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SEISMIC PERFORMANCE OF EXISTING BRIDGES IN CROATIA:

shortcomings, hidden reserves and seismic assessment perspective

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https://www.grad.unizg.hr/images/50012407/Chair%20for%20Bridges_2020_07_10.pdf

Contents

1. Bridges in Croatia

2. Seismic Assessment during regular operation
   - Case study 1: Precast prestressed simply supported girder bridge
   - Case study 2: Reinforced concrete frame bridge with V shaped piers
   - Case study 3: Set of six continuous grill type continuous superstructures

3. Seismic assessment developed for arch bridges
   - Revealing ductility levels

4. Post Earthquake Rapid Damage Assessment
   - Case study: Eight bridges in Glina County

5. Shortcomings vs. Hidden reserves

6. Conclusions

BRIDGES IN CROATIA

1. BRIDGES IN CROATIA

- Croatia is a seismic-prone country → earthquake effects should be appropriately considered in existing transport infrastructure management
- bridges are often its key elements → ability to use infrastructure immediately after an earthquake is extremely important
- first and most important step → to determine present state and capacity of existing bridges in regard to their seismic resistance

1. BRIDGES IN CROATIA

- 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.
- Large number of bridges on key roads in Croatia were designed and built before HRN EN 1998 were made mandatory or even existed.
- No legislative regarding to seismic resistance of existing bridges

SEISMIC ASSESSMENT DURING REGULAR OPERATION

2. SEISMIC ASSESSMENT DURING REGULAR OPERATION

- Bridges in high seismicity area
  - peak ground acceleration

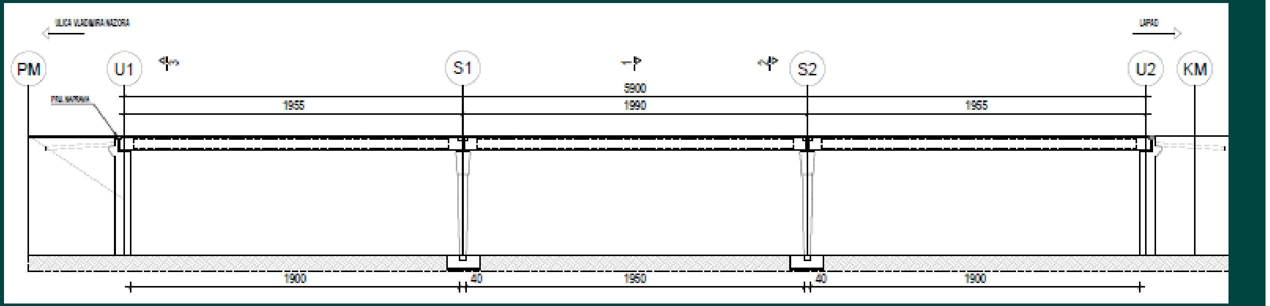
- Case study 1: Precast prestressed simply supported girder bridge
  - a_g=0.3g
  - built in 1980’s

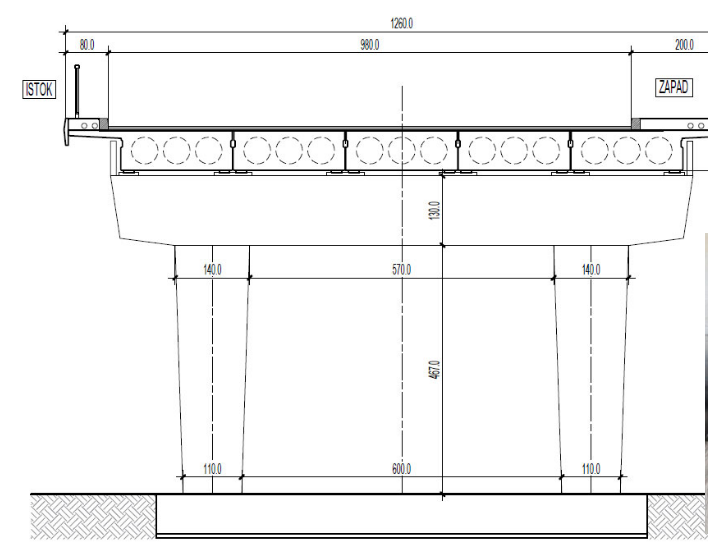
- Case study 2: Reinforced concrete frame bridge with V shaped piers
  - a_g=0.29g
  - built in 1963

- Case study 3: Set of six continuous grill type superstructures over three spans
  - a_g=0.23g
  - built in 1973

Case study 1: Precast prestressed simply supported girder bridge

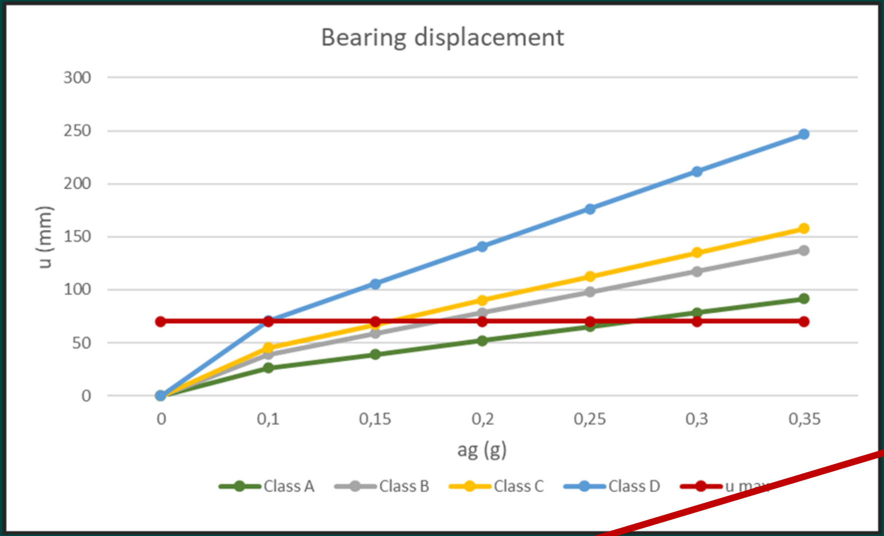
- static system of each span is simply supported beam
- typical span of bridge is L=19,9 m
- cross-section of such bridges consisted only of precast girders, without in-situ concreted slab
- “SAN” type girders, utilized especially in overpasses and smaller bridges
- girders are supported by elastomeric bearings
  - 200*150*50 mm (type 1)
  - anchored neither to the superstructure nor to the substructure
  - maximum possible displacement due to earthquake - **70 mm** - reached at approx. $a_g = 0.25g$.
  - critical elements under seismic load

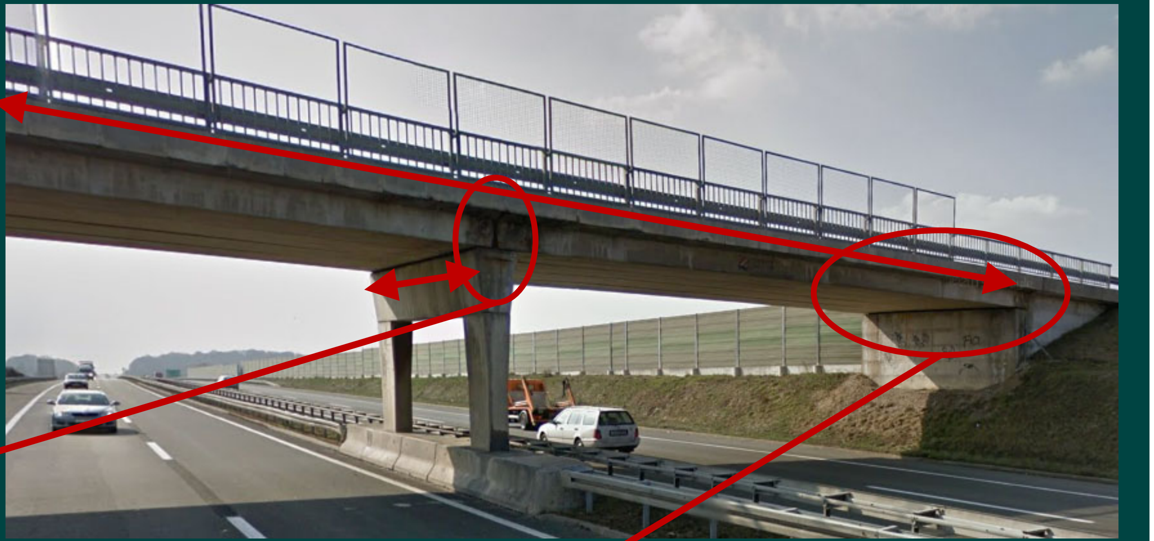




Case study 1: Precast prestressed simply supported girder bridge

- to gain insight into seismic response of such bridges, linear dynamic analysis – response spectrum method was performed
- analysis was made for different intensities of seismic action and for ground types A, B, C, D

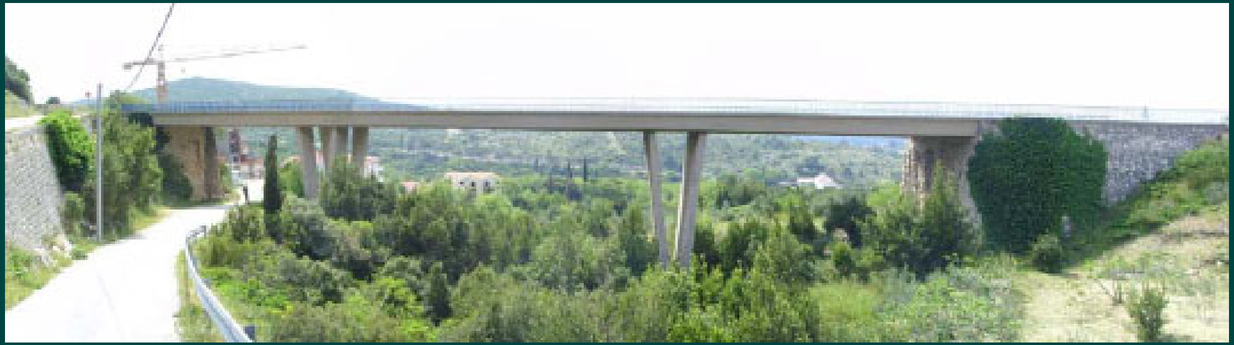




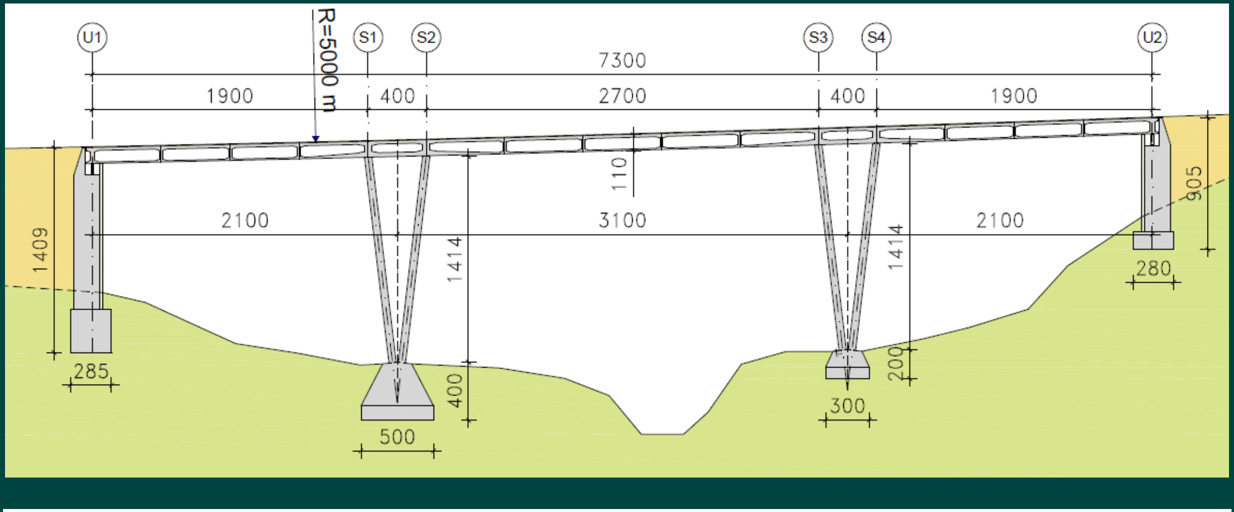
in transverse direction, there are no elements limiting displacements of bridge deck, so that after breakage of bearings, large displacements may occur, depending on intensity of seismic action

in longitudinal direction - movement of superstructure is limited by abutment, and any displacement, larger than one allowed by the expansion joint, would result in bridge deck pounding into abutment wall, with probable damage to both, and with crushing of expansion joint device

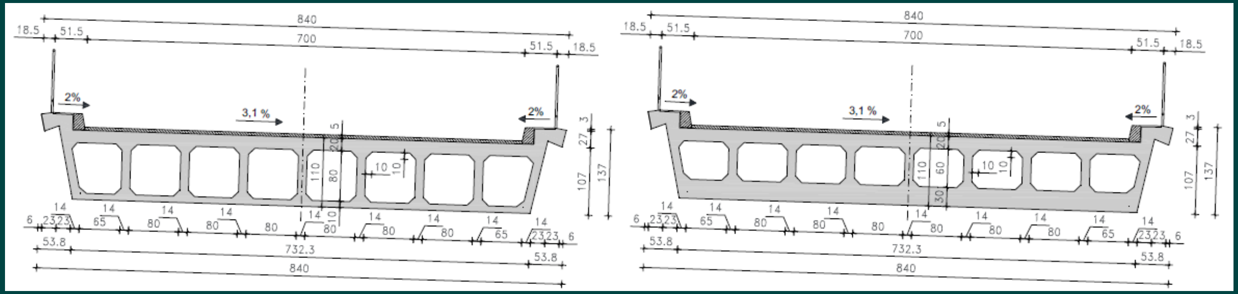
Case study 2: RC frame bridge with V shaped piers



- static system is a hinged strut frame bridge with longest span of 27 m



- superstructure is supported by V-shaped pier bents and concrete hinge bearings at abutments

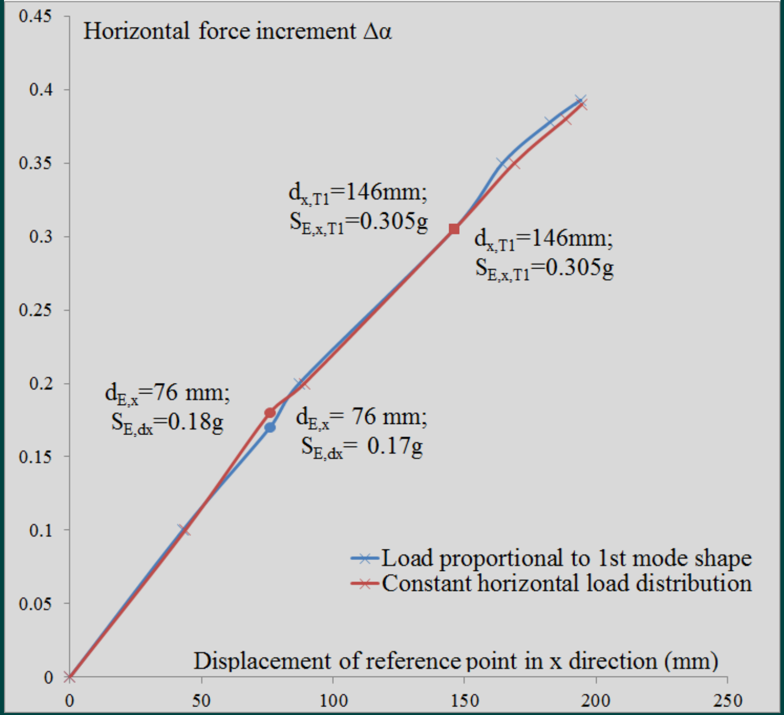


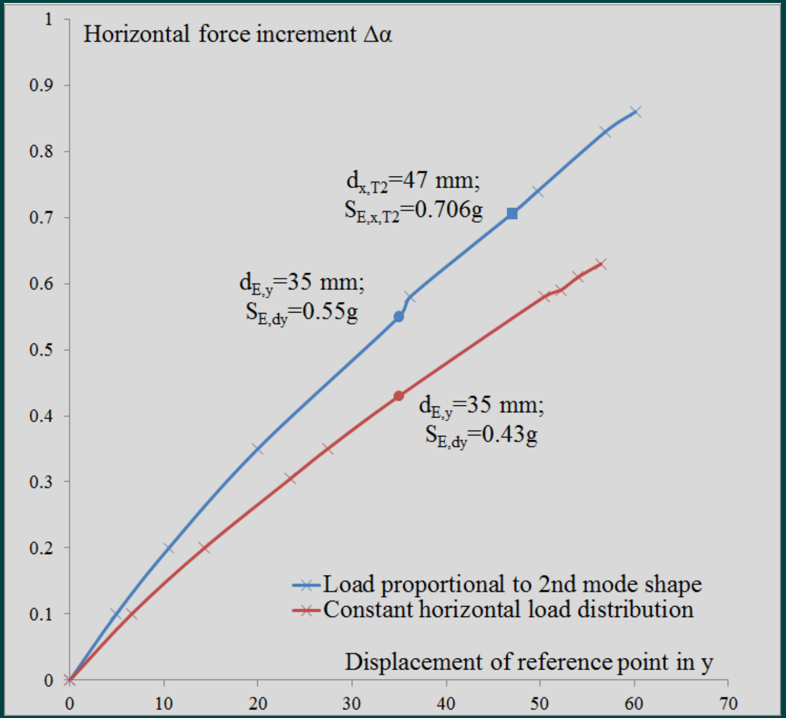
- bridge deck is a reinforced concrete voided slab

Case study 2: RC frame bridge with V shaped piers

- Nonlinear static pushover analysis - bridge structure was loaded with a horizontal load until target displacement of reference point was reached
  - target displacement - obtained from linear response spectrum analysis
  - pushover analysis was performed in both horizontal directions, longitudinal and transverse
  - force-displacement curve of the structure ("capacity curve") - deformation requirements of the plastic hinges up to target displacement

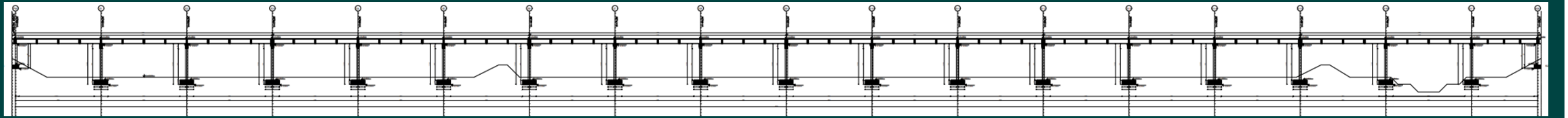
→ Displacements corresponding to the two dominant modal shapes T_1 and T_2 exceed the target displacements $d_{x,T1} > d_{Ex}$ and $d_{y,T1} > d_{Ey}$



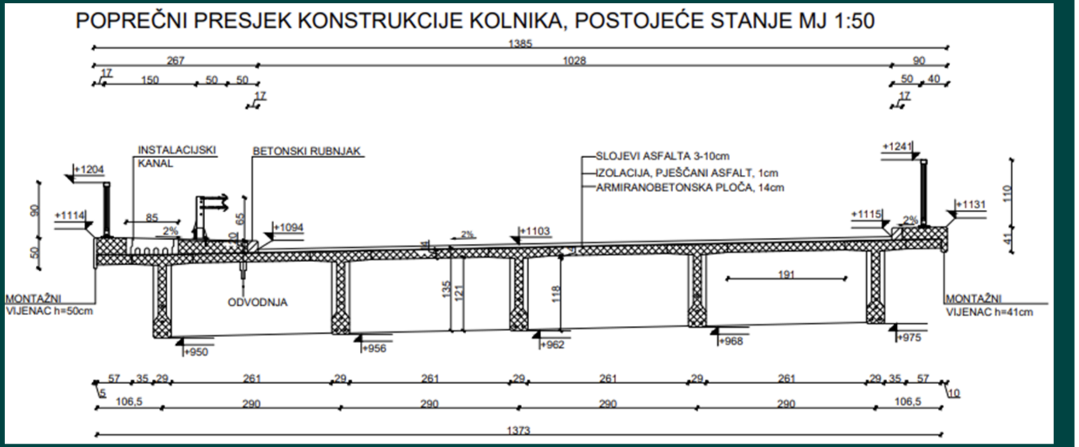


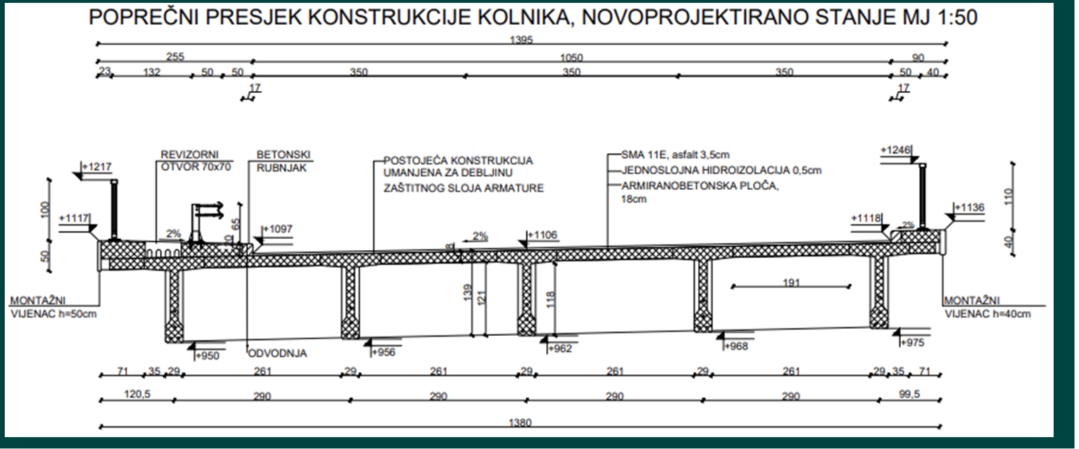
Case study 3: Set of 6 continuous superstructures over 3 spans

- L_{tot} = 435,42 m
- Spans 24.5 m
- Expansion joints at 7 places



- In 2007, a project was launched to rehabilitate the bridge.
- A major part of the rehabilitation involved the restoration of the protective reinforc. layer.
- The most demanding measure was the rehabilitation of the bridge deck.
  - This involved the process of deepening the concrete by 2 cm, and then installing new reinforcement and concreting.
  - altogether 4 cm of new concrete was poured, 2 cm of concrete below the installed reinforcement, and 2 cm above it.
- After the completion of the repair work on the bridge deck, the installation of waterproofing and asphalt, expansion joints were installed.





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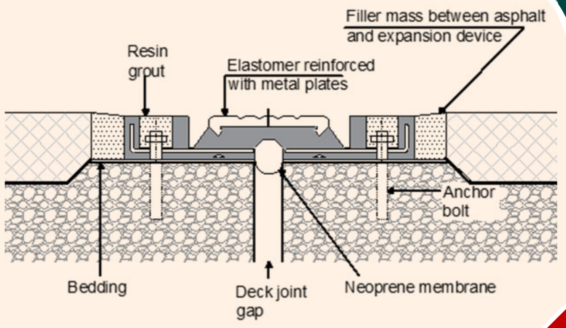
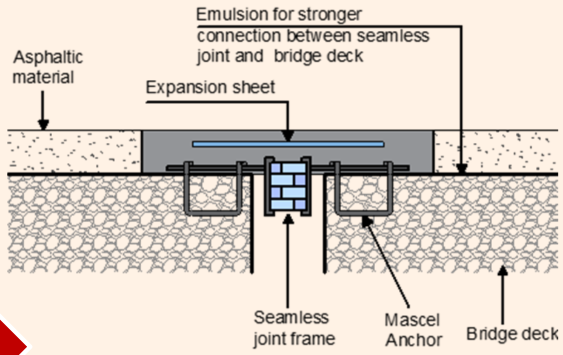
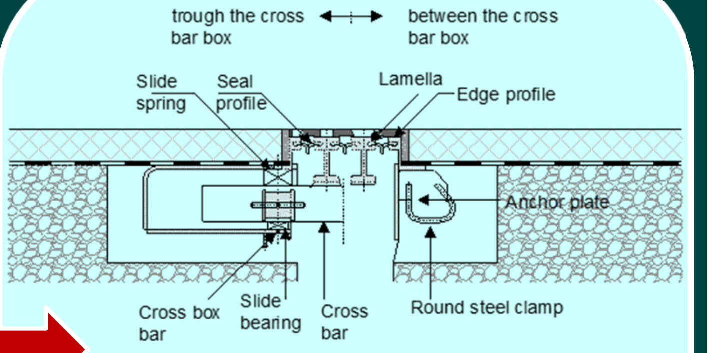


- original rehabilitation project - 2007
- reinforced elastomeric expansion joint 50 mm
- in practice, these devices did not prove to be of high quality because they allowed water to penetrate the structure



- decision during the rehabilitation - 2012
- asphaltic flexible plug joints 40 mm
- the equipment was installed in Dec. at 0ºC, in high humidity, and on a wet concrete slab
- subsequently the ex. joint leaked in almost all 7 places where it was installed
- higher temperatures to bond aggregates and binders during installation required



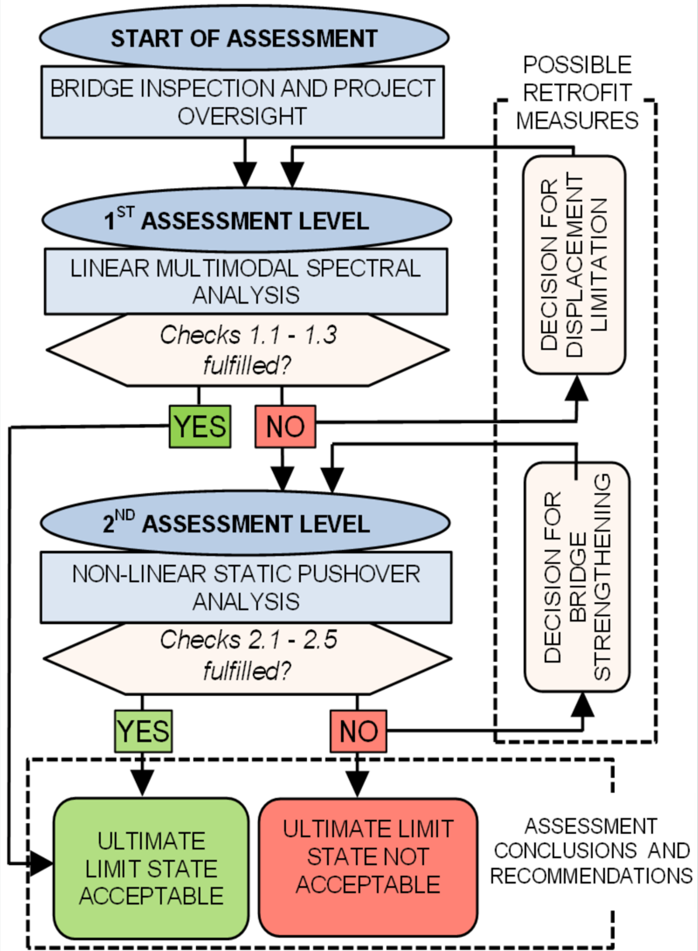
- Master's thesis design according EC - 2022
- elastomeric in metal runners girder grid expansion joint ± 60 mm
- T = 475 years, ag = 0.23g, q = 1.0, γ= 1.0, soil C
- 40% E + 50% T action allow damage under severe earthquakes, while damage under frequent values can still be avoided

SEISMIC ASSESSMENT DVELOPED FOR ARCH BRIDGES

3. SEISMIC ASSESSMENT OF ARCH BRIDGES

- …is consisted of two levels and several evaluation checks at each assessment level.
- 1st level of assessment results with more conservative estimate of the bridge condition.
- 2nd requires more numerical and computational effort, but it results with less conservative estimate and thus with economically favorable retrofitting measures.
- If retrofitting measures will be taken, it is important to apply this same procedure again on the model of retrofitted bridge and evaluate the results following the same steps.

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	$A_{t,built}/s_{T,built} \geq \min(A_t/s_T)$



START OF ASSESSMENT

BRIDGE INSPECTION AND PROJECT OVERSIGHT

1^{ST} ASSESSMENT LEVEL

LINEAR MULTIMODAL SPECTRAL ANALYSIS

Checks 1.1 - 1.3 fulfilled?

YES

NO

2^{ND} ASSESSMENT LEVEL

NON-LINEAR STATIC PUSHOVER ANALYSIS

Checks 2.1 - 2.5 fulfilled?

YES

NO

ULTIMATE LIMIT STATE ACCEPTABLE

ULTIMATE LIMIT STATE NOT ACCEPTABLE

ASSESSMENT CONCLUSIONS AND RECOMMENDATIONS

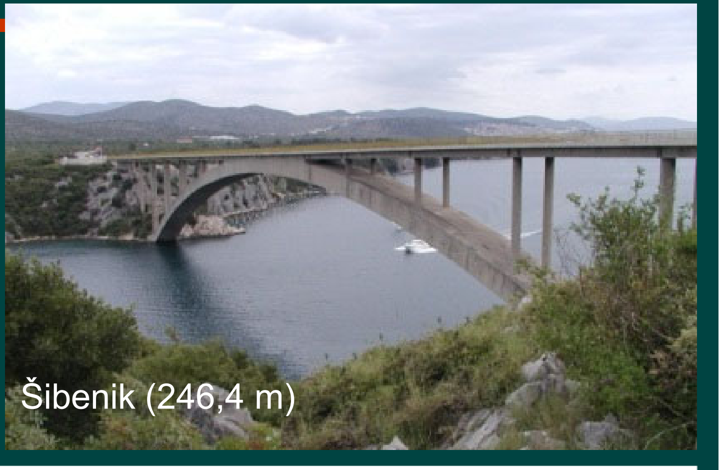
POSSIBLE RETROFIT MEASURES

DECISION FOR DISPLACEMENT LIMITATION

DECISION FOR BRIDGE STRENGTHENING

3. SEISMIC ASSESSMENT OF ARCH 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



Šibenik (246,4 m)

Assessment checks related to linear multimodal spectral analysis	
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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 $f(N_E, M_E)$
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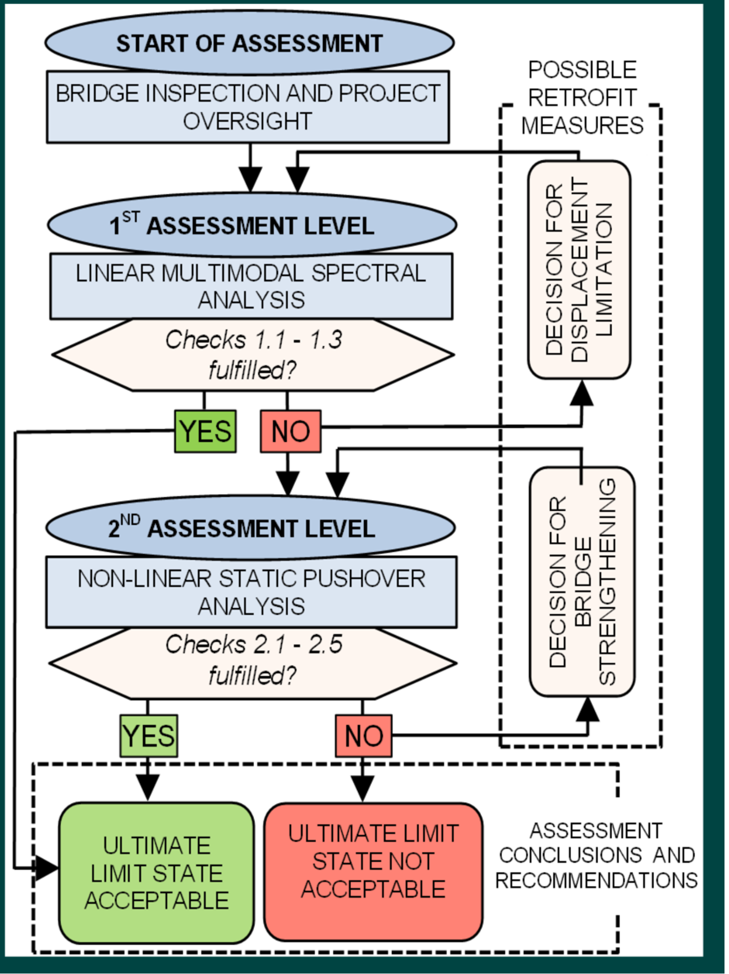


START OF ASSESSMENT

BRIDGE INSPECTION AND PROJECT OVERSIGHT

1ST ASSESSMENT LEVEL

LINEAR MULTIMODAL SPECTRAL ANALYSIS

Checks 1.1 - 1.3 fulfilled?

YES

NO

2ND ASSESSMENT LEVEL

NON-LINEAR STATIC PUSHOVER ANALYSIS

Checks 2.1 - 2.5 fulfilled?

YES

NO

ULTIMATE LIMIT STATE ACCEPTABLE

ULTIMATE LIMIT STATE NOT ACCEPTABLE

POSSIBLE RETROFIT MEASURES

DECISION FOR DISPLACEMENT LIMITATION

DECISION FOR BRIDGE STRENGTHENING

ASSESSMENT CONCLUSIONS AND RECOMMENDATIONS

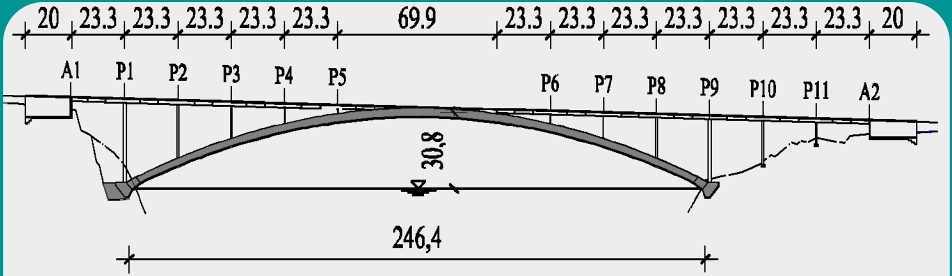
3. SEISMIC ASSESSMENT OF ARCH BRIDGES

- The dynamic specificity of arch bridges is the flexibility of an arch as support for spandrel columns, and the fact that a great amount of the bridge mass is generally located in the middle of the bridge.

→ During inelastic response of arch bridge due to initial seismic stroke, the greatest deformation demands affect the shortest columns, which results in their excessive cracking and, finally, after a damage causing earthquake, in the need for their repair or retrofit.

→ Upon the cracking of shortest columns and appurtenant stiffness reduction, deformation requirements are moved from the crown to coastal columns, which results in their degradation as well.

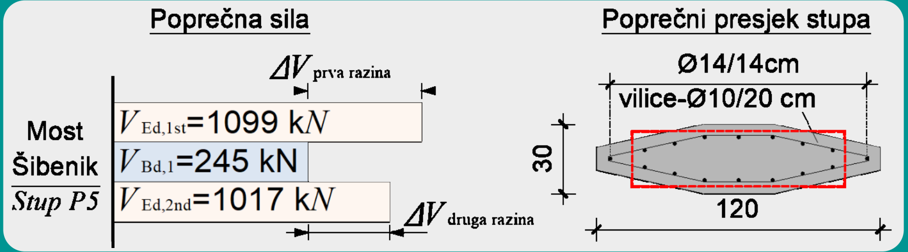
→ That excessive cracking should be adequately taken into account with effective stiffness of column cross-sections using iterations procedure.



P1	P2	P3	P4	P5	E_cI_{eff}/E_cI_{gross} (%)	P6	P7	P8	P9	P10	P11
100	70	45	25	10	uzdužno	15	30	55	80	55	30
100	60	30	15	10	poprečno	10	15	35	70	55	35

The stiffness ratio of cracked and un-cracked column cross-sections in regions of potential plastic hinges

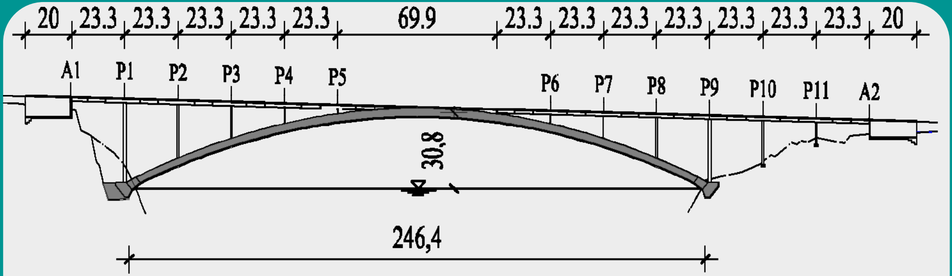
Shear seismic demands on the most critical piers



3. SEISMIC ASSESSMENT OF ARCH BRIDGES

- Due to the excesive shear demand,
  - → rather than by greatly changing the critical pier cross-sectional dimensions,
  - → a more appropriate retrofitting solution would be to transfer seismic forces along the deck from piers to abutments by installing seismic dampers at bridge abutments.
- Accurate evaluation of the ultimate rotational capacity of reinforced concrete members,
  - → due to numerous geometrical and mechanical parameters and uncertainties involved:

    load type - cyclic or monotonic, seismic detailing, concrete confinement, spalling of concrete cover, ribbed or smooth bars, overlapping length, plastic hinge length, bending contribution, height of the section, etc.)
  - → may only be based on experimental data.



P1	P2	P3	P4	P5	E_cI_{eff}/E_cI_{gross} (%)	P6	P7	P8	P9	P10	P11
100	70	45	25	10	uzdužno	15	30	55	80	55	30
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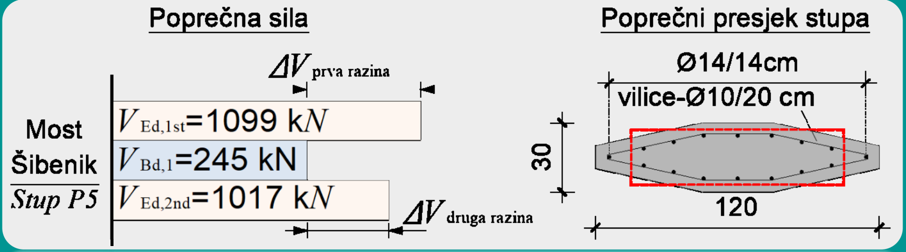
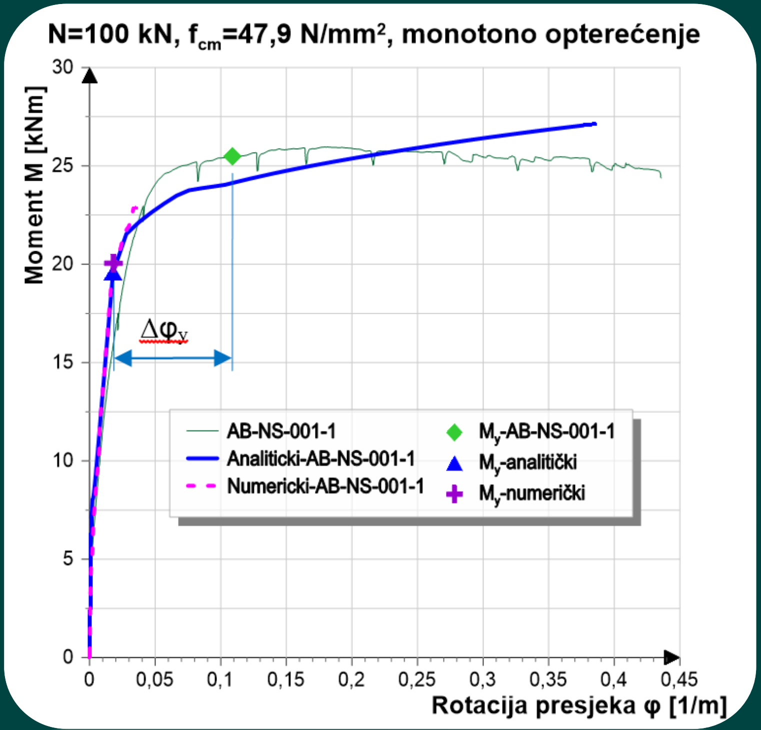
Shear seismic demands on the most critical piers



Revealing ductility levels

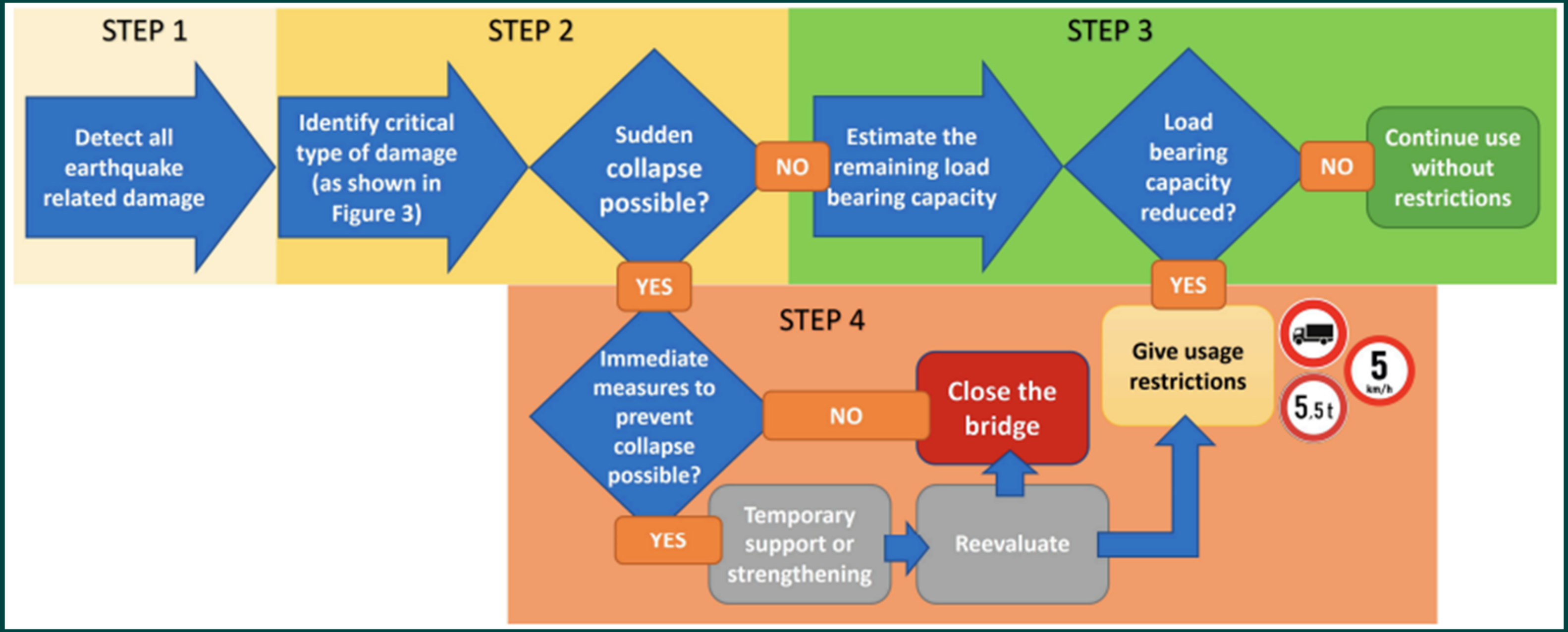
- Non standard sections, smooth reinforcement, no rules for ductile behaviour
- Seismic performance indicators:
  - M/φ diagrams - showing the rotational capability of plastic hinges
  - end section rotation and chord rotation capacity at the yielding point and at the ULS
  - plastic hinge lenght
- M/φ 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



POST EARTHQUAKE RAPID DAMAGE ASSESSMENT

4. POST EARTHQUAKE RAPID DAMAGE ASSESSMENT

- On 29 December 2020, a devastating M_L = 6.2 earthquake hit the Sisak-Moslavina county of Croatia.
- Immediately after the earthquake, structural engineers' teams were dispatched to conduct rapid damage assessment and evaluate the usability of structures.



STEP 1

Detect all earthquake related damage

STEP 2

Identify critical type of damage (as shown in Figure 3)

Sudden collapse possible?

NO

STEP 3

Estimate the remaining load bearing capacity

Load bearing capacity reduced?

NO

Continue use without restrictions

YES

YES

STEP 4

Immediate measures to prevent collapse possible?

NO

Close the bridge

Give usage restrictions

5 km/h

5,5t

YES

Temporary support or strengthening

Reevaluate

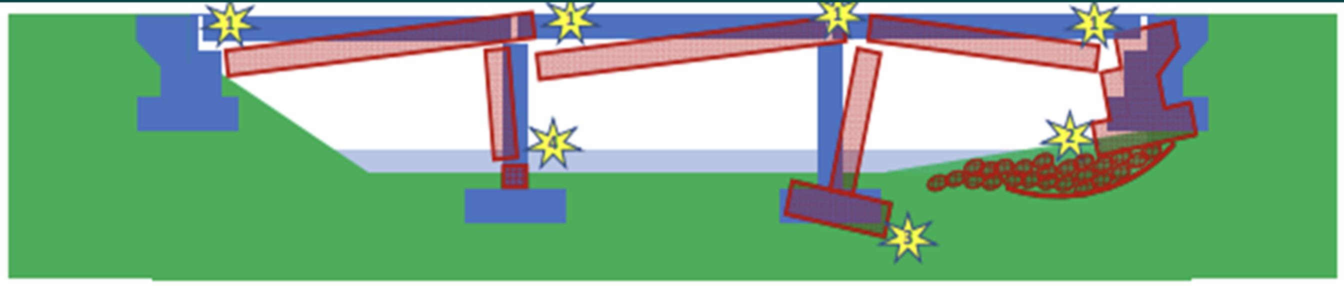
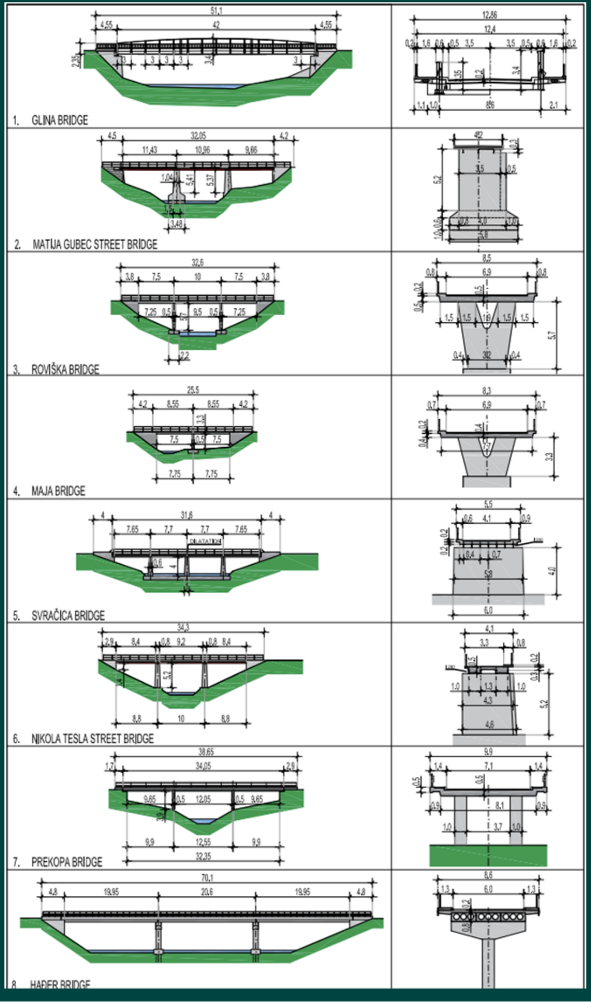
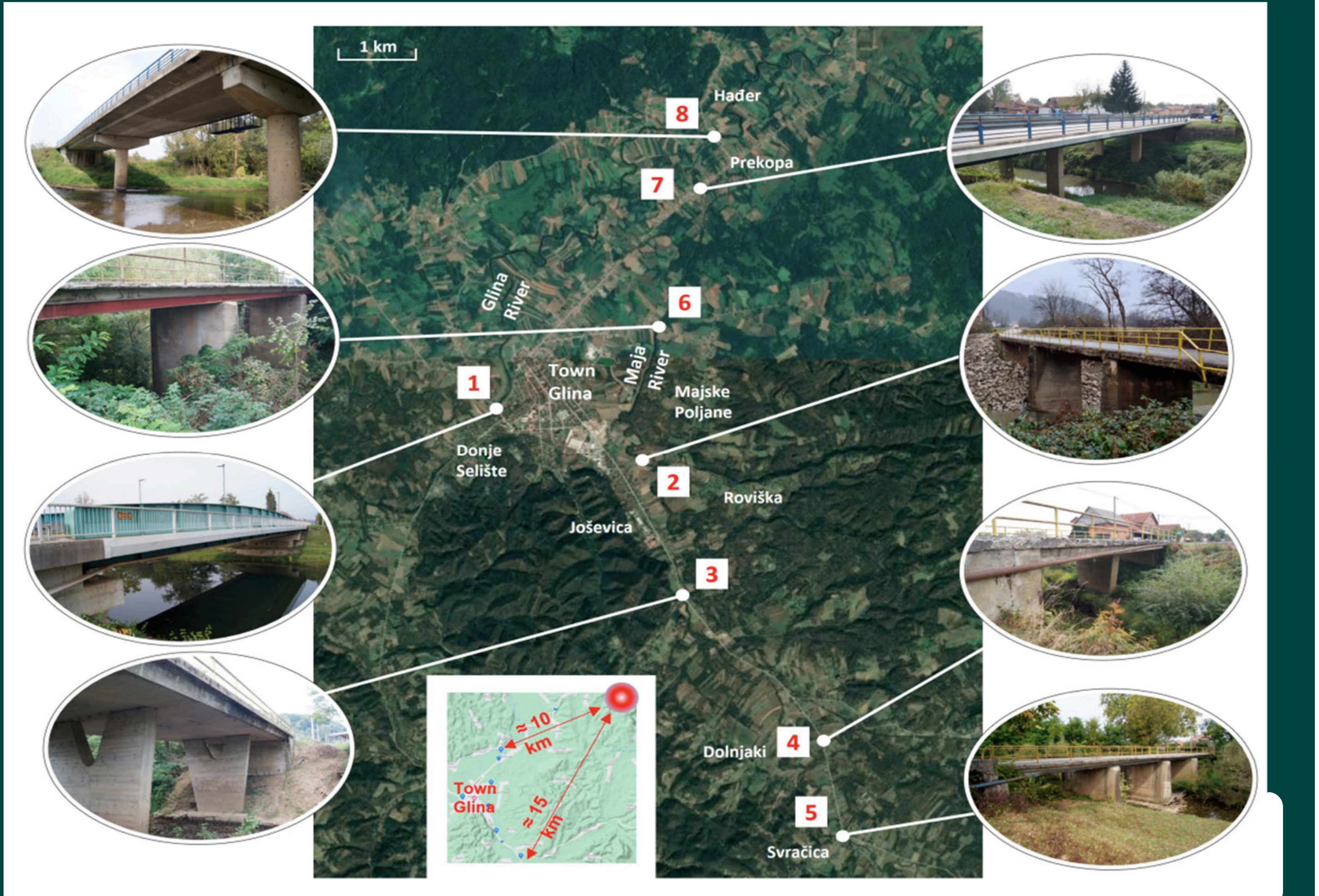


Figure 3 Most common earthquake types of bridge sudden collapses (any or all can occur): 1—bearing slippage; 2—abutment foundation soil landslide; 3—column turnover; 4—column shear failure.

Case study: Eight bridges in Glina County

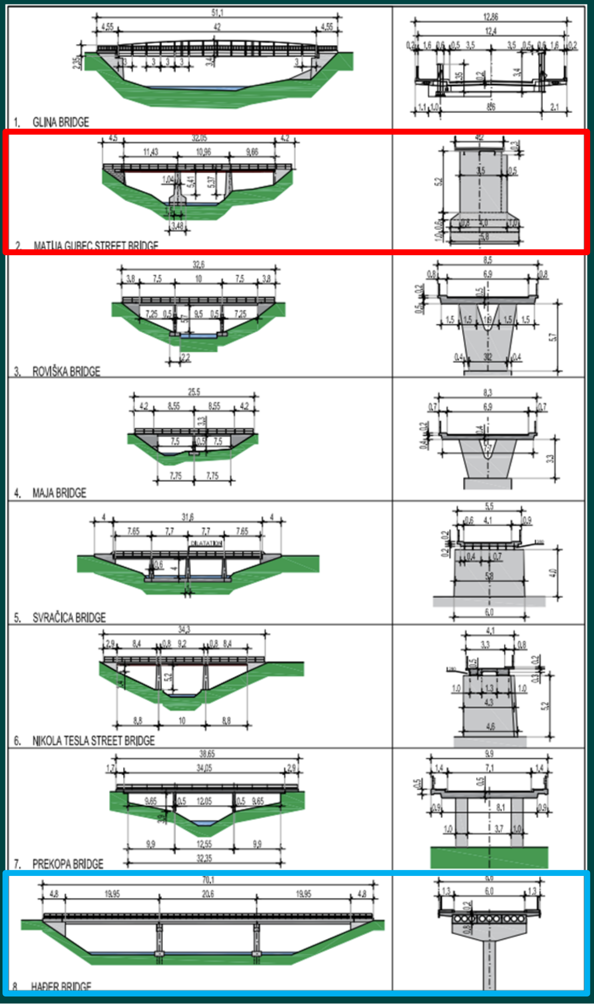
- This area is located 10–15 km from the epicenter of the earthquake and was therefore strongly affected.
- All examinations were carried out in 1 day, with follow-up for most critical bridge no 2. in the next 2 days.
- Most of bridges 50 or more years old. Number 1, 7, and 8 were built in the last 30 years.
- All bridges have simply supported or continuous girders with spans 7 - 20 m.
- The superstructures are concrete slabs or composite steel-concrete ribbed section.
- Glina Bridge is a steel girder bridge with a span of 40 m.

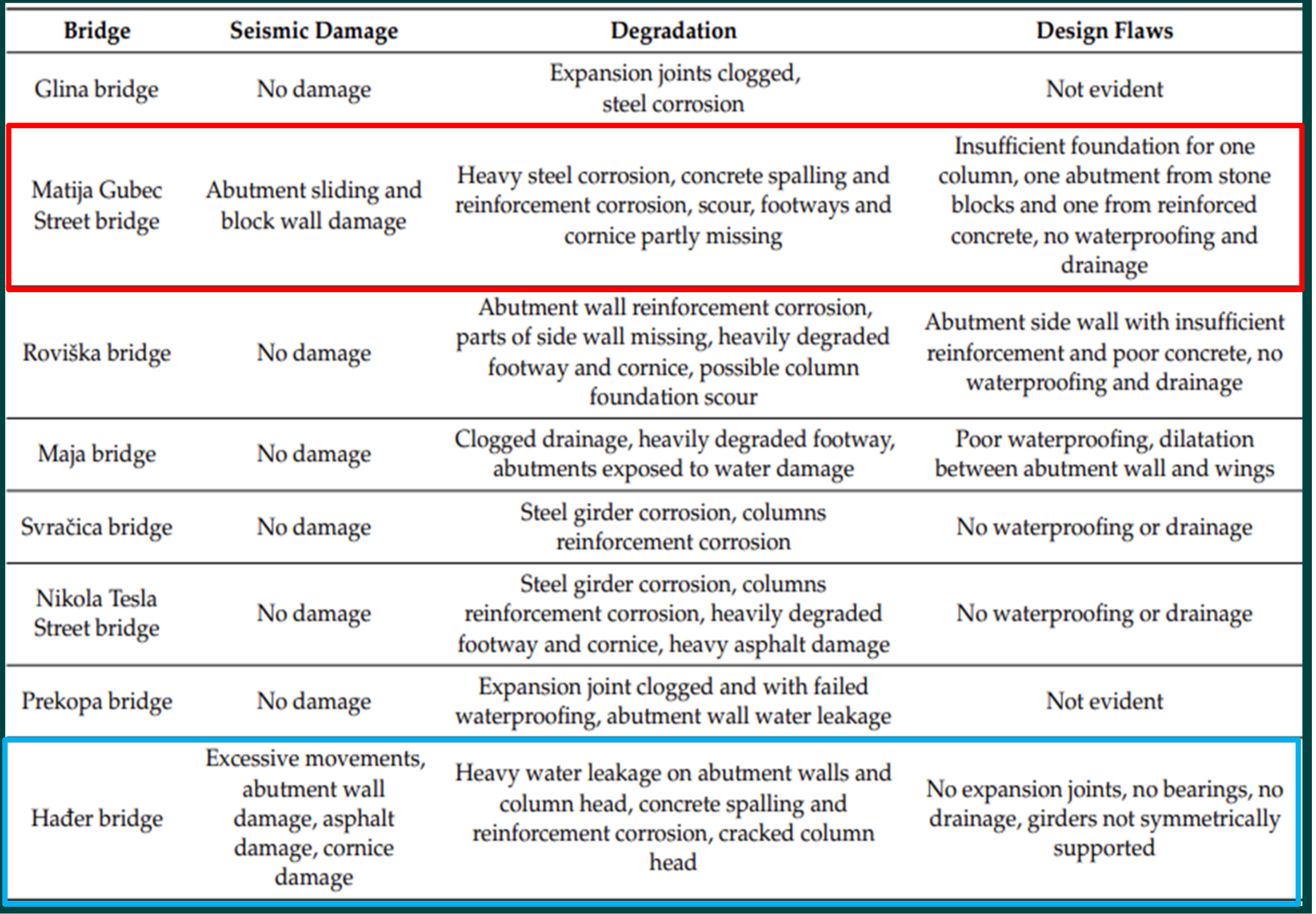




Case study: Eight bridges in Glina County

- The main problem of all bridges, was the lack of maintenance, which, in combination with poor waterproofing, led to progressive material deterioration and subsequent damage to the bridges.
- Most of the bridges performed well in the earthquake and were opened for use without restrictions.
- Only one bridge with major damage - Matija Gubec - was closed for traffic and leter on retroffited.
- For the bridge with minor damage - Hader bridge - it is recommended to add expansion joints allowing for seismic movements and to check the movements with nonlinear analysis to prevent slippage of girders.





Bridge	Seismic Damage	Degradation	Design Flaws
Glina bridge	No damage	Expansion joints clogged, steel corrosion	Not evident
Matija Gubec Street bridge	Abutment sliding and block wall damage	Heavy steel corrosion, concrete spalling and reinforcement corrosion, scour, footways and cornice partly missing	Insufficient foundation for one column, one abutment from stone blocks and one from reinforced concrete, no waterproofing and drainage
Roviška bridge	No damage	Abutment wall reinforcement corrosion, parts of side wall missing, heavily degraded footway and cornice, possible column foundation scour	Abutment side wall with insufficient reinforcement and poor concrete, no waterproofing and drainage
Maja bridge	No damage	Clogged drainage, heavily degraded footway, abutments exposed to water damage	Poor waterproofing, dilatation between abutment wall and wings
Svračica bridge	No damage	Steel girder corrosion, columns reinforcement corrosion	No waterproofing or drainage
Nikola Tesla Street bridge	No damage	Steel girder corrosion, columns reinforcement corrosion, heavily degraded footway and cornice, heavy asphalt damage	No waterproofing or drainage
Prekopa bridge	No damage	Expansion joint clogged and with failed waterproofing, abutment wall water leakage	Not evident
Hađer bridge	Excessive movements, abutment wall damage, asphalt damage, column head damage, cornice damage	Heavy water leakage on abutment walls and column head, concrete spalling and reinforcement corrosion, cracked column head	No expansion joints, no bearings, no drainage, girders not symmetrically supported

5. SHORTCOMINGS VS. HIDDEN RESERVES

- Depending on the structural system, materials used, approach to design, construction details existing bridges may have

Disadvantages/shortcomings

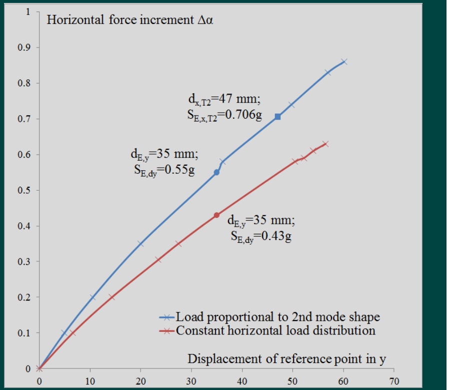
- Floating support without antiseismic blocks
- Large displacements - insufficient movement capacity
- Insufficient overlap lengths in girder bridges
- No detailing for ductile behaviour
- Lacking in regular maintenance or even periodical inspection

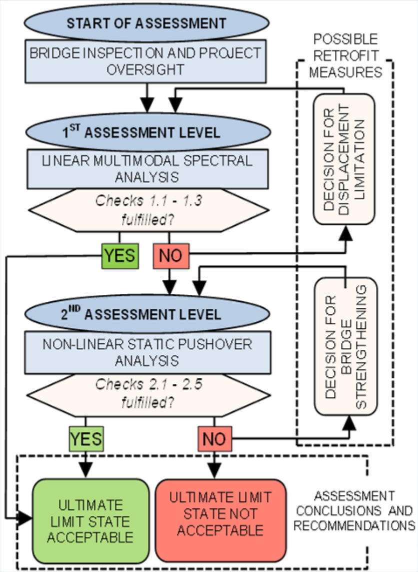
Advantages/hidden reserves

- Robustnes of integral/frame and arch bridges
- Smooth reinforcement, which due to properties of materials and lower adhesion to concrete allows greater deformations
- Smaller dimensions – lower seismic forces
- Most of the bridges performed well during earthquake event and continued to be used for rescue and evacuation purposes.

5. CONCLUSIONS

- Despite long service lives and insufficient maintenance,
  - most of the examined bridges performed well during this earthquake event
  - and continued to be used after for rescue and evacuation purposes.
- But there are exceptions –
  - bridges with major or minor damages, with critical or poor condition –
  - which, if neglected, could lead to excess movements and possibly catastrofic failures.
- In addition, results of analysed case study bridges under service reveal that
  - they do not possess sufficient load-bearing capacity for seismic actions, according to currently valid seismic codes.
- Therefore, main steps in strategy of bridge infrastructure anti-seismic management are
  - to establish a pro-active regular maintenance based on visual inspection supported with adequate testing techniques to determine present condition
  - Perform multi level assessment methods of existing bridges by structural bridge engineers to evaluate the capacity of existing bridges in regard to their seismic resistance
- In the meantime we are trying to educate new type of engineers with knowledge from different disciplines
  - structures, materials, durability, management, …?





SEISMIC PERFORMANCE OF EXISTING BRIDGES IN CROATIA:

shortcomings, hidden reserves and seismic assessment perspective

Thank you for your attention!

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