Società Italiana di Scienza delle Costruzioni

CONSIGLIO NAZIONALE INGEGNERI

AISI – ASSOCIAZIONE ITALIANA DI STORIA DELL'INGEGNERIA

Ars Pontificia et Scientia: alcune riflessioni

WEBINAR – 2 luglio 2021

IDENTIFICAZIONE DINAMICA DEL DANNO IN UN PONTE IN CEMENTO ARMATO

Antonino Morassi

Università degli Studi di Udine

Introduction - 1

- Dynamic methods are a powerful tool to identify modifications that may have occurred in structures during service
- One of the main difficulties lies in the **small sensitivity** of the dynamic parameters to damage
- This is a **source of important indeterminacy** and the effects still are not completely clarified for complicated structures
- As a consequence, **when diagnostic techniques are applied to the study of real-world civil engineering systems, such as in-situ bridges, serious obstacles arise**, owing to modeling uncertainty, measurement errors, incomplete experimental data and changes in environmental and operational conditions

Introduction - 1

- It is probably because of these difficulties that, so far, **a limited number of studies** have investigated the effect of damage on modal parameters of full-scale bridges and have developed suitable strategies for damage identification

  Farrar et al. (I-40 Bridge 1994); Maeck & De Roeck (Z24 Bridge 2003); Maas et al. (2012); Chang & Kim (2016)

- A critical review of the literature on this topic shows that **there is still no general consensus** among experts on the type of data to be taken as good indicator of damage and also on the effectiveness of a diagnostic method rather than another

An overview - 1

- Some authors agree that **changes in natural frequencies** are measurable and do provide some indication of the structural modifications

  Kato & Shimada (1986); Salane & Baldwin (1990); Chang & Kim (2016); Maas et al. (2016)

- The experience of other researchers is different and they reported that **natural frequencies could not reliably identify** the location and level of damage

  Toksoy & Aktan (1994); Farrar & Jauregui (1998)

An overview - 2

- Also **changes in mode shapes have been judged sometimes poor indicators of damage**. However, from several studies emerged that **mode shapes are the best indicators of where the damage is occurring**

  Mazurek & De Wolf (1990); Salane & Baldwin (1990)

- In particular, **the ability to identify damage by mode shapes turns out to be improved** by applying suitable damage identification techniques, such as those based on:
  - **modal flexibility reconstruction** (Toksoy & Aktan 1994; Catbas, Brown & Aktan 2006)
  - **modal curvature reconstruction** (Wahab & De Roeck 1999)
  - application of **variational methods** including mode shape information (Teughels & De Roeck 2004; Xia et al. 2008; Whelan et al. 2010)

Dynamic testing of a damaged RC Bridge

The bridge on the Fella River (Dogna, Udine)

Research Project 2008 funded by the ''Dipartimento della Protezione Civile'' of Friuli Venezia Giulia

Dogna Bridge

- Built in 1979
- Four nominally equal spans
  - Span length 16.0 m
  - Lane width 4.0 m
  - Two footways 0.90 m width
- Structure:
  - Three longitudinal RC beams of rectangular cross-section 0.35x1.20 m and a RC slab deck of 0.18 m thickness
  - RC diaphragms of rectangular cross-section 0.30x0.70 at mid-span, at the ends and at span-quarters
- Constraints: longitudinal beams simply supported at both ends

Exceptional flood – August 31, 2003

Existing degradation (April 2008)

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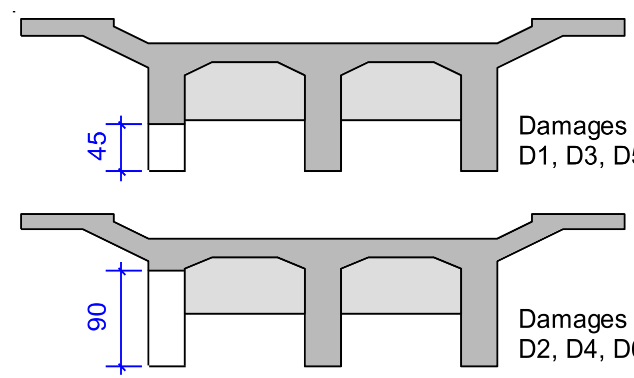
Damage configurations

Sequence of notches produced by a hydraulic saw

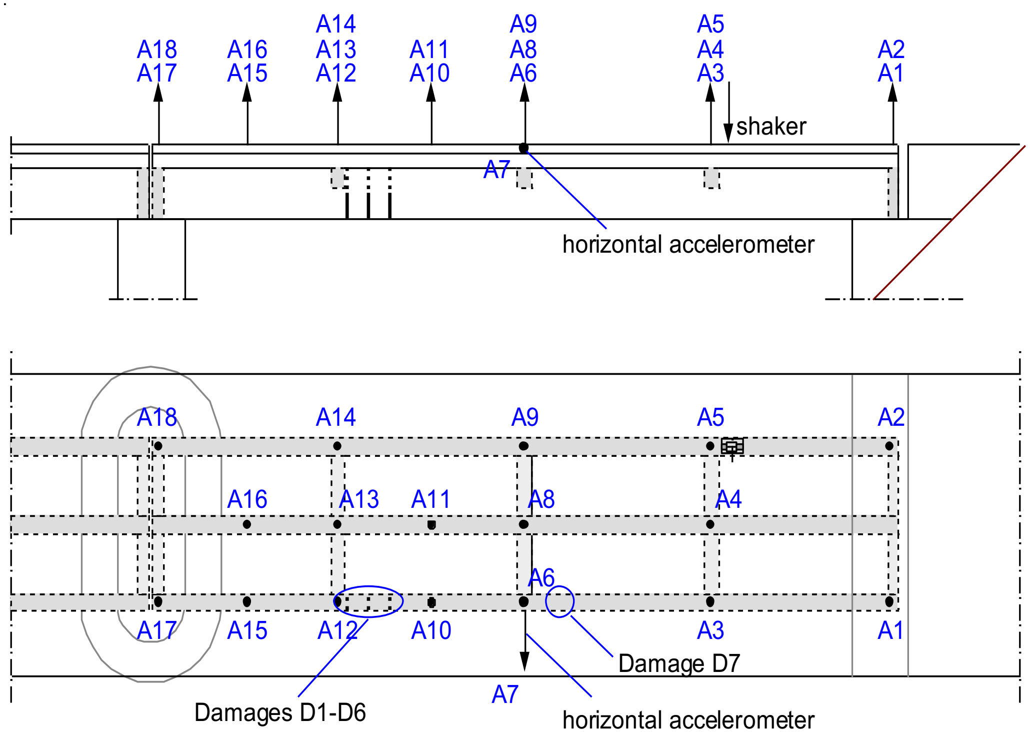
Damage D1-D6

Damage D7



Damaged cross-section

Harmonically forced tests (April 2-11, 2008)

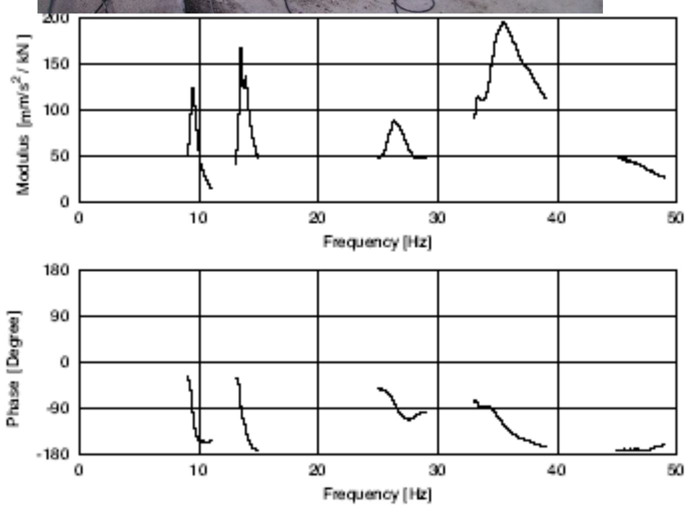


Instrumental layout

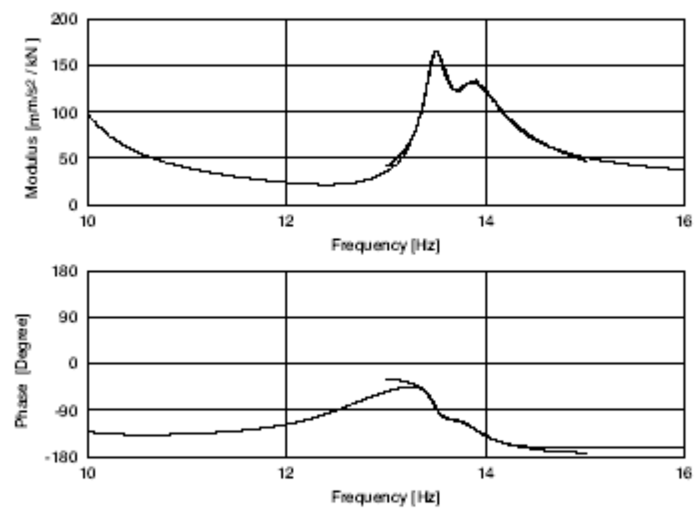
- 18 accelerometers (1 horizontal)
- Inertance measurements in the range 5-50 Hz
- Frequency resolution: from 0.02 Hz (up to 15 Hz) to 0.04 Hz
- Maximum force amplitude: 15 kN

Modal parameter estimation

- Zoom analysis in a neighborhood of every natural frequency
- Modal parameter extraction via *multiple curve fitting* techniques



FRF at A5



FRF detail

Reference configuration

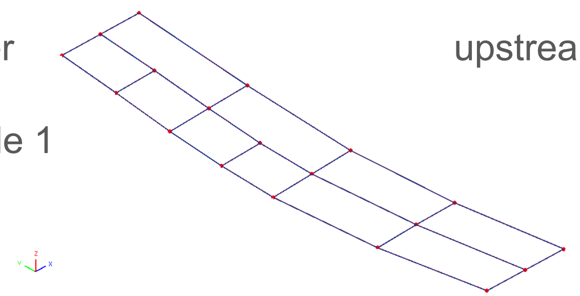
Mode number	Frequency [Hz]	Damping [%]
1	9.430 ± 0.001	2.24 ± 0.02
2	13.487 ± 0.002	0.79 ± 0.01
2A	13.841 ± 0.003	1.99 ± 0.03
3	26.218 ± 0.035	2.85 ± 0.13
4	34.764 ± 0.173	3.28 ± 0.46
5	47.171 ± 0.027	1.13 ± 0.09

Mean values of natural frequencies and damping factors and their maximum deviations (harmonically forced tests)

pier

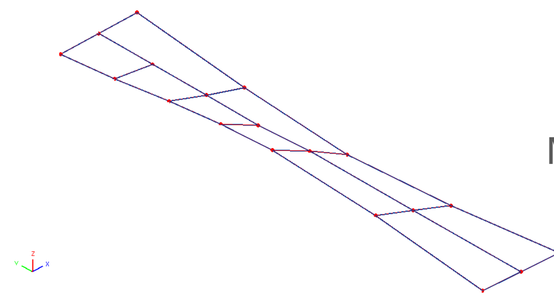
upstream

Mode 1



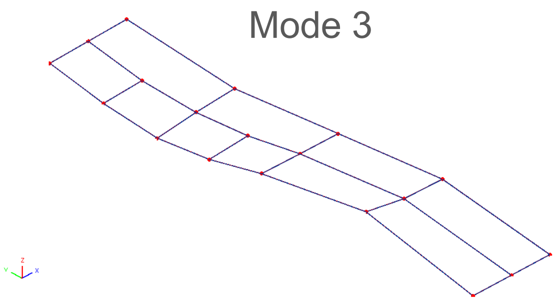
downstream

abutment

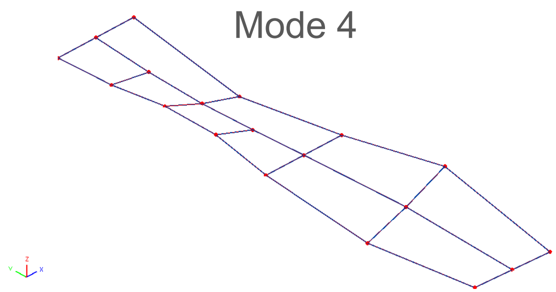


Mode 2

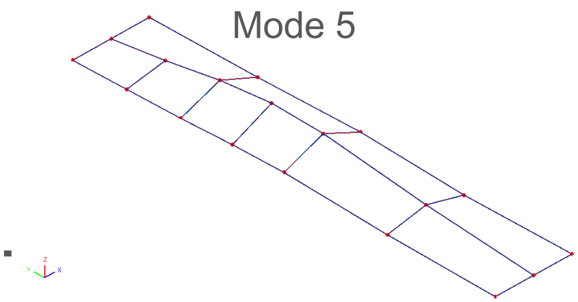
Mode 3



Mode 4

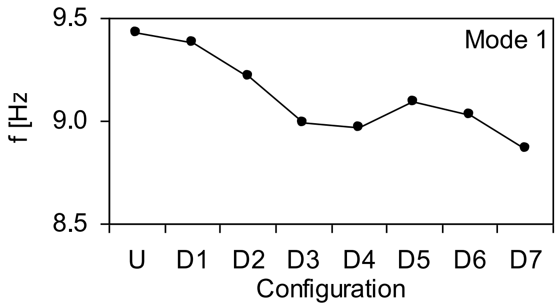


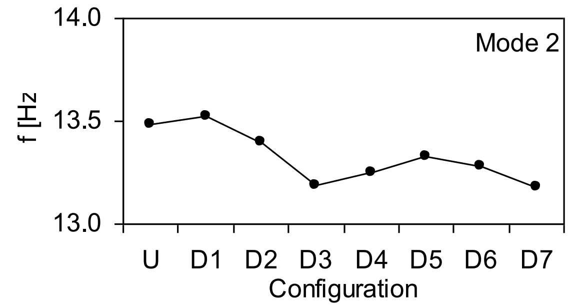
Mode 5

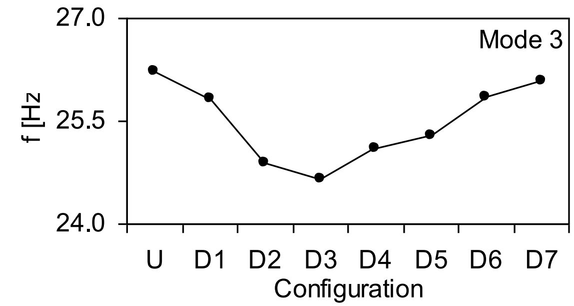


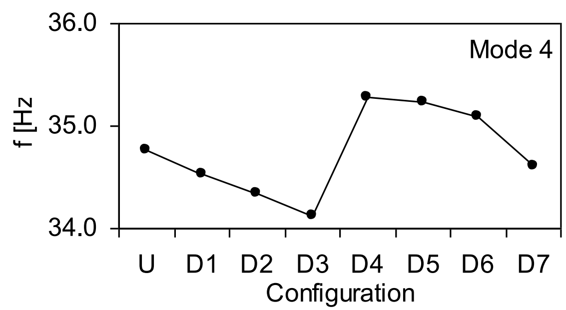
Evolution of the natural frequencies w.r.t. damage (Hz)

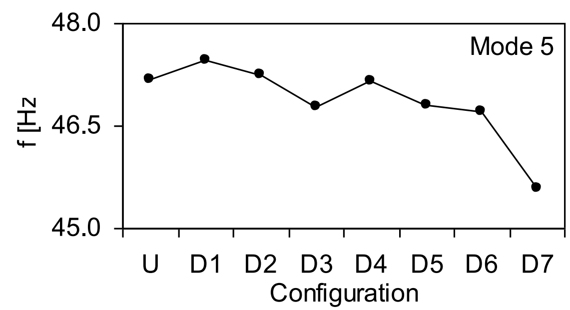
Mode number	Ref	D1	D2	D3	D4	D5	D6	D7
1	9.430	9.382	9.215	8.994	8.970	9.092	9.030	8.871
2	13.487	13.520	13.402	13.190	13.247	13.329	13.284	13.182
2A	13.841	13.920	13.889	13.754	13.957	13.908	13.924	-
3	26.218	25.834	24.897	24.650	25.096	25.288	25.860	26.077
4A	-	-	-	33.532	-	-	-	-
4	34.764	34.535	34.340	34.130	35.283	35.230	35.094	34.613
5	47.171	47.467	47.251	46.786	47.151	46.800	46.722	45.591



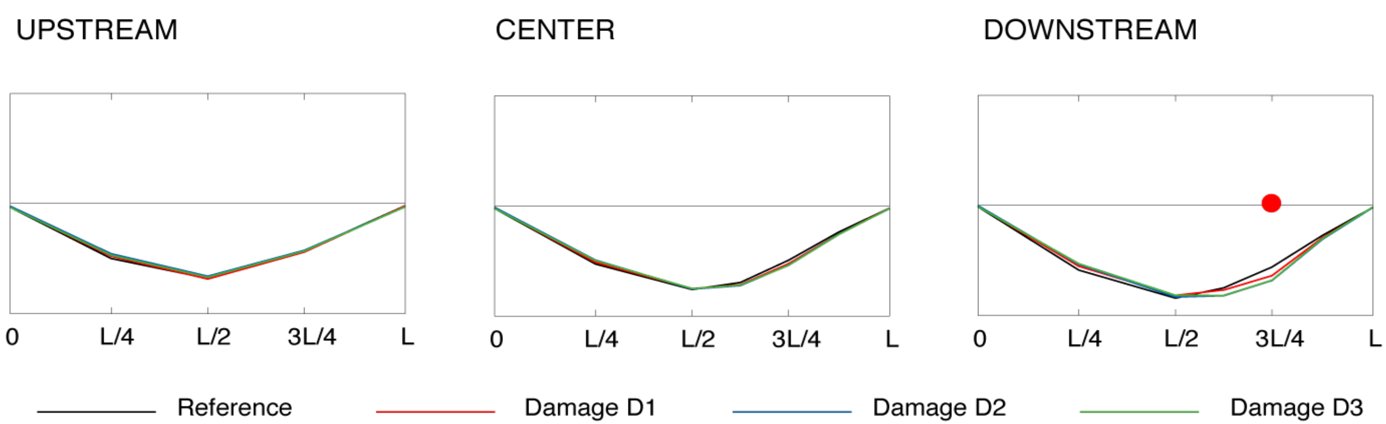


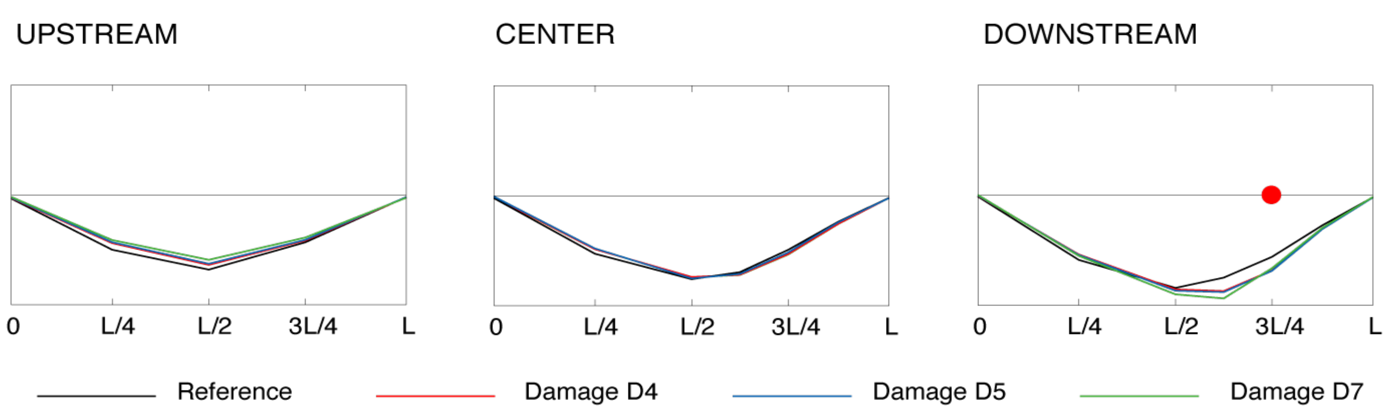






Evolution of Mode 1 w.r.t. damage

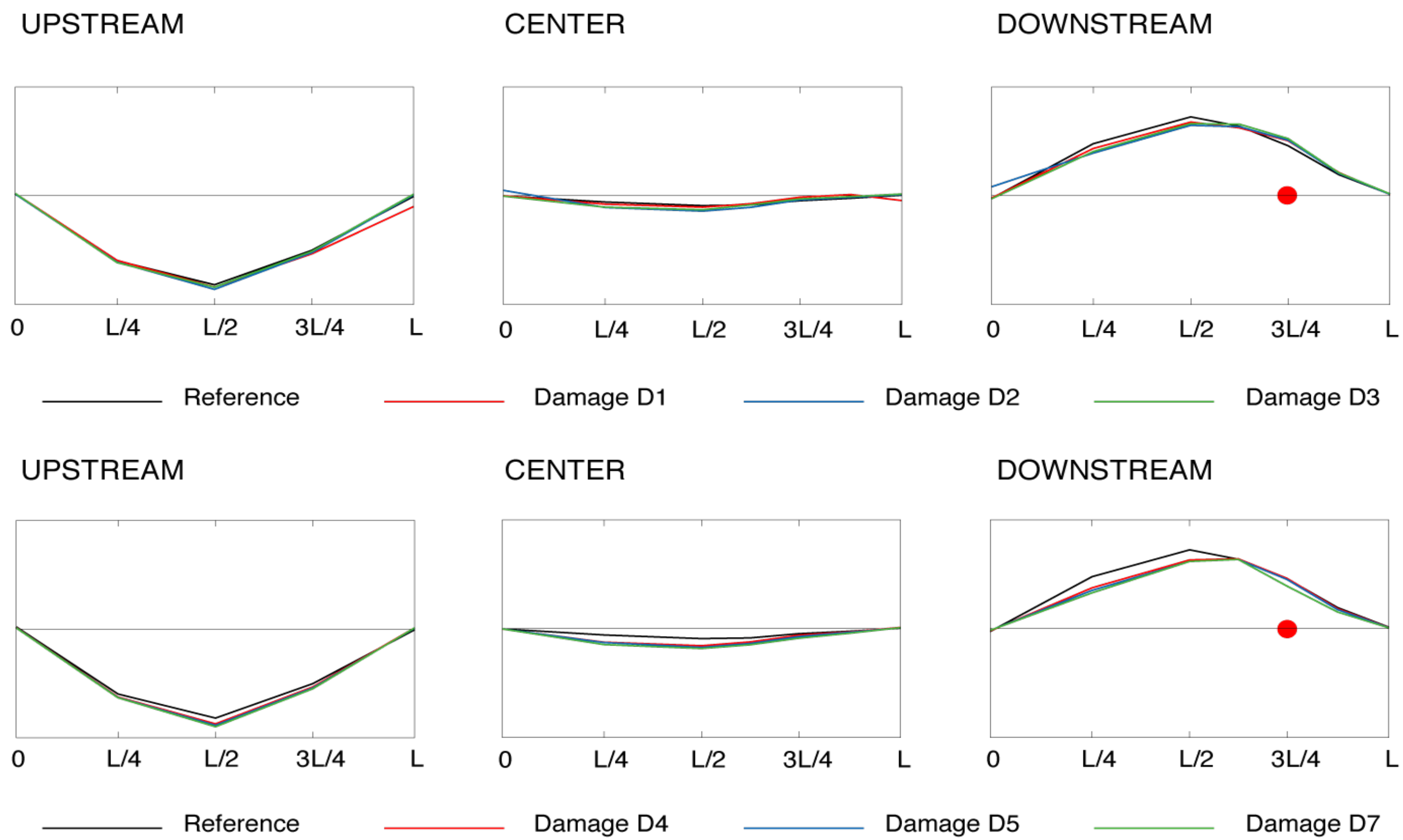




Abutment: X=0; pier: X=L

● = Damage location

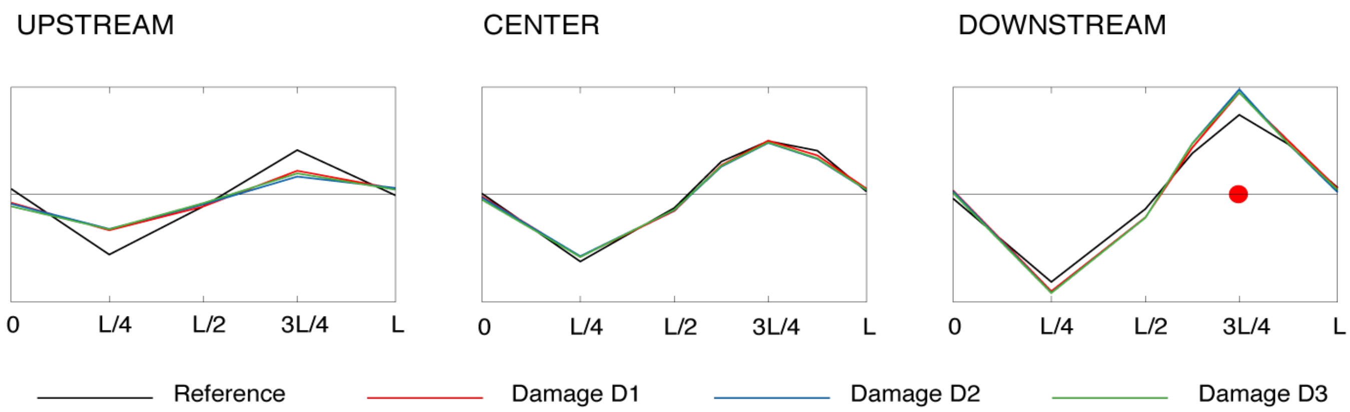
Evolution of Mode 2 w.r.t. damage

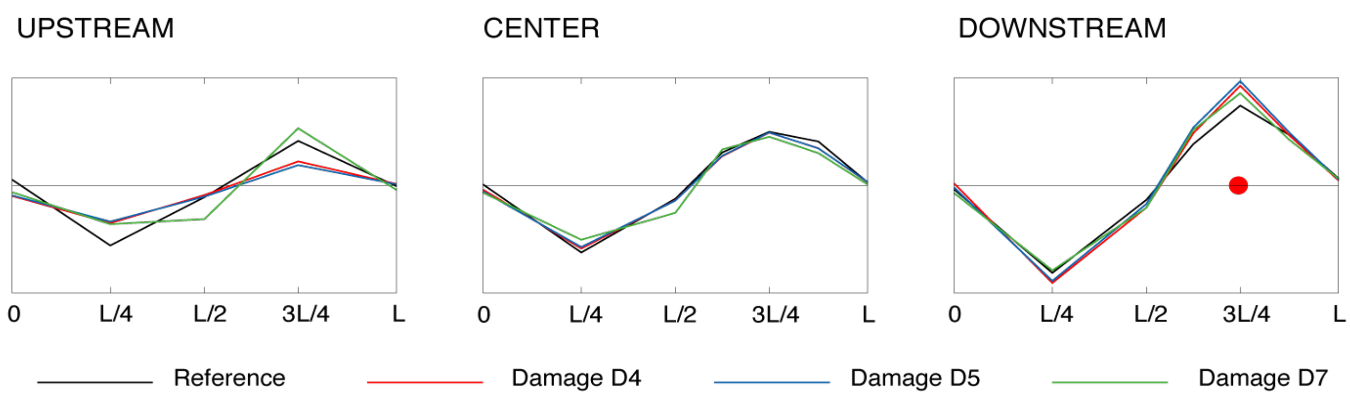


Abutment: X=0; pier: X=L

● = Damage location

Evolution of Mode 3 w.r.t. damage

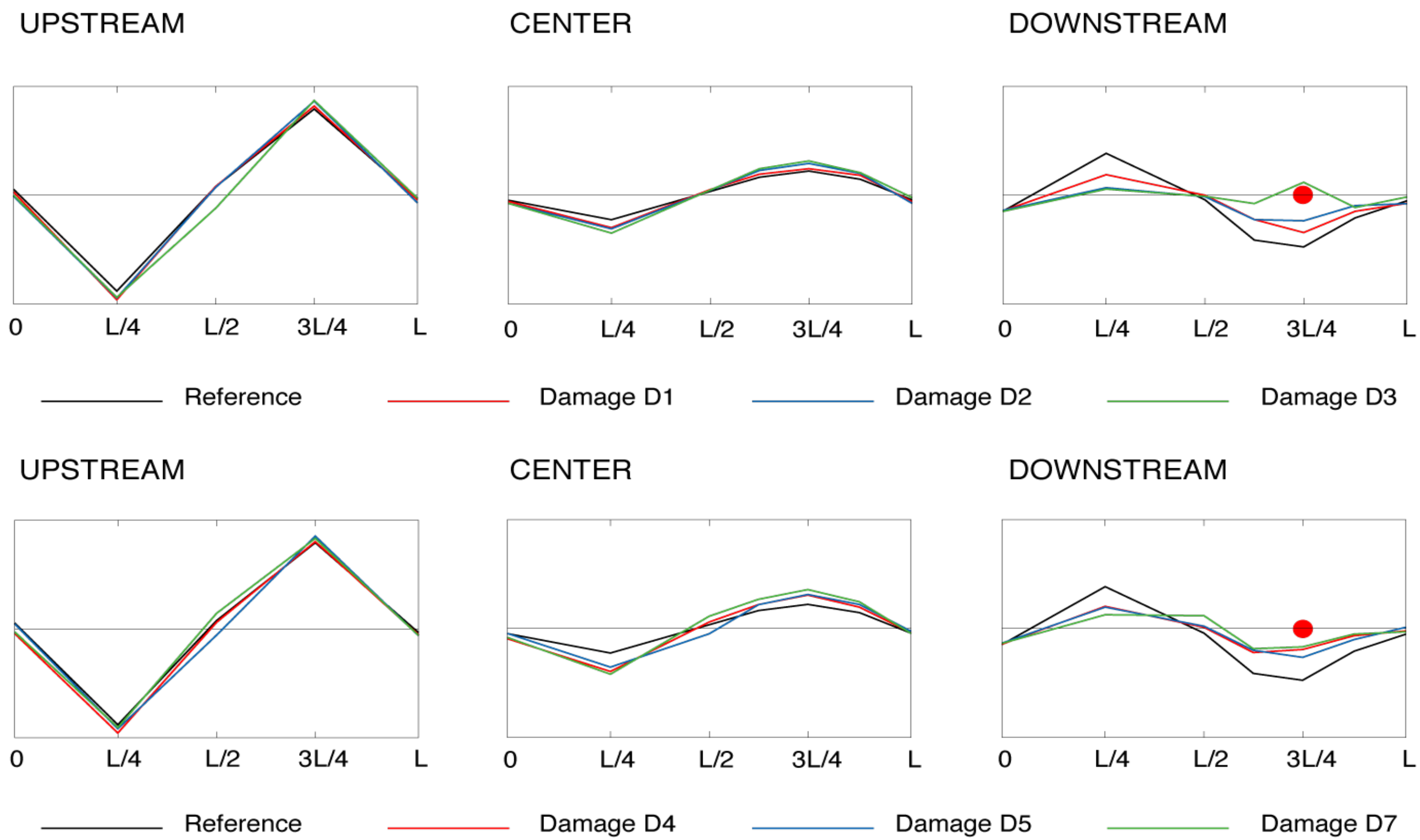




Abutment: X=0; pier: X=L

● = Damage location

Evolution of Mode 4 w.r.t. damage

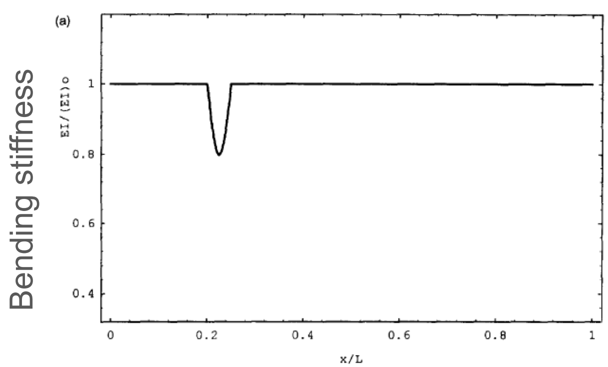


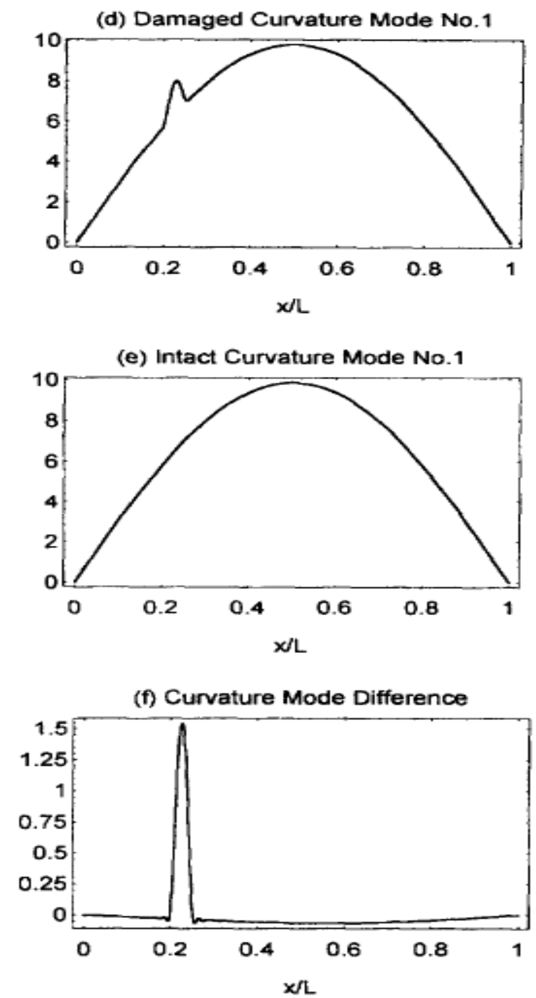
Abutment: X=0; pier: X=L

= Damage location

Damage localization from modal curvature changes

EXAMPLE
- Simply supported uniform beam under bending vibration with a localized damage (e.g., an open crack or notch)





Change in modal curvature is localized near the damaged region

Pandey, Biswas & Samman (1991); Luo & Hanagud (1997); Vestroni et al. (2015, 2019)

Difficulties

- Need to estimate the second derivative of the mode shape with sufficient accuracy
- Not easy extension of the method to less simple structural models (beam grillage, plates or combination of plates and beams)

Applications to bridge structures: few

Wahab, De Roeck (1999)

Application to Dogna Bridge

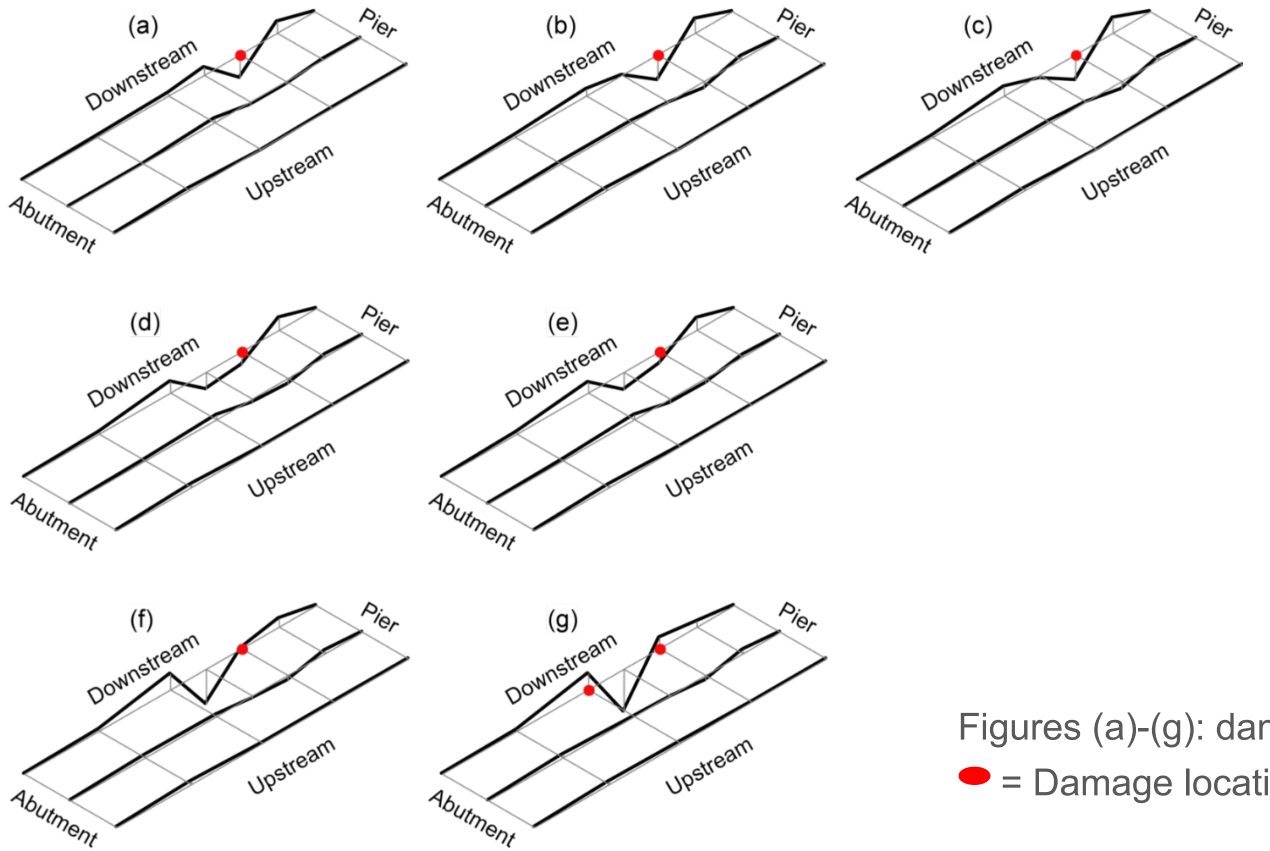
- Pros:
  - The dynamic behavior of the lower modes of the bridge deck is strongly influenced by the three longitudinal beams (e.g., 1D behavior)
  - Localized damage
- Cons:
  - Coarseness of the mesh of experimental points
  - Accuracy of the vibration mode measurements

Determination of modal curvature

- Modal components measured on main beams were interpolated by *natural cubic spline functions* (C^2-functions on the beam axis interval [0,L] and with f''(0)=f''(L)=0)
- Modal curvatures were deduced from spline expressions for reference (R) and damage (D1-D7) configurations
- Reconstruction of the modal curvature changes of the first vibration modes from the (known) reference configuration

Damage localization based on Mode 1

Variation of the modal curvature from the reference configuration

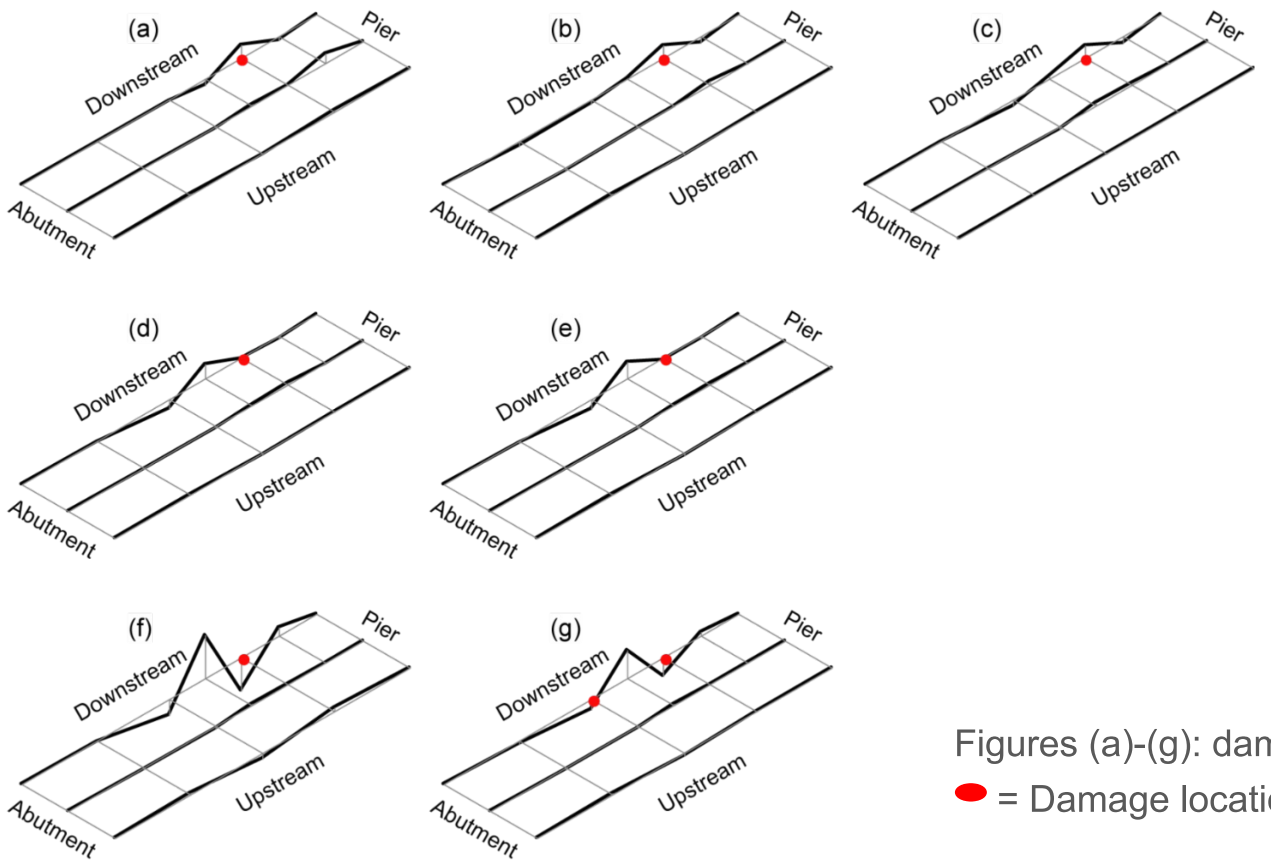


Figures (a)-(g): damage D1-D7

= Damage location

Damage localization based on Mode 2

Variation of the modal curvature from the reference configuration

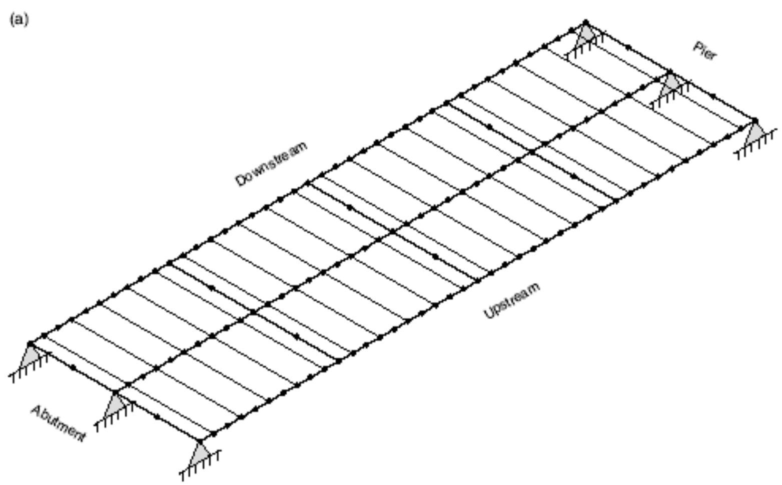


Figures (a)-(g): damage D1-D7

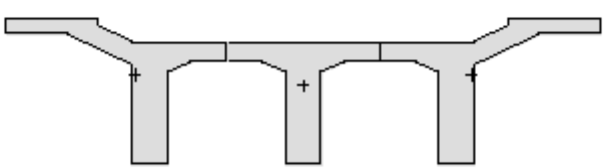
= Damage location

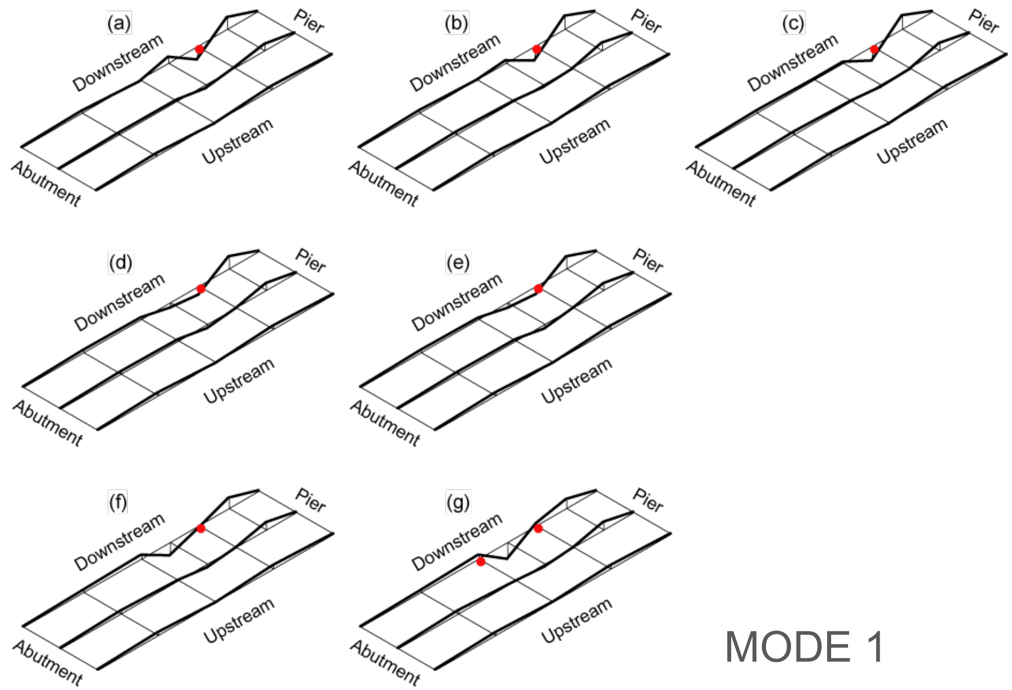
Unknown reference configuration

Modal curvature of the reference configuration estimated by FEM



Plane grillage of beams





MODE 1

Figures (a)-(g): damage D1-D7

= Damage location

Concluding remarks

- This paper was mainly addressed to damage localization from mode shape data in a RC bridge

- Results seem to be of some interest for two reasons:
  - the modal curvature method can also be applied in real situations and on full-scale bridges with a not excessive number of measurement points
  - the method does not require the development of a numerical model, as working directly with the experimental data

- The accuracy of the FRF measurements, the typology of the damage and the features of the bridge were probably decisive for the success of the identification. In other contexts, the sensitivity of the problem to the accuracy and completeness of the data may become important

Comments - 1

Concerning **natural frequencies**:

– Natural frequencies decrease with increasing of the damage from the reference configuration to configuration D3

– Natural frequencies **increase** in the transition from D3 to D4 and, in some cases, also from D4 to D5. After that natural frequencies continue to decrease

– This behavior was confirmed by ambient tests

Comments - 2

Concerning **vibration modes:**

– There is a **loss of symmetry** on the deformed shapes of the reference configuration with respect to the transverse direction. For example: the amplitudes of vibration for Mode 1 of the two lateral beams differ of about 20 per cent.

– Variations induced by damage are **appreciable** for configuration D1 and become **clearly measurable** in subsequent damaged configurations.

– From visual comparison, the third and fourth modes are the most sensitive to damage, and **changes are large even in regions far from the damage location**

See Dilena, Morassi, Perin (2011) for a justification

References

Dilena, M., Morassi ,A. (2011), **Dynamic testing of a damaged bridge.** *Mechanical Systems and Signal Processing,* 25(5), 1485-1507.

Dilena, M. , Morassi, A, Perin, M. (2011), **Dynamic identification of a reinforced concrete damaged bridge.** *Mechanical Systems and Signal Processing,* 25(8), 2990-3009