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12 December 2019
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Increased Resilience of Critical Infrastructure under Natural and Human-Induced Hazards

CROATIAN PRACTICE AND RESEARCH IN ASSESSMENT OF EXISTING BRIDGES

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CHAIR FOR BRIDGES

- is the oldest technical Chair of University of Zagreb founded in 1919
- is enrolled as scientific centre in the field of bridges
- is a very productive core where many big bridges are designed


Maslenica bridge, 1997


Dubrovnik bridge, 2002

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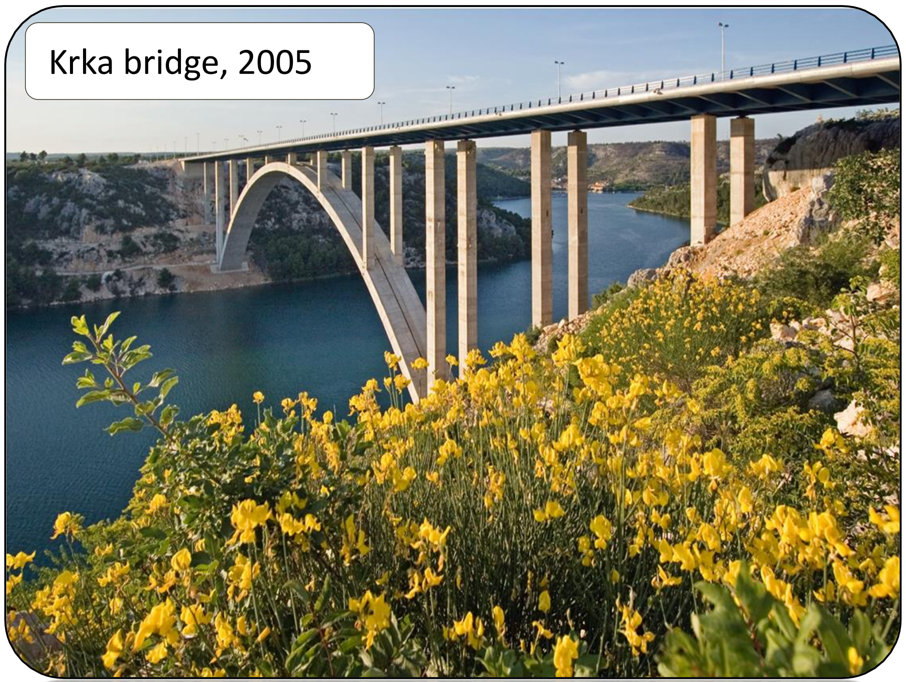

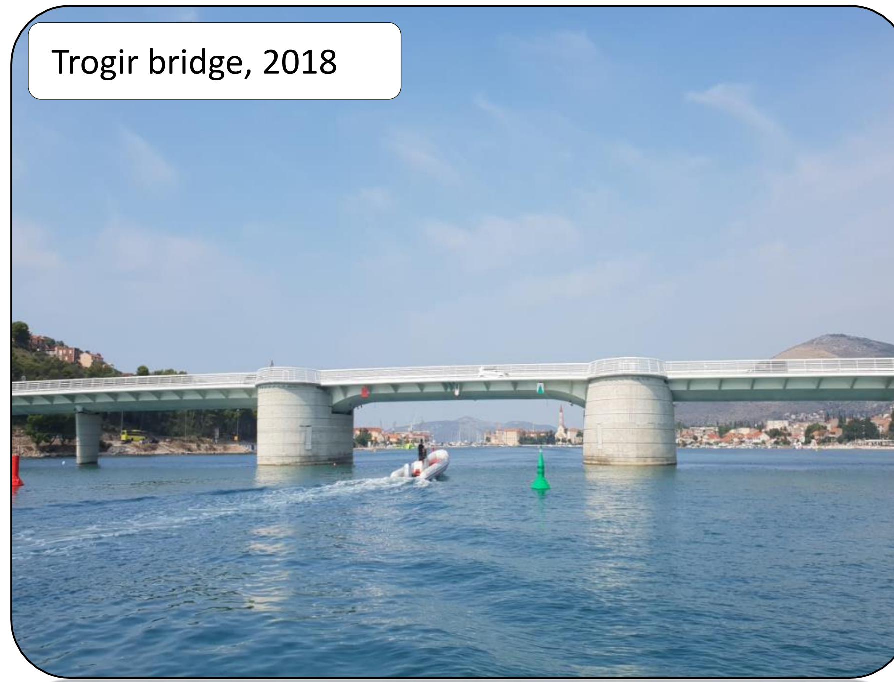

CHAIR FOR BRIDGES

Through several projects collecting data on bridge databases, inspections, maintenance and management

- Influence of concrete damage on reinforcement corrosion - computer simulation and in service performance of bridges: CODEbridges; https://www.grad.unizg.hr/codebridges
- Action TU1402: Quantifying the value of structural health monitoring; www.cost-tu1402.eu
- Action TU 1406: Quality specifications for road bridges, standardisation at a European level; www.tu1406.eu


Pag bridge and Homeland bridge

PRESENTATION OVERVIEW

1. Bridge databases in Croatia, collection and management of data
2. Developments on the (seismic) assessment of existing bridges
3. Monitoring or data acquisition systems for existing bridges, with a particular focus on old, deteriorating bridges

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Bridge databases in Croatia, collection and management of data

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Five road authorities responsible for approximately 3500 bridges

Road authority	Croatian Motorways	Rijeka- Zagreb Motorway	Croatian Roads	City of Zagreb	County roads of Krapina-Zagorje County
Total length of road network [km]	2 x 920.5 (full motorway profile)	2 x 175.0 (full motorway profile)	7129.62	2589.00	661.23
Road classification	Motorways	Motorways	National roads	Unclassified roads	County and local roads
Number of bridges	1 213 (L > 5 m)	75 large bridges; > 100 overpasses, underpasses and other passages/ crosses	≈ 1 800 (L > 2 m)	≈ 228 (L > 2 m)	70 (L > 5 m)
Duration of the program for investment in the maintenance	1 year	1-2 years	4 years	1 year	1 year
Updated bridge inventory	Yes	Yes	Yes	Yes	Yes
Bridge management system	Yes, since 2008	No	Yes, since 1996, updated in 2001	No	No
Basis for decision on repairs, reconstruction or demolition of bridges	Periodical visual inspection; Hazards followed by non-periodical visual inspection	Periodical visual inspection; Hazards followed by non-periodical visual inspection	Periodical visual inspection; Hazards followed by non-periodical visual inspection	Periodical visual inspection; Hazards followed by non-periodical visual inspection	Periodical visual inspection; Hazards followed by non-periodical visual inspection
Developed standardized procedure for visual inspection of bridges	Yes	Yes	Yes	No	No
Type and frequency of periodical visual inspection of bridges					
Routine – regular road patrol	min 3x/day	min 3x/day	min 1x/day	n/a	min 3x/day
Seasonal visual inspection	2x/year	2x/year	-	-	2x/year
Annual visual inspection	-	-	1x/2 years	1x/2 years	-
Main visual inspection	1x/6 years	1x/6 years	1x/6 years	1x/6 years	1x/6 years

Bridge Management Systems in Croatia

- established only by Croatian Motorways and Croatian Roads
- adequate algorithm to evaluate condition of each structural element based on the comprehensive data on detected damage
- CM: computer system, CR: manual basis.

Document	Doc. Type
Handbook of damages on bridge elements	Evaluation
Guidelines for bridge inspections	Inspection
HRMOS manual – Bridge management	Inspection
HRMOS manual – Bridge management – General bridge inspection	Inspection
Handbook of damages on bridges	Inspection /evaluatio
Guideline for bridge evaluation	Evaluation
Bridge Management Planning	Backgroun d document

Categorisation of damages
1. *in relation to component and*
2. *according to material*

Categorisation of damages
1. *according to material and*
2. *in relation to component*

Rasing to system and network level

Croatian roads ltd.

Croatian motorways ltd.

Bridge Condition Assessment in Croatia

- For other road bridges (county, local and un-classified roads) → **visual inspections** without standardized procedure → less objective results

- **Periodical visual inspection** → basis for development of bridge maintenance program and making decisions on non-regular maintenance (repair, strengthening and reconstruction)

- **Non-periodical visual inspection** → after natural hazards (flood, landslide, earthquake, vehicle impact and boat collision)

- **Special visual inspection** (complemented by testing on a structure and/or in a laboratory) → carried out after decision on required increased maintenance, in order to define scope and complexity of rehabilitation work.

- Most of the road authorities develop a **maintenance plan** for only 1 year in advance based on the 4-year program for maintenance of public roads

PI ↔ PG: COMPONENT LEVEL

- Inspection carried out by components forming three main sub-systems

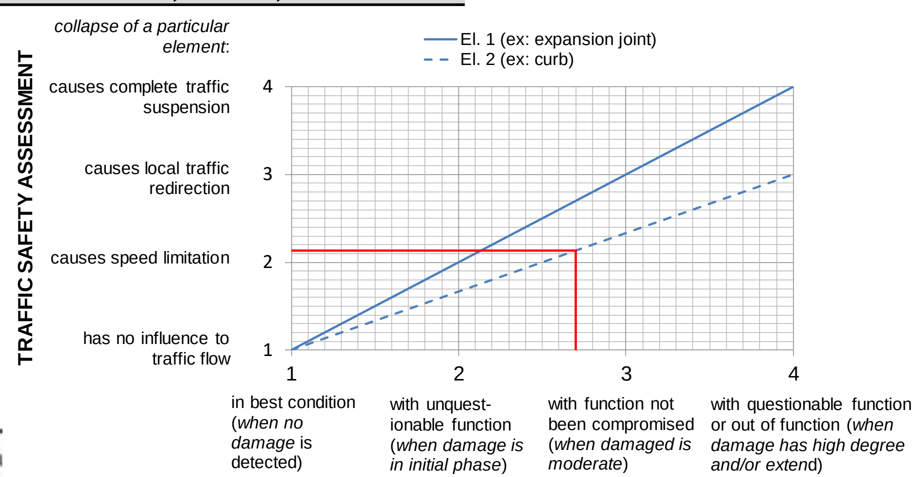
Substructure	Superstructure	Roadway + equipment
Foundations (concrete)	Superstructure (reinforced concrete)	Pavement
Deep foundations, piles (concrete)	Superstructure (prestressed concrete)	Curb & Cornices
Deep foundations, piles (steel)	Superstructure (steel)	Railings & anchorage, barriers
Deep foundations, piles (timber)	Superstructure (composite)	Sidewalk (Pedestrian walkway)
Abutments (concrete)	Superstructure (timber)	Bearings
Abutments (masonry)	Superstructure (brick)	Expansion joints
Piers (concrete)	Superstructure (stone)	Drainage
Piers (steel)	Arch (concrete)	Lighting
Piers (masonry)	Arch (masonry)	Signalization
…	…	…



PI ↔ PG: SYSTEM LEVEL

- Importance of the component to evaluate impact to the entire structure

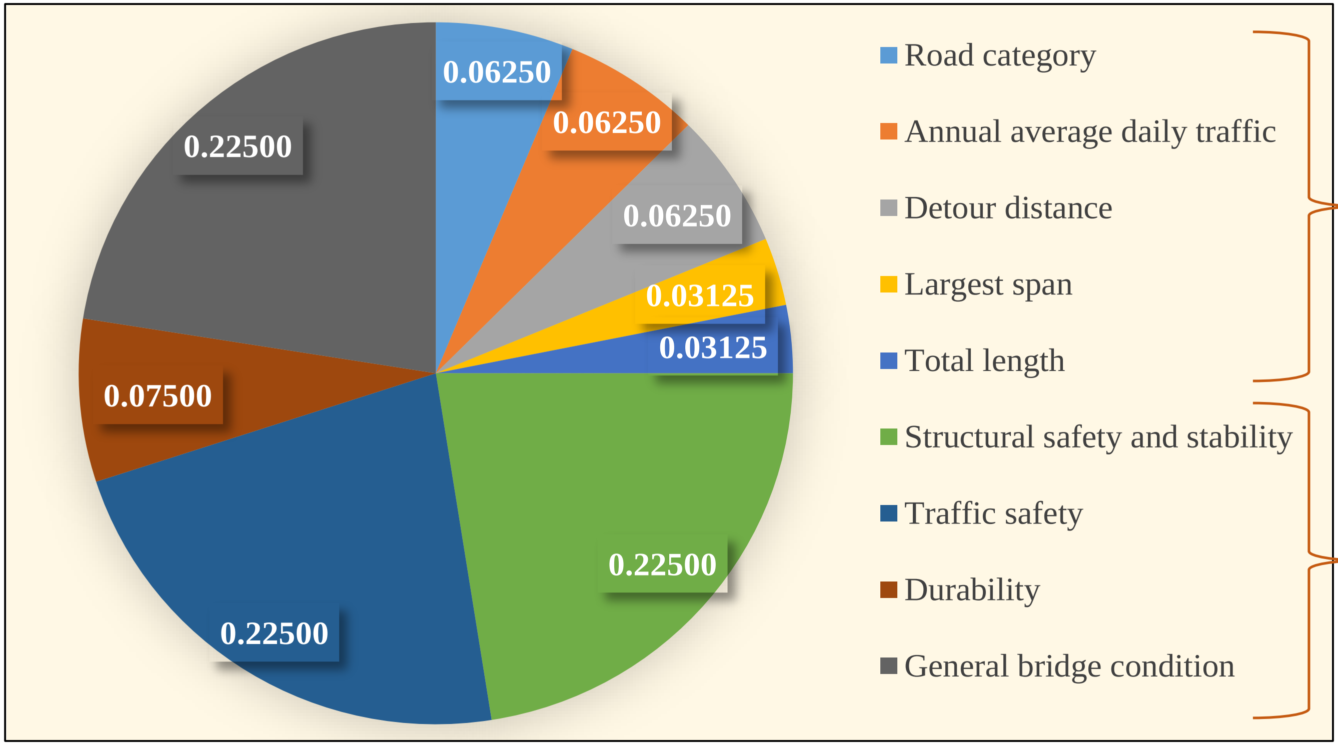
Structural safety criteria	Traffic safety criteria	Durability criteria
collapse of particular element…		
have no influence to the bridge safety 1 *railing, curb, embankment,…*	has no influence to traffic flow 1 *cornices, …*	have no influence to durability of other components 1 *railing, main girder, arch, pier, foundation, …*
has influence to a part of a bridge structure 2 *cornices, cross girders, bearing, wing, …*	causes speed limitation 2 *sidewalk with barrier, …*	will cause reduced durability of other components 2 *expansion joint, pavement, curb, drain, …*
has influence to an entire bridge structure 3 *main girders, arch, pier, foundation,…*	causes local traffic redirection 3 *sidewalk, embankment, curb, drainage,*	
	complete traffic suspension 4 *barriers, pavement, expansion joint, roadway slab, …*	



$T=1+((EL-1)*(T_{MAX}-1)/3)$

PI ↔ PG: NETWORK LEVEL

- Example of weight of performance criteria for priority repair ranking



Indicating bridge importance in the network: 25% weight

Indicating bridge condition assessment: 75% weight

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DAMAGE ASSESSMENT

- Four main approaches in damage detection are:
  - visual inspection,
  - non-destructive testing,
  - probing and
  - SHM

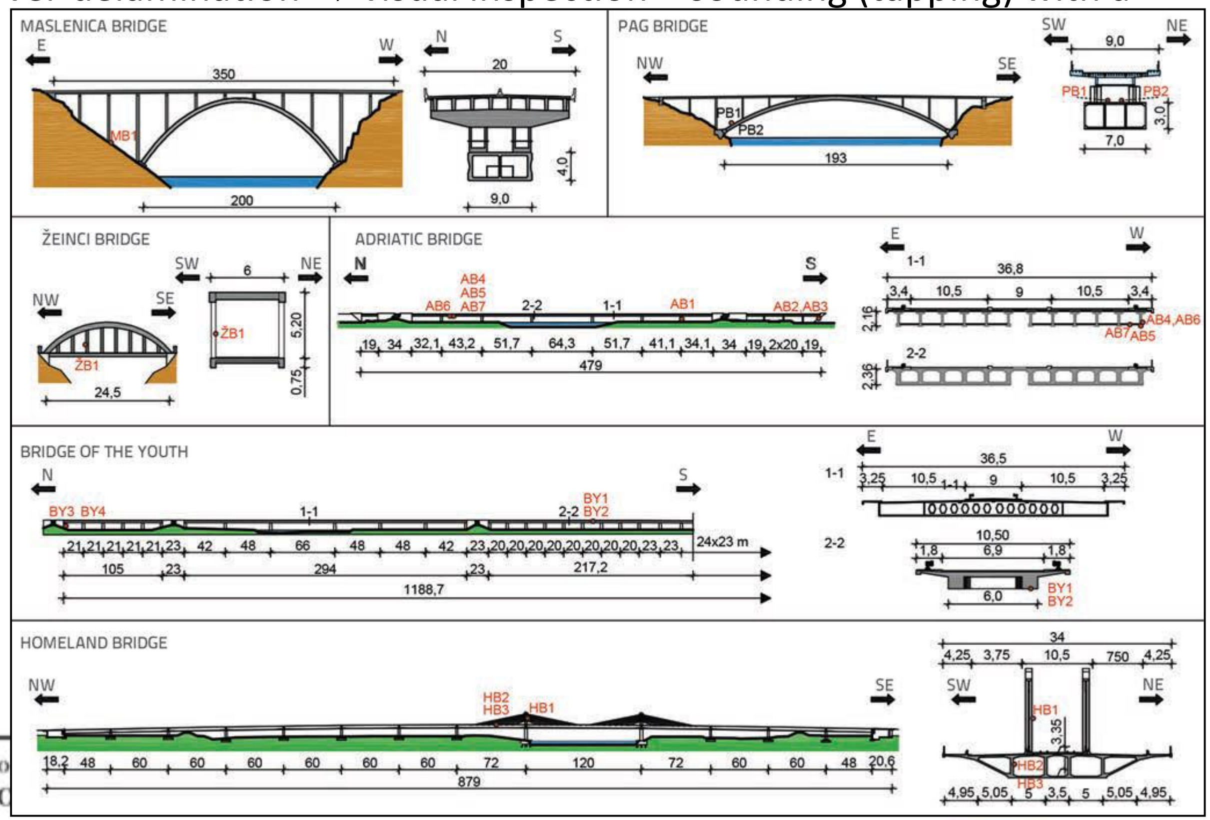
key activity in current bridge management

corrosion can be detected only at the advanced stage, when structural repairs are required → chance for optimal maintenance of bridges is lost

PRO-ACTIVE MAINTENANCE

- new approach: visual inspection + simple and efficient NDT methods

1. Reinforcement grid, concrete cover and rebar diameter → cover meter
2. Crack width → ruler (crack width rod) and optical microscope
3. Crack depth and E_{dyn} → ultrasonic pulse velocity device
4. Crack pattern and concrete cover delamination → visual inspection + sounding (tapping) with a hammer
5. Concrete strength → Schmidt hammer
6. Corrosion assessment → half-cell potential and concrete resistivity



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Developments on the (seismic) assessment of existing bridges

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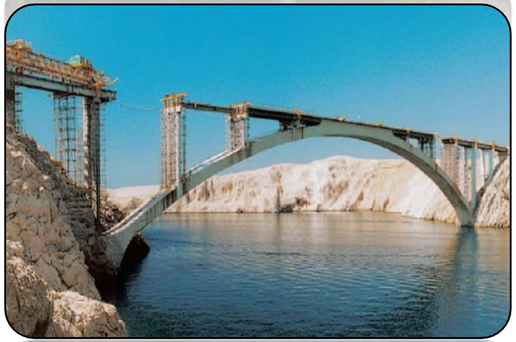
Adequate assessment of bridges?

- Evaluation of bridge performance in remaining service life
  - determine whether it requires repair or retrofitting
- Current codes for design:
  - do not offer optimum approach
  - based on conservative assumptions
  - could result in extremely large costs for bridge maintenance
- Sophisticated methods:
  - probabilistic approach
  - additional knowledge and assets
  - more complicated for practical application



SOLUTION?

MULTI-LEVEL ASSESSMENT METHODS
accuracy & complexity increase on subsequent levels

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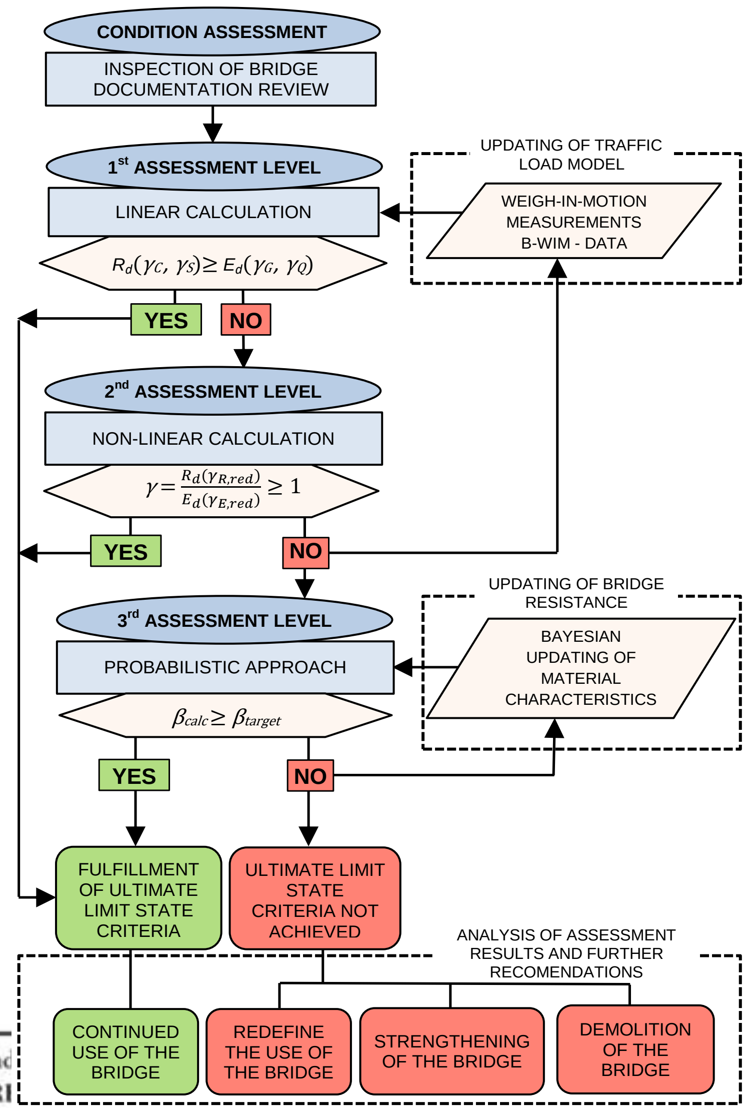
ASSESSMENT OF ROAD BRIDGES FOR TRAFFIC LOAD

- N>> small and medium span bridges, built during 70s and 80s, are designed according to outdated regulations.
- Uncertainties are covered
  - with partial factors in first two levels.
  - In the 3rd level adequate uncertainty will be joined to each separate variable depending on its type and amount of data
- Extent of inspections and tests greatly depends on the available costs provided by the investor
  - very often the engineer will need to assess the bridge based on a limited data collection.
  - Bayesian method provides reliable values of material characteristics, combining prior information, obtained from literature or past experiments, with test results in order

Linear calculation	
Bending resistance	$M_{Ed}(\gamma_G, \gamma_Q) \leq M_{Rd}(\gamma_c, \gamma_s)$
Shear resistance	$V_{Ed}(\gamma_G, \gamma_Q) \leq V_{Rd}(\gamma_c, \gamma_s)$
Non-linear calculation	
Global safety factor	$R_d(\gamma_{G,red}, \gamma_{Q,red}) \geq E_d(\gamma_{c,red}, \gamma_{s,red})$
Probabilistic approach	
Limit state equation	$Z = R-E$; $\beta = \mu_Z/\sigma_Z$; $\beta_{calc} \geq \beta_{target}$



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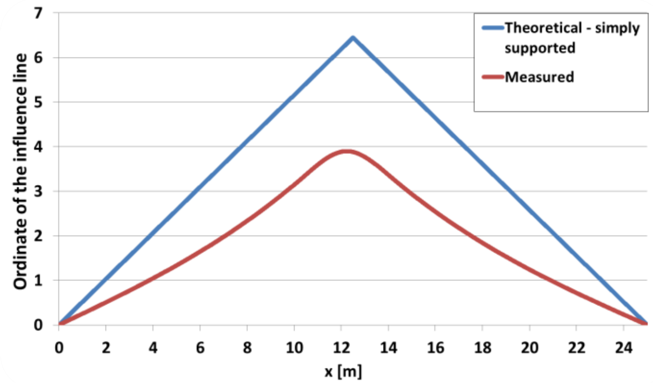
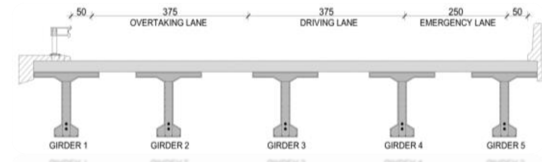
UNDERGOING RESEARCH: Implementation of VoI for quantifying the value of B-WIM

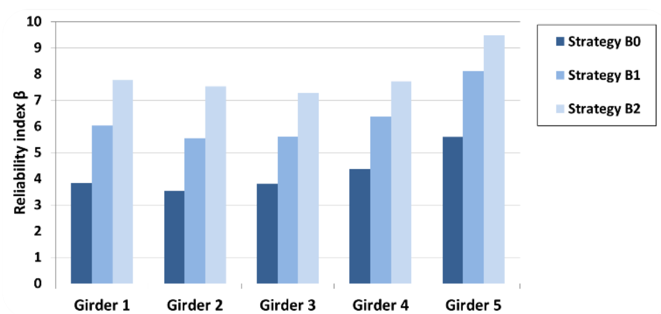
- Possibilites/goals:
  - reveal hidden bridge reserves
  - predict bridge reliability development over a specified lifetime
  - permit unrestricted use of a bridge over a much longer remaining service life
- B-WIM
  - Short: IL, GDF
  - Long: DAF, site-specific load models
- Under progress:
  - modelling of all the associated probabilities,
  - costs and benefits required for the decision tree,
  - classification of bridge based on its importance in the infrastructure networks



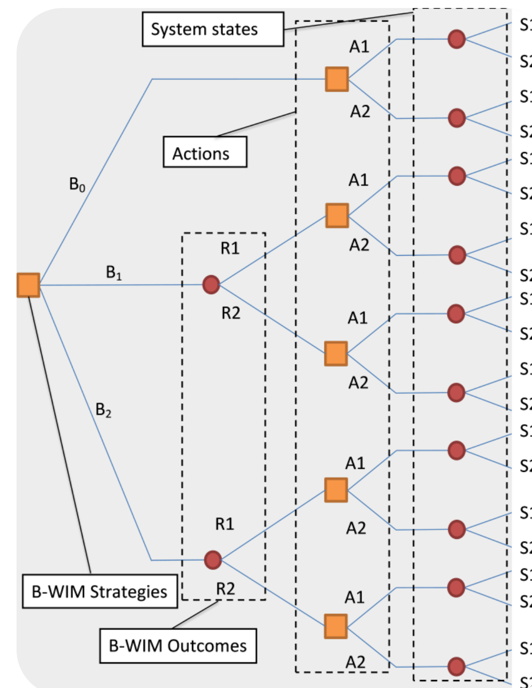
Difference between measured and theoretical influence line



Cross Section of Case Study Bridge



Reliability assessment with and without additional SHM data



Decision tree for VoI analysis of Case Study Bridge

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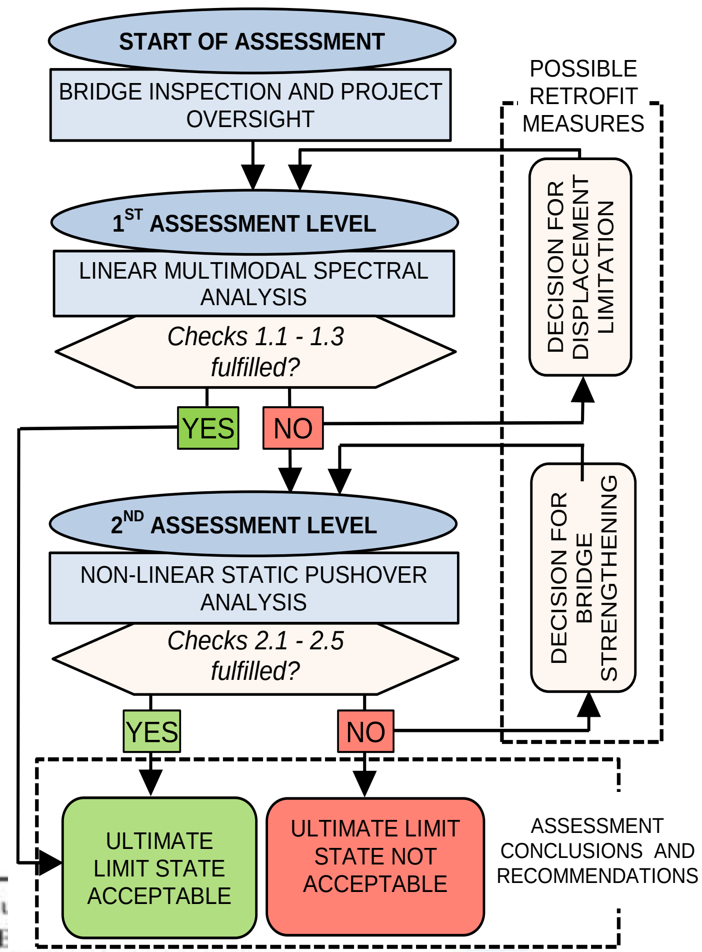
SEISMIC ASSESSMENT OF ARCH BRIDGES

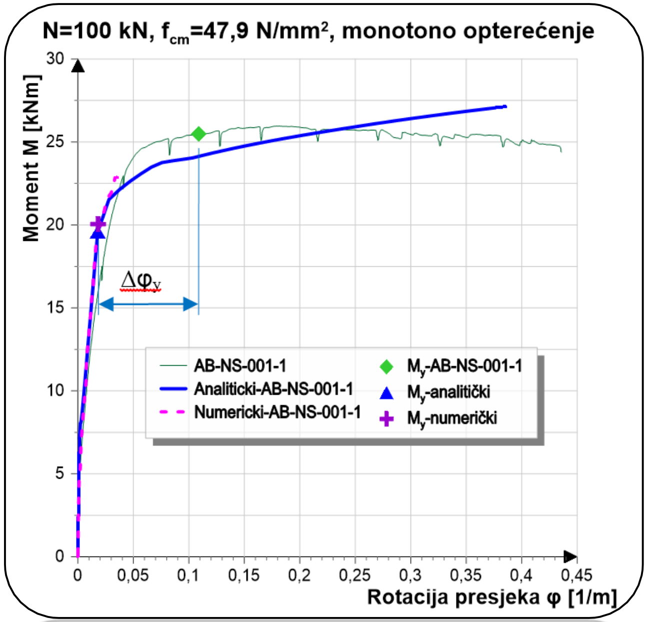
- Whole of Cro territory is seismically active, earthquake is often governing for element design (espec. columns), material consumption, detailing, and overall mechanical resistance and stability of bridges.
- RC arch bridges are particular owing to their robustness.
  - Performance of arches may be proved already at the 1st level
  - For spandrel columns (particularly short ones near the arch crown) it will be necessary to go through the 2nd level

Assessment checks related to linear multimodal spectral analysis	
1.1 Displacements compared to allowable ones at the abutment	$d_{allow} \geq d_e$
1.2 Design resistances for the interaction of axial force and bending moment	$f(N_{Rd}, M_{Rd}) \geq f(N_E, M_E)$; $f_{i,m}$ za $f(N_{Rd}, M_{Rd})$ i $f(N_E, M_E)$
1.3 Seismic shear force demand	$V_{Bd,1}=V_{Rd}/\gamma_{Bd,1} \geq V_E$; $CF\times f_{i,m}$ za V_E; $f_{i,m}/CF\times\gamma$ za V_{Rd}
Assessment checks related to non-linear static pushover assessment	
2.1 Rotation capability at locations of potential plastic hinges	$\theta_{ls} \geq \theta_{p,E}$
2.2 a) Stresses of unconfined i b) and confined concrete	$f_{cm}/(CF\times\gamma_{c,acc}) \geq \sigma_{c,E}$ (in elastic regions) $f_{cm,c}/(CF\times\gamma_{c,acc}) \geq \sigma_{c,E}$ (in plastic regions)
2.3 Stresses in reinforcing steel	$f_{ym}/(CF\times\gamma_{s,acc}) \geq \sigma_{y,E}$
2.4 Verification against non-ductile failure through shear	$V_{Bd,1}=V_{Rd}/\gamma_{Bd,1} \geq V_E$; $CF\times f_{i,m}$ za V_E; $f_{i,m}/CF\times\gamma$ za V_{Rd}
2.5 Outward buckling of longitudinal compression reinforcement between transverse ties	$A_{t,built}/s_{T,built} \geq \min(A_t/s_T)$



UNDERGOING RESEARCH: Testing of piers for revealing ductility levels

- Non standard sections, smooth reinforcement, no rules for ductile behaviour
- Seismic performance indicators:
    - M/ϕ diagrams - showing the rotational capability of plastic hinges
    - end section rotation and chord rotation capacity at the yielding point and at the ULS
    - plastic hinge lenght
- M/ϕ diagrams - analytical, experimental and numerical approach:
    - effect of the slippage of the smooth reinforcement causes larger section rotation up to the yield point but it gets smaller as we are approaching to the ULS



Monitoring or data acquisition systems for existing bridges, with a particular focus on old, deteriorating bridge

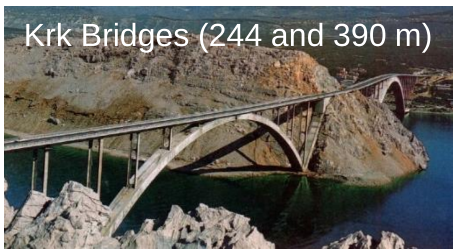
RC ARCH BRIDGES

FIRST GENERATION

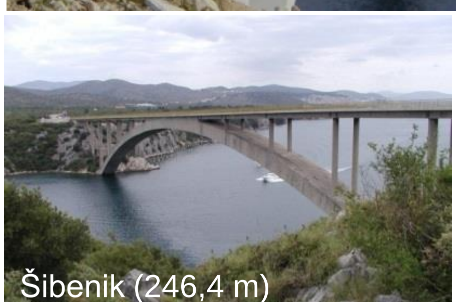
Krk 1980 | Pag 1968 | Šibenik 1966

SECOND GENERATION

Maslenica 1997 | Skradin 2005 | Cetina 2007


Krk Bridges (244 and 390 m)


Pag (193,2 m)

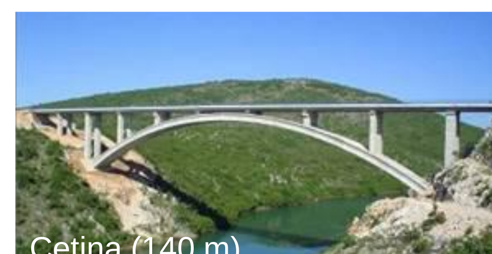

Šibenik (246,4 m)

Which monitoring method (technique) to be used for measure certain quantity in order to define adequate performance indicator?

Uncertainties in measured data and in collecting data?


Maslenica (200 m)


Skradin (203 m)


Cetina (140 m)

RC ARCH BRIDGES

FIRST GENERATION

- Krk 1980
- Pag 1968
- Šibenik 1966

SECOND GENERATION

- Maslenica 1997
- Skradin 2005
- Cetina 2007

STANDARD PERIODIC Collecting experience from past inspection and assessment

- geometrical surveying
- visual inspection
- loading tests

- hammer sounding
- rebound hammer
- half-cell potentials
- ultrasonic method
- crack width measurements

- pull of test
- physical and mechanical prop.
- permeability properties
- alkalinity properties
- chloride content
- bond strength

+ establish regular inspection and include any other necessary technique

PERIODIC LONG-TERM OR CONTINUOUS

Activate monitoring and collecting new long-term data

- wind direction and speed

- displacements
- corrosion progress
- humidity

- strain, temperature

RC ARCH BRIDGES

Šibenik Bridge: deterioration at the underside of bridge deck

Pag: delamination at the edge of the arch abutment

Maslenica: Reinforcement corrosion on column S10

Krk: optical sensors embedded into columns

More strict and demanding maintenance and management approach in highly aggressive environment and for structures of great importance

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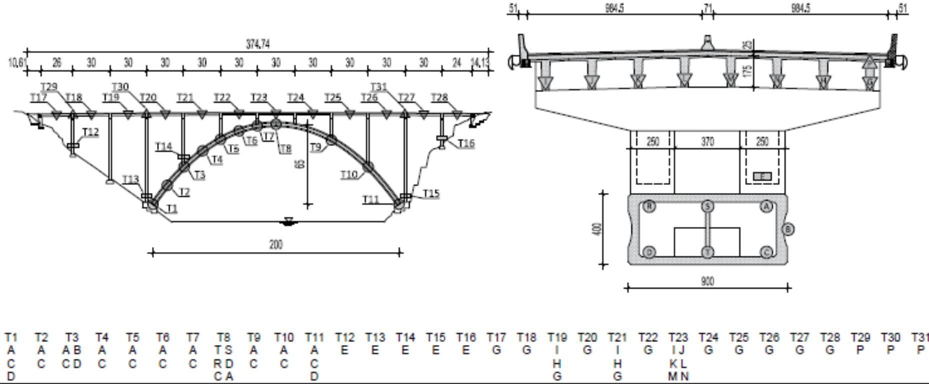
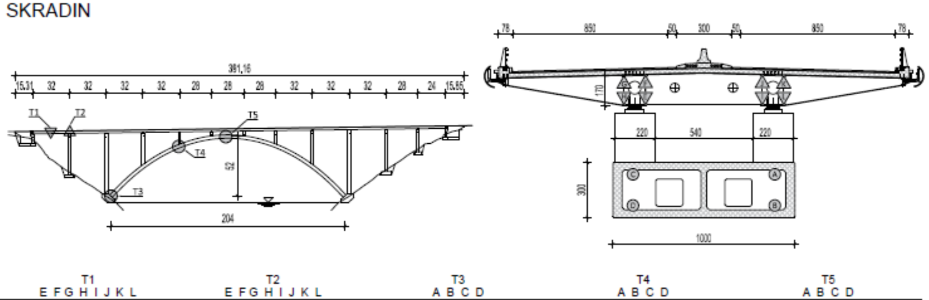
RC ARCH BRIDGES

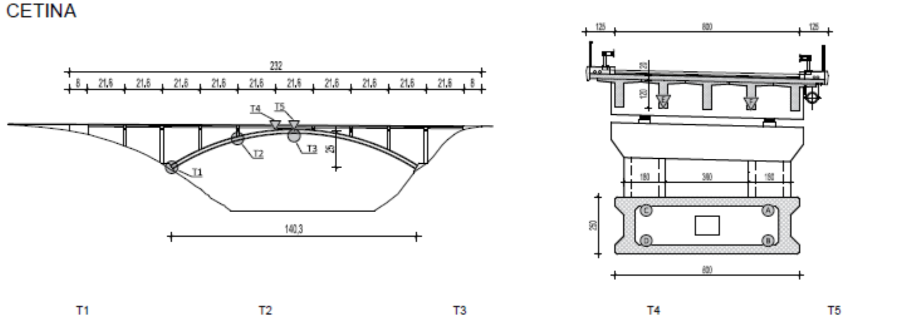
MASLENICA

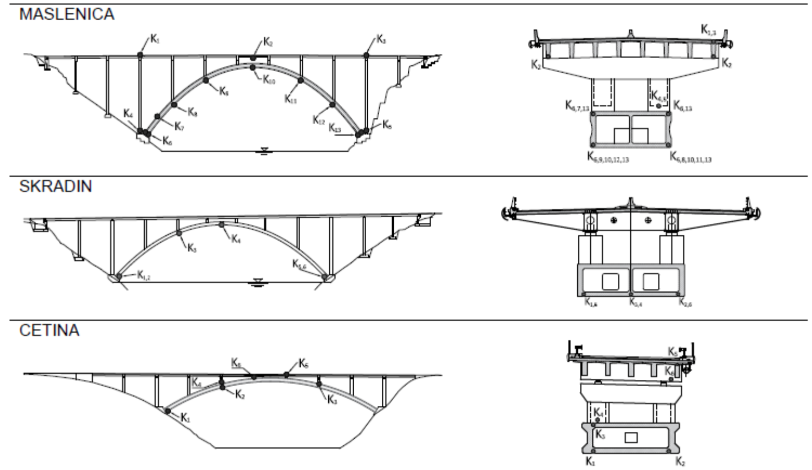


SKRADIN



CETINA





Location of strain gauges (left) & corrosion sensors (above) installed on Maslenica, Skradin and Cetina bridges

Monitoring system is installed based on the design request; unfortunately, after releasing the system and collecting first results (in a year or a two years period) no one (investor) showed interest to finance costs of monitoring results and maintenance of the system.

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OLD BRIDGE SISAK

From presentation created by D. Damjanović, I. Duvnjak, M. Bartolac, J. Košćak, Department of Engineering Mechanics

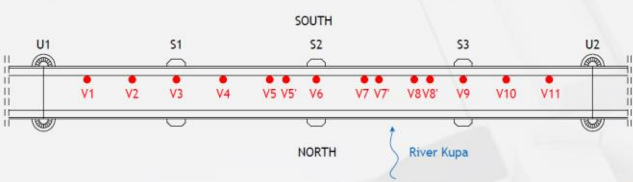
The bridge was built in 1934. as a replacement to an older wooden bridge dating from 1862. At a time when the concrete was already in widespread use, this bridge was built from traditional materials, stone and brick, which highlight its graceful forms. The citizens spontaneously named it „Stari most" (Old bridge), eventually the name became official and the bridge became one of the symbols of the city of Sisak.

PROBLEM

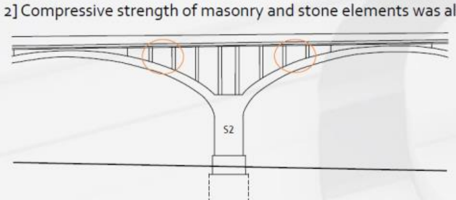
Extensive damage of non load bearing elements were observed especially visible on the heads of the columns and on the edge of the arch. Stability and durability of the structure were threatened with the direct penetration of precipitation from the road surface into the interior structure of the bridge. Another important phenomenon that threatened the sustainability and stability of the structure was condensation in the form of droplets of water on the surfaces of load bearing elements of the bridge structure.

PROBLEM → MEASUREMENTS

1] Compressive strength of concrete slab was determined on 14 test specimens taken on the field.

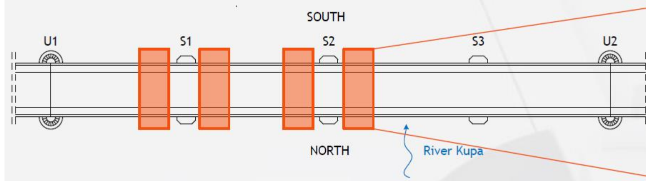


2] Compressive strength of masonry and stone elements was also determined on 14 test specimens.

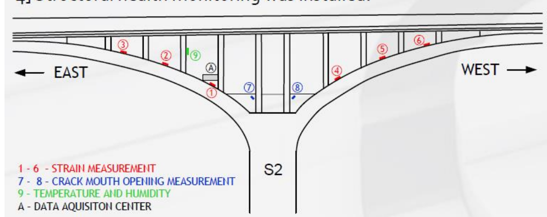


PROBLEM → MEASUREMENTS

3] Corrosion parameters of structural elements of the bridge were measured.

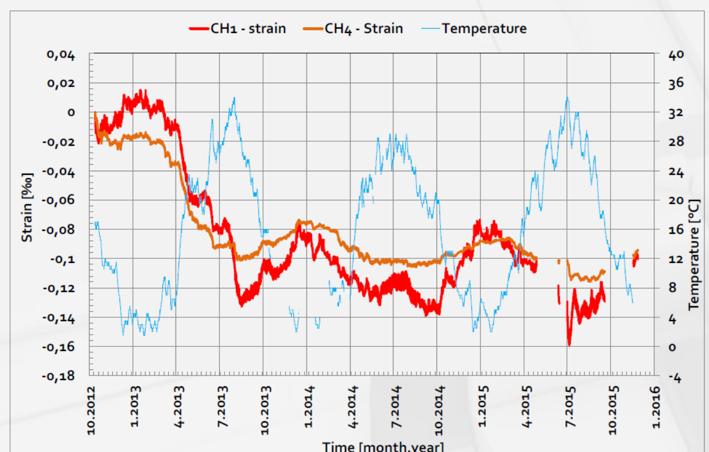


4] Structural health monitoring was installed.



Measured parameters:
displacements
strains
cracks opening
temperature and relative humidity

PROBLEM → MEASUREMENTS → RESULTS | CONCLUSIONS



Measured strain values are low.

Monitoring is still active!

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REPARE

CONCLUSION

1. Establish a pro-active regular maintenance based on visual inspection supported with adequate testing techniques
2. Perform multi level assessment methods of existing bridges by structural bridge engineers
3. Activate monitoring methods proven as valuable and collect long term data as inputs for more precise assessment
4. New type of engineers with knowledge from different disciplines (structures, materials, durability, management, ...?)

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Project Final Event
Pavia, Italy
12 December 2019
www.infra-nat.eu

Increased Resilience of Critical Infrastructure under Natural and Human-Induced Hazards

CROATIAN PRACTICE AND RESEARCH IN ASSESSMENT OF EXISTING BRIDGES

Thank you for your attention!

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