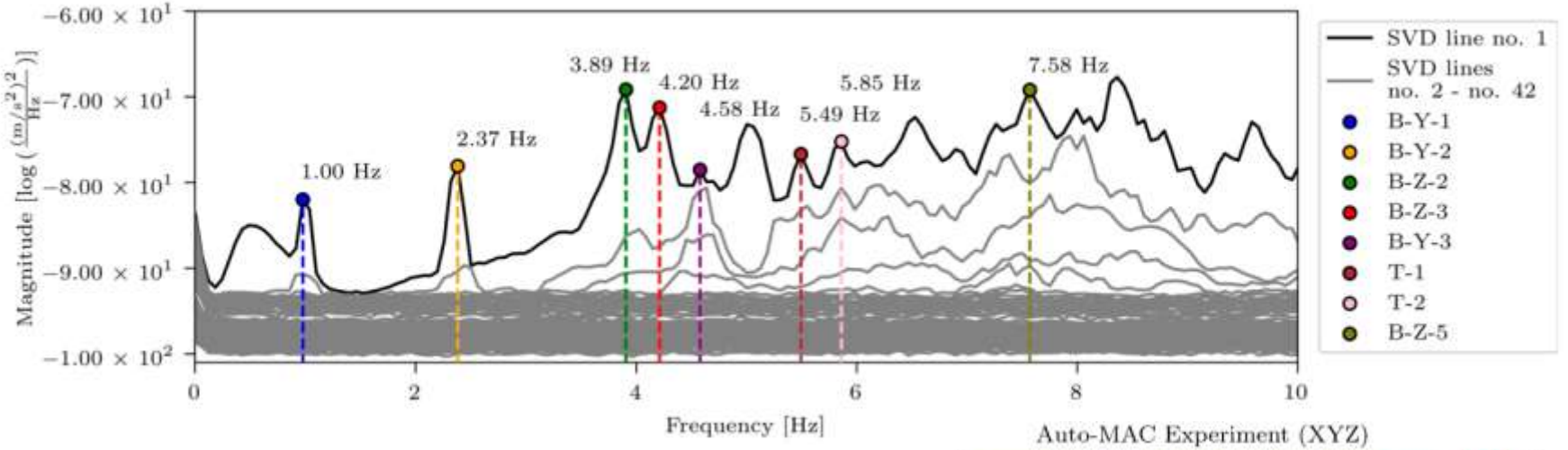
$$s(t_j) = \sum_{i=0}^{N} A_i I(v_i(t_j - t_i));\ j = 1 \ldots M$$

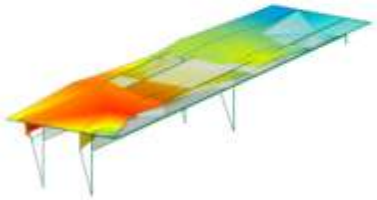
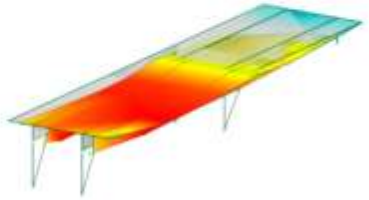
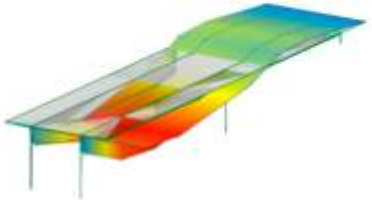
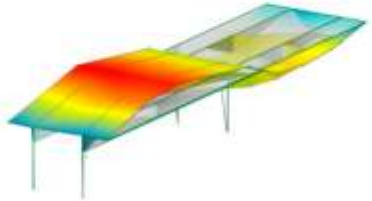
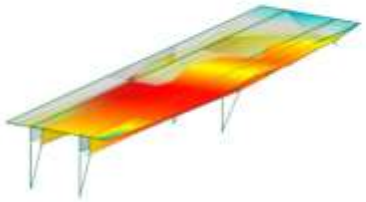
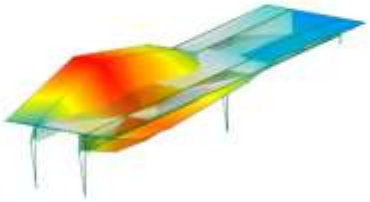
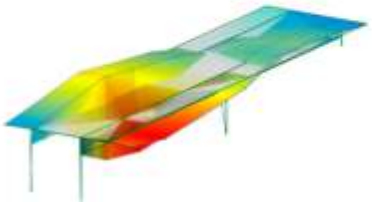
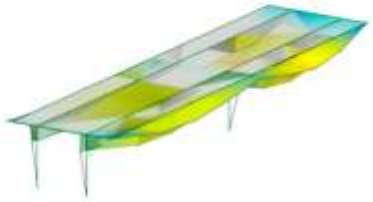


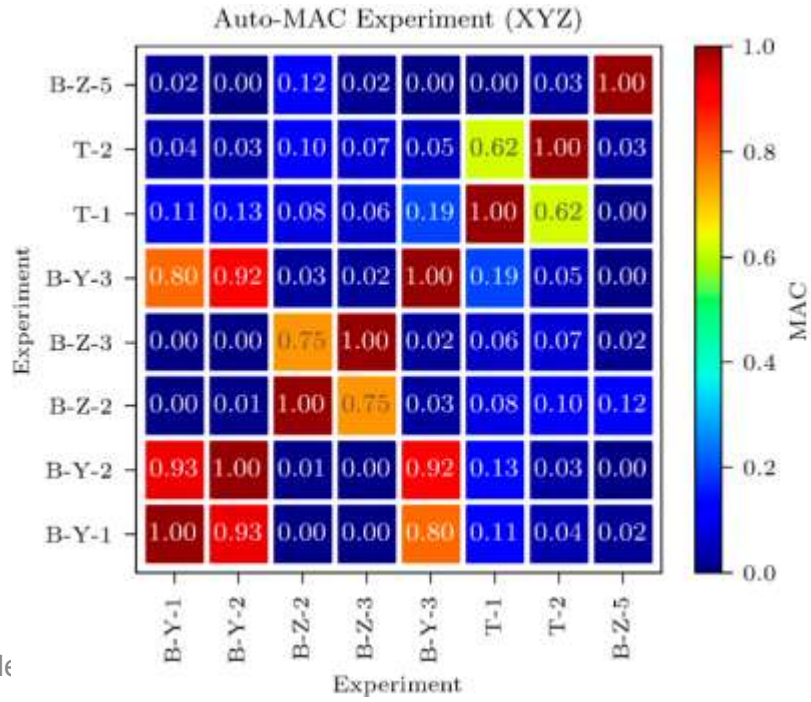


- Small deviation
- Mean influence line for both strain-sensors were determined and

Ambient and traffic induced vibrations and extraction of modal parameters

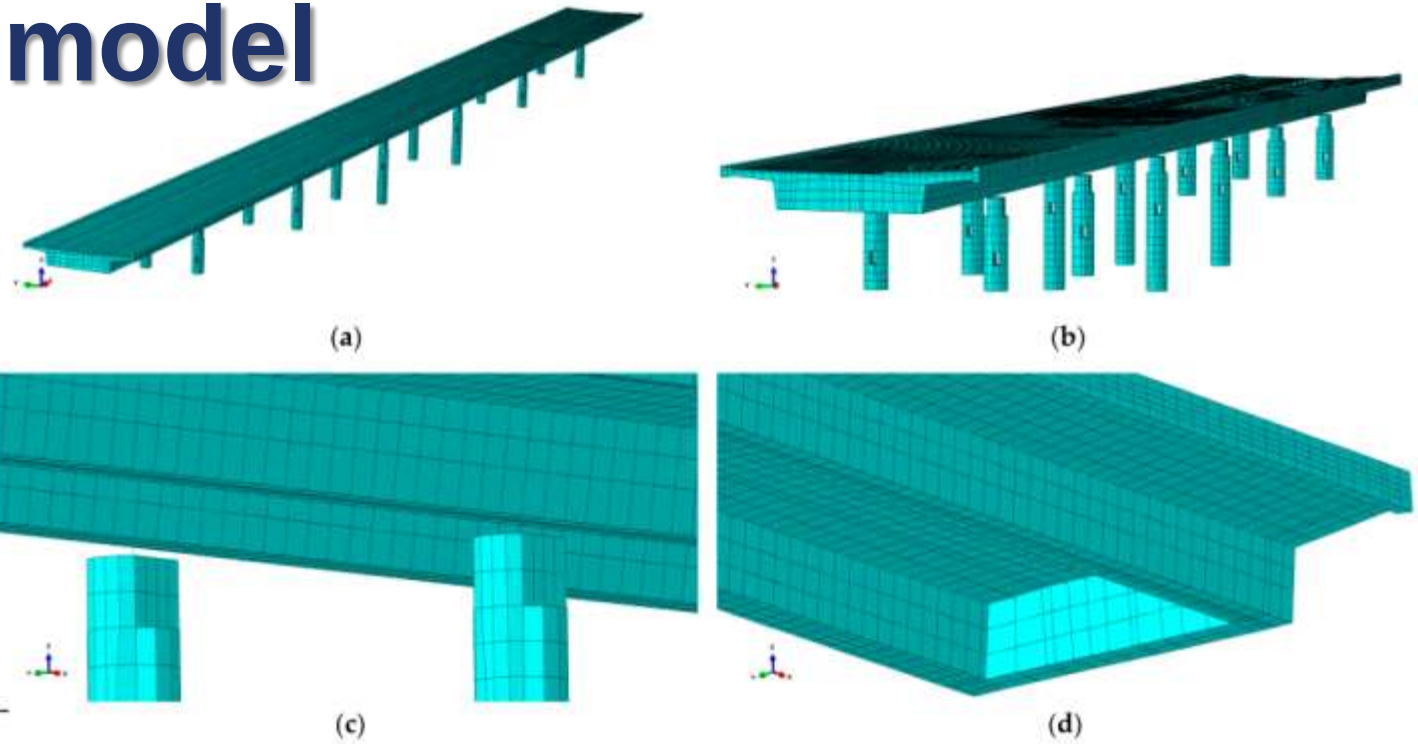


B-Y-1	B-Y-2	B-Z-2	B-Z-3
1.00 Hz	2.37 Hz	3.89 Hz	4.20 Hz
			
B-Y-3	**T-1**	**T-2**	**B-Z-5**
4.58 Hz	5.49 Hz	5.85 Hz	7.58 Hz
			



Finite element (FE) model

- Seven spans (entire bridge)
- AutoCAD 3D solids → Abaqus CAE 2023
- C3D20R finite elements for superstructure
- C3D8R finite elements for the piers
- Elastomeric bearings → springs
- Properties from design documentation

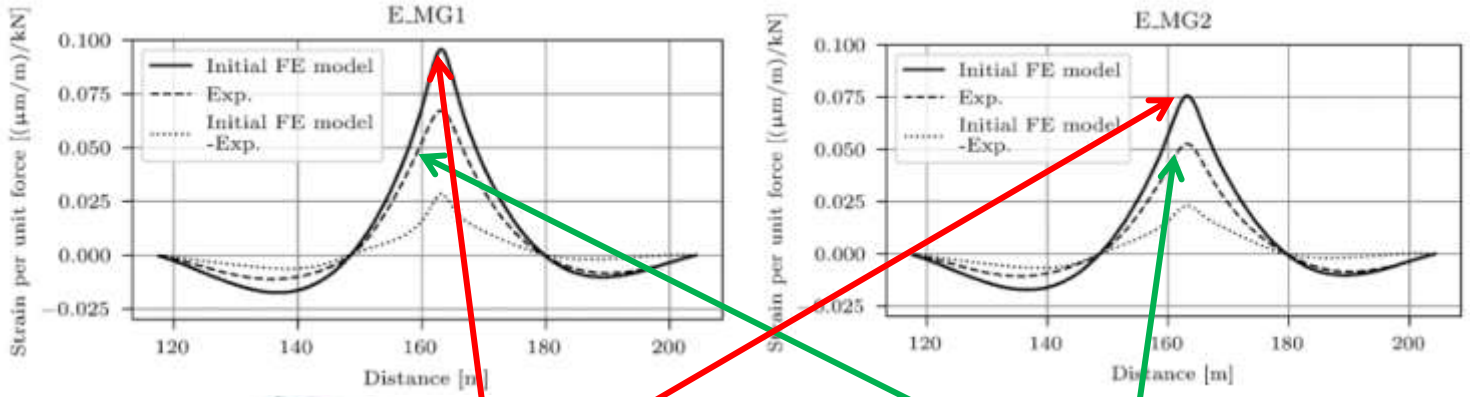


Element	Abbreviation	Young's Modulus (GPa)	Poisson Ratio	Density (t/m^3)
Asphalt	ASPH	8.00	0.35	2.582
Edge beam 1	EB1	31.00	0.20	2.710
Edge beam 2	EB2	31.00	0.20	2.580
Main girder 1	MG1	35.00	0.20	2.500
Main girder 2	MG2	35.00	0.20	2.500
Slab 1	SLAB1	35.00	0.20	2.500
Slab 2	SLAB2	35.00	0.20	2.500
Slab 3	SLAB3	35.00	0.20	2.500
Slab 4	SLAB4	35.00	0.20	3.573
Slab 5	SLAB5	14.59	0.20	1.177
Pier (bottom part) [1]	PIER_BOTTOM	31.00	0.20	2.500
Pier (upper part, bearing region) [1]	PIER_TOP	34.00	0.20	2.500
Cross girder	CG	35.00	0.20	2.500

[1] PIER_BOTTOM represents the bottom parts, and PIER_TOP represents the top parts (bearing region) of all pier pairs: P1, P2, P3, P4, P5, and P6.

Bearing	Position (Abutment, Pier)	Translational Stiffness (kN/m)		Vertical Stiffness (kN/m)	Rotational Stiffness (kNm)
		X Direction	Y Direction		
Elastomeric bearing type 1	P1, P6	3.18×10^3	3.18×10^3	1.77×10^6	3.41×10^4
Elastomeric bearing type 2	P2, P3	3.61×10^3	3.61×10^3	2.01×10^6	3.90×10^4
Elastomeric bearing type 3	P4, P5	4.19×10^3	4.19×10^3	2.33×10^6	4.55×10^4
Unidirectional pot bearing	ABUT1, ABUT2	Free	Rigid	Rigid	Free (<0.01°)

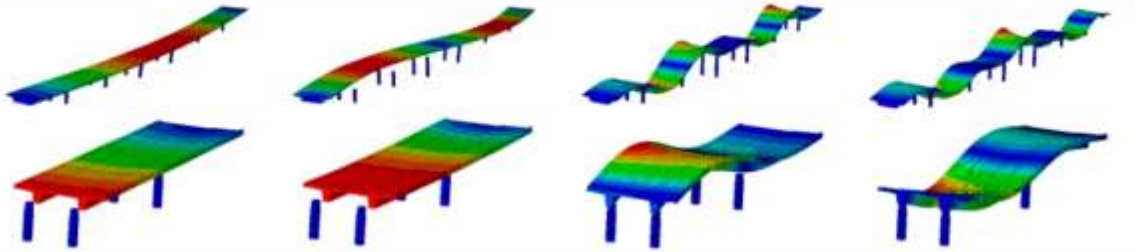
FE model vs. measurements



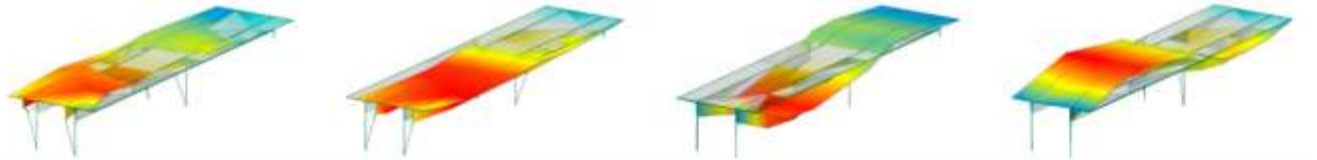
MODELLED

MEASURED

B-Y-1	B-Y-2	B-Z-2	B-Z-3
0.72 Hz	2.01 Hz	3.79 Hz	4.41 Hz



B-Y-1	B-Y-2	B-Z-2	B-Z-3
1.00 Hz	2.37 Hz	3.89 Hz	4.20 Hz



Sensitivity study

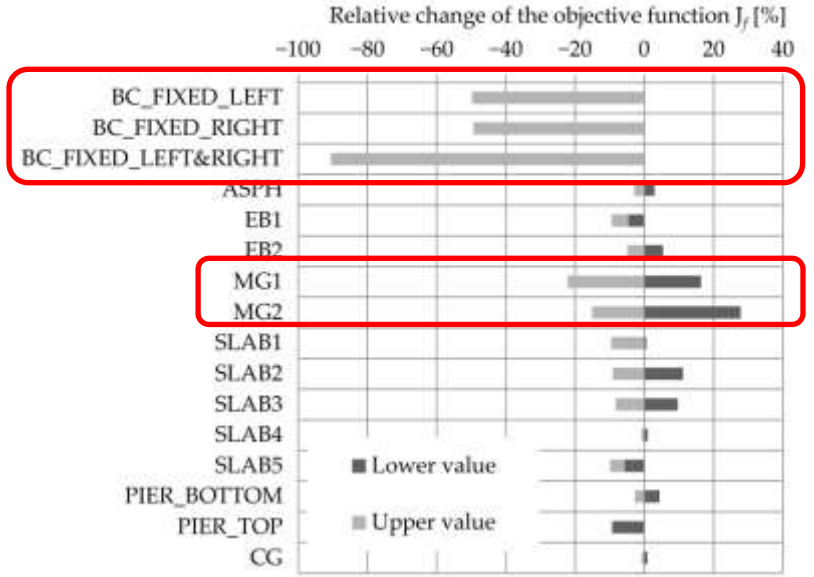
- Deterministic sensitivity study was performed to select the variables (parameters) to update
- 2 objective functions were defined to perform the sensitivity study
  - Natural frequencies

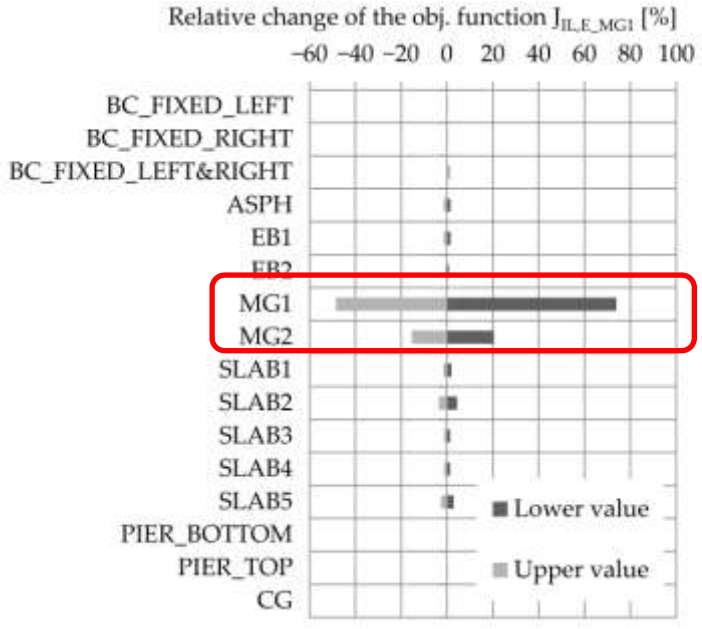
$$J_f = \sum_{i=1}^{n} \left(\frac{f_{i,\text{num}} - f_{i,\text{exp}}}{f_{i,\text{exp}}} \right)^2$$

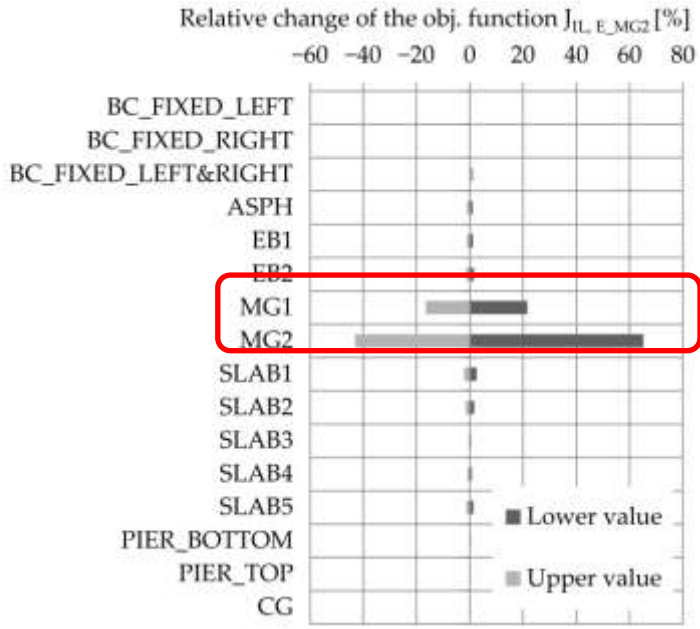
  - Strain influence line

$$J_{\text{IL}} = \text{RMSE} = \sqrt{\frac{\sum_{j=1}^{m} \left(\text{IL}_{\text{num},j} - \text{IL}_{\text{exp},j} \right)^2}{m}},$$

- The following properties/elements are the most sensitive:
  - Boundary conditions (abutments's bearings)
  - Main girder 1 (MG1), main girder 2 (MG2)





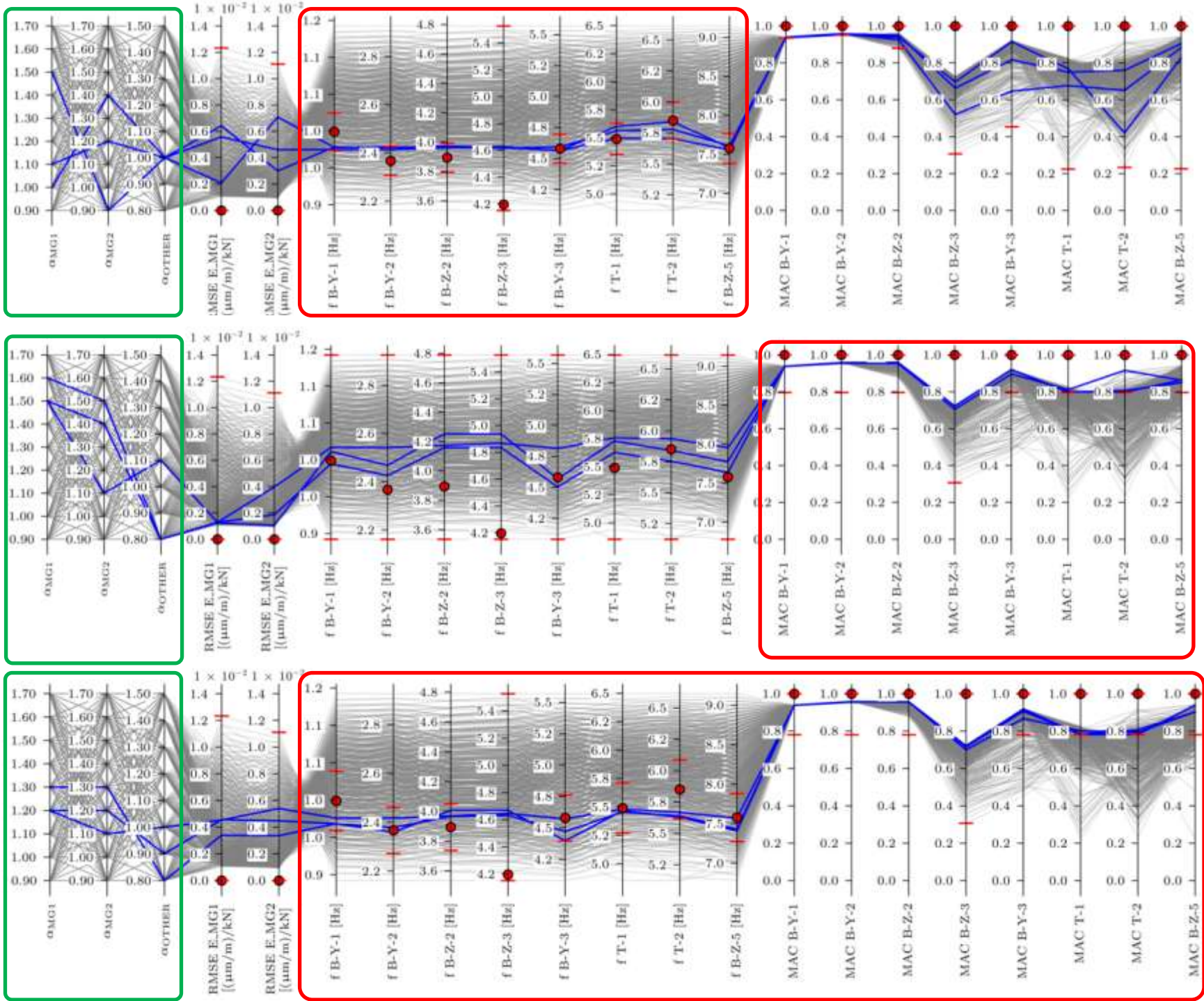


List of performed studies (4 + validation)

- Frequency-based EDMF
  - Only natural frequencies are considered
- MAC-based EDMF
  - Only mode shapes are considered
- Frequency & MAC-based EDMF
  - Both frequencies and mode shapes are considered
- Strain IL-based EDMF
  - Influence line is considered
- Validation
  - Validation is performed for the acceleration-based (frequency and MAC-based EDMF) and for the strain IL-based EDMF

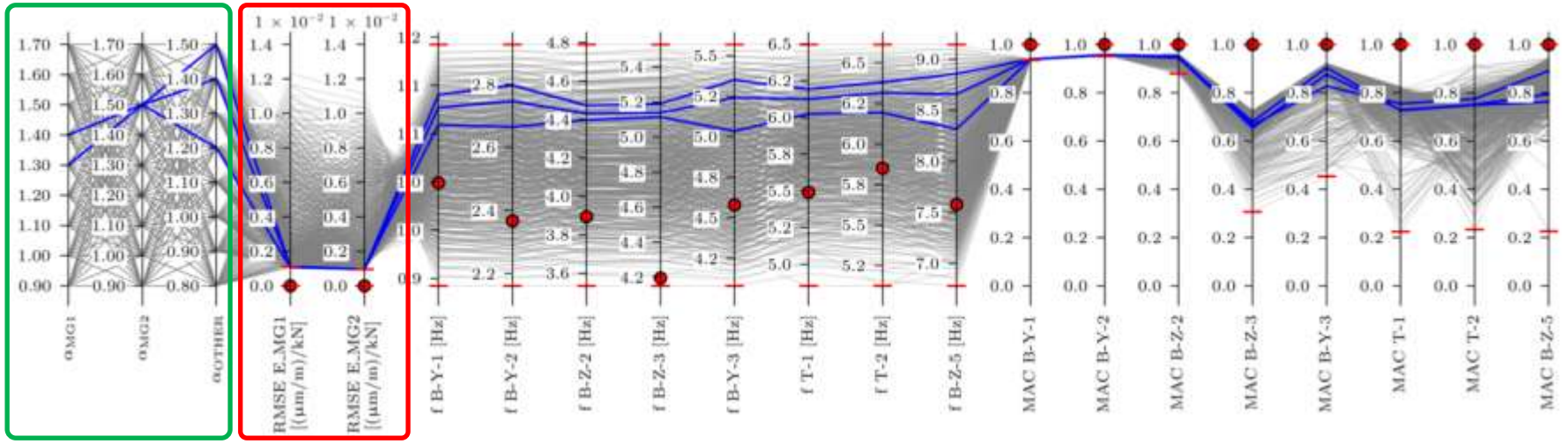
EDMF results

- Frequency-based EDMF results are consistent with the 2nd PhD paper (high $\alpha_{\mathrm{IM}^{\mathrm{G}}}$ and low α_{EMG} and vice-versa),
  → not engineeringly expected
- MAC-based EDMF gives very high values of both α_{MG1} and α_{MG2}
  → not engineeringly expected
- Combination of frequency and MAC-based EDMF gives the best, sensible



Strain IL-based EDMF and comparison of EDMF results

- Frequency-based EDMF primarily improved the frequency values; a minor improvement was also seen for E-MG1 and E-MG2 strain ILs. The MAC values decreased.
- MAC-based improved MAC values, improvement in E-MG1 and E-MG2 strain Ils was greater than that in the frequency-based EDMF.
- Frequency and MAC-based EDMF improved frequencies and MACs, closely matching the results of frequency-based EDMF (for frequencies) and MAC-based EDMF (for MAC values), while both strain ILs did not align more closely with the measured ones.
- Strain-based EDMF only



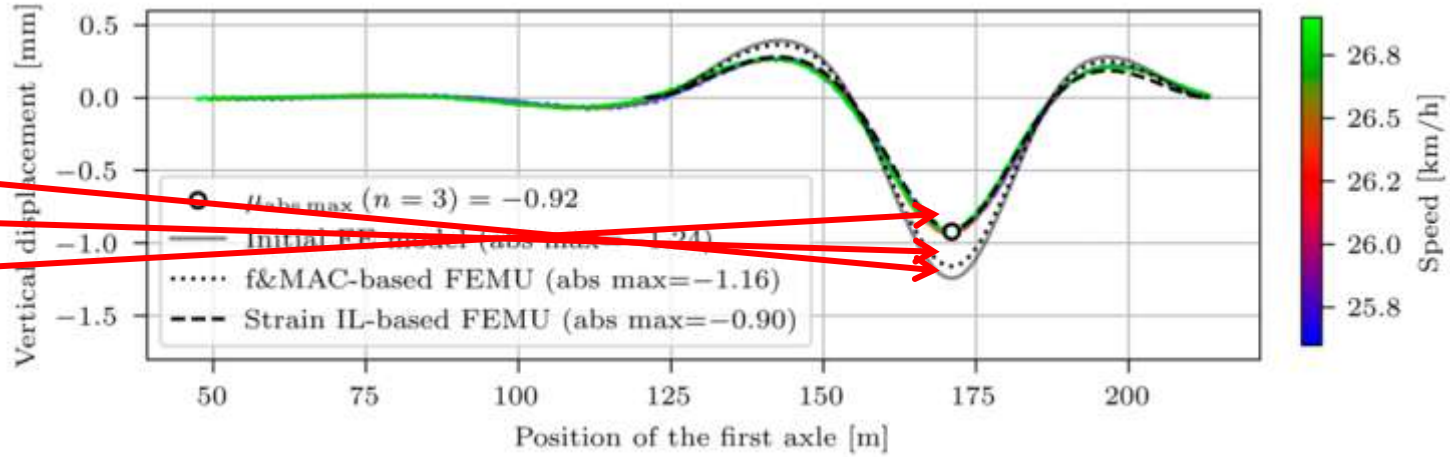
FEMU Results	α_{MG1}	α_{MG2}	α_{OTHER}
Initial FE model	1.0	1.0	1.0
Frequency-based	1.0–1.5	0.9–1.4	1.0
MAC-based	1.5–1.6	1.1–1.5	0.8–1.1
Frequency and MAC-based	1.2–1.3	1.1–1.3	0.8–1.0
Strain IL-based	1.3–1.4	1.5	1.2–1.5

Validation (example for main girder 2)

D-MG2 mid-span vertical displacements under passage of calibration vehicle V2 -F

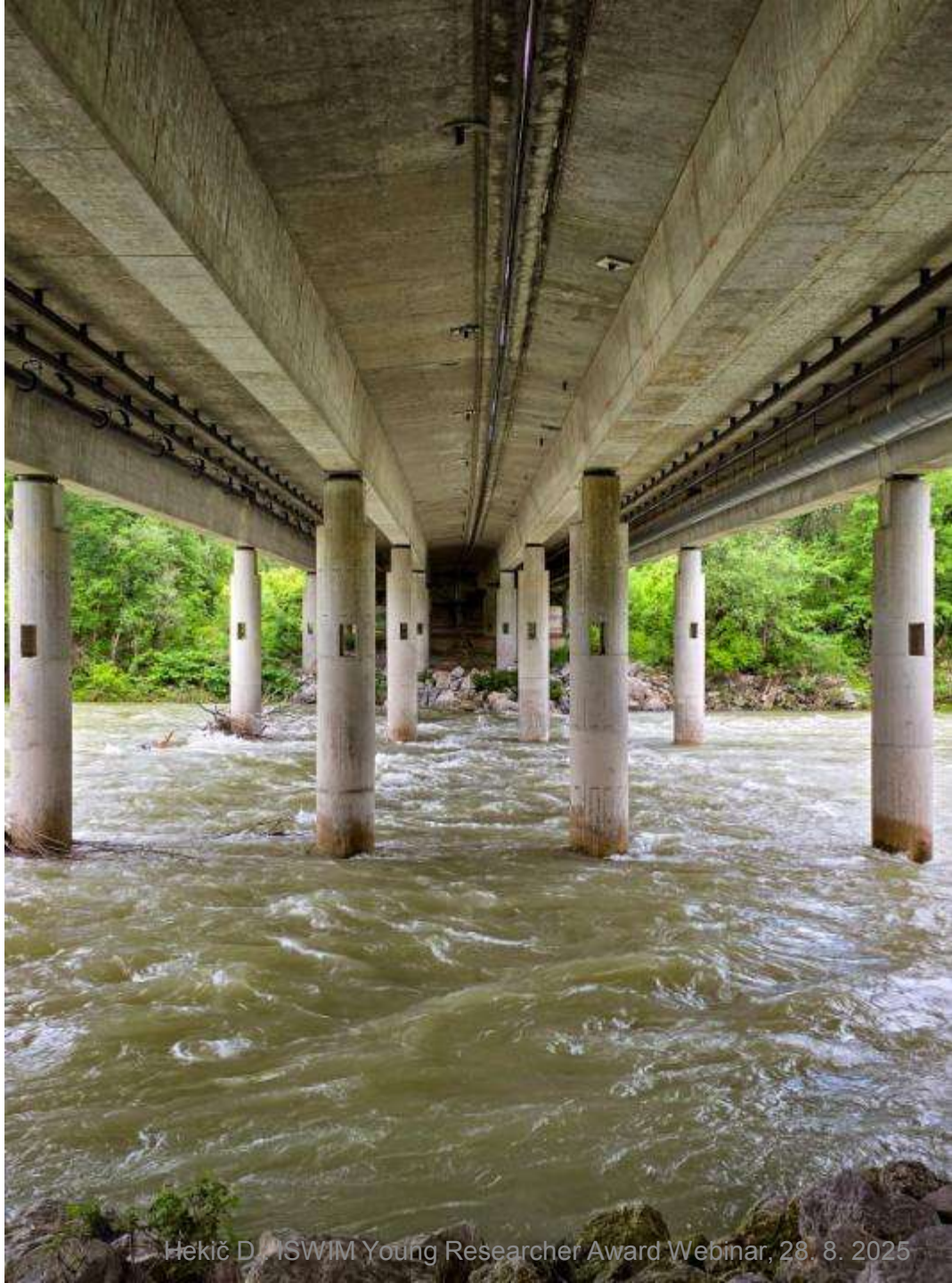
Max. response overestimation:

- Initial FE model: 35%
- Freq & MAC-based EDMF: 25%
- Strain-based IL EDMF: -2%



Conclusions

- Extensive experimental campaign, capturing **strains under calibration vehicles and ambient&traffic induced vibrations.**
- **Upgrading the ZAG's influence line** from normalised to absolute definition, investigating its load and speed dependence.
- **4 separate FEMU studies** to investigate the strain IL-based with the more common, acceleration-based FEMU results.
- **Validation** of the updated FE model with **independently measured vertical displacements.**
- **Relying solely on automatic FEMU**, without prior manual refinement, **can lead to misleading parameter estimates** due to unaccounted non-structural elements or incorrect boundary conditions.
- B-WIM extracted strain Ils can be used for FEMU
- **Strain IL-based FEMU results better matches with the measured displacements** and strains under calibration vehicles **than acceleration-based**
- **Bending stiffness** of the case study viaducts is **≈30% higher than designed.**
- Importance of aligning the measurement types with the intended model application: **acceleration data for dynamic behaviour** and **strain data for strain or displacement responses (safety analyses).**
- The thesis represents **step forward in bringing B-WIM systems closer to SHM**



Thank you for your attention!

doronhekic

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ZAG

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