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Seismic designs of some recent bridges created by the structural department of Zagreb Faculty of civil engineering

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Abstract

Over the last 20 years, beside their primary educational activities, members of the Bridge Chair of the Zagreb Faculty of Civil Engineering Structural Department also worked professionally on main and execution designs of many bridges. Most of them are mid-span to large span bridges, requiring detailed seismic design, especially since their locations are predominantly in highly seismic active regions. These bridges were designed during the transition period from old seismic standards, to ENV pre-standards, and finally to EC8 standards. The evolution of these codes had a great impact on the design. New demands in terms of seismic behaviour influenced all aspects of design, from conceptual design (structural system and material options), sizing of elements, foundation type, bearing and damper layouts, special equipment selection, erection details, to maintenance requirements. An overview of seismic design requirements, solutions, and peculiarities for each of these bridges, which were recently constructed or are currently under construction, is presented in the paper. Since the design of the cable stayed bridge Franjo Tuđman in Dubrovnik, where fluid viscous dampers were first employed in Croatia, to the recent bridge designs, various approaches were utilized to mitigate and take over the seismic actions. Adequate solutions were found either by structural detailing and/or by installation of seismic isolators, depending on bridge structural systems, utilized materials, but also on the characteristics of foundation soil.

Key words: bridges, seismic design, seismic behaviour, Eurocode, seismic isolators, structural detailing

1 Introduction

Teams from the Bridge Chair of the Zagreb Faculty of Civil Engineering Structural Department worked professionally on main and execution designs of many bridges. Many Croatian bridges were destroyed during the Homeland War and reconstruction designs of many of them, such as Hasan Brkić Bridge in Mostar (1996) were done, but the highlight was the design of the Maslenica Arch Bridge [1], signalling the beginning of construction of the new Adriatic Highway, opened to traffic in 1997. Reconstruction designs were based on then valid seismic codes, which did not consider specific properties of bridges, but rather uncritically utilized methodologies developed primarily for the analysis and design of buildings, but already in the design of Maslenica Arch Bridge provisions of EC-8 pre-standard [2] were adhered to, although this standard was not officially accepted in Croatia until 2005. Since the arrival of the contemporary design codes, with major changes regarding earthquake design, bridges are to be designed according to their provisions. Calculations of these new bridges were considerably aided by computer analysis software, allowing more complex studies of their behaviour under seismic loads. Over the last 20 years quite a few bridges were designed by teams from the Bridge Chair of the Zagreb Faculty of Civil Engineering Structural Department, with some of them belonging to the category of mid-span to large span bridges (shown in Table 1). These bridges will be the subject of this paper. An overview of the earthquake design concepts and solutions for each of them shall be provided.

Table 1. Major bridges designed in the last 20 years by the Bridge Chair of Zagreb Faculty of Civ. Eng.

Bridge	Design documentation year	Seismic Design Code	Open for Traffic
Dubrovnik	2000	ENV 1998-2 [2]	2002
Jasenovac	2003	ENV 1998-2 [2]	2005
Krka	2002	ENV 1998-2 [2]	2005
Mirna	2002	ENV 1998-2 [2]	2005
Rječina	2007	HRN ENV 1998-2 [3]	2009
Trogir	2010	HRN EN 1998-2 [4]	2018
Gradiška	2018	HRN EN 1998-2 [4]	in construction

2 Overview of the Design Codes

In the past bridges were considered as rather simple structures, whose seismic response could be easily predicted. Design methodologies, developed primarily for the seismic analysis and design of buildings, were usually incautiously also applied to bridges. This approach was in many cases inappropriate because the seismic response of bridges is considerably different from that of buildings. Bridges are specific structures and seismic design methodologies had to be modified to pertain to their properties, such as the structural system, their dimensions and expected seismic response. The bridge seismic design practice in Europe has been fundamentally changed when the pre-standard EC8/2 [2] was issued. This pre-standard already included many modern design principles of the seismic engineering, which represent a vast improvement over the seismic design practices in the past. We have utilized its requirements since it came out, although it was not officially accepted in Croatia until 2005, as shown in Table 1. Nowadays, the application of Eurocodes is mandatory in Croatia, and the seismic design of all new bridges should be done in compliance with provisions of HRN EN 1998-1 and HRN EN 1998-2, and also Croatian National Application Documents HRN EN 1998-1/NA and HRN EN 1998-2/NA.

3 Bridges seismic design

3.1 Dubrovnik Bridge

For the purposes of designing the Dubrovnik Bridge, the site-specific seismological and seismotectonic Study was conducted at the Faculty of Science of Zagreb University, and the peak design ground acceleration of 0,38g was defined for 500-year return period. The bridge consists of two structurally different parts, a PC box single span with long cantilever girder and a cable stayed bridge (Fig. 1) [5]. The dynamic seismic analysis was performed utilizing the spectrum analysis procedure, according to EC 8, for soil class B [6]. The cable stayed superstructure was analyzed as limited ductile with the behavior factor q=1,5. This behavior factor was utilized for the composite superstructure, the pylon and east bank abutment. The seismic design of the PC beam bridge on the west coast was especially demanding. It was performed using equivalent linear dynamic analysis of the bridge. Obtained forces were modified by behavior factors, according to EC 8/2 [2]. The reduction of the seismic forces, by the behavior factor q > 1,2 could have been performed under the condition that adequate measures were provided to avoid premature damage in the dissipative zone. The additional non-linear analysis by direct integration procedure was performed by the RWTH (Institute for Steel Structures) in Aachen using artificial accelerograms, based on records of actual earthquakes around Dubrovnik has shown that the behavior factor q = 3,5 may be applied [5]. The most sensitive part is the dissipative zone at the pier bottom. Preliminary studies showed that sufficient ductility must be achieved by introducing the plastic hinge at the base of the pier. The RWTH study concluded that the design horizontal displacements must be increased by 1,43 times elastic movements (q=1) [6]. The connection of the pier to the foundation and the part of the pier above the plastic joint was calculated for bearing capacity factored by 1,4, i.e. with the behaviour factor of 3,5 / 1,4 = 2,5. The entire concrete box was dimensioned with the same factor. For the vertical earthquake action all elements were calculated with the behaviour factor of 1,0 (elastic behaviour). To prevent large longitudinal displacements of PC superstructure hydraulic dampers, manufactured by the company Maurer&Söhne, were installed on abutment U1 (Fig. 1).

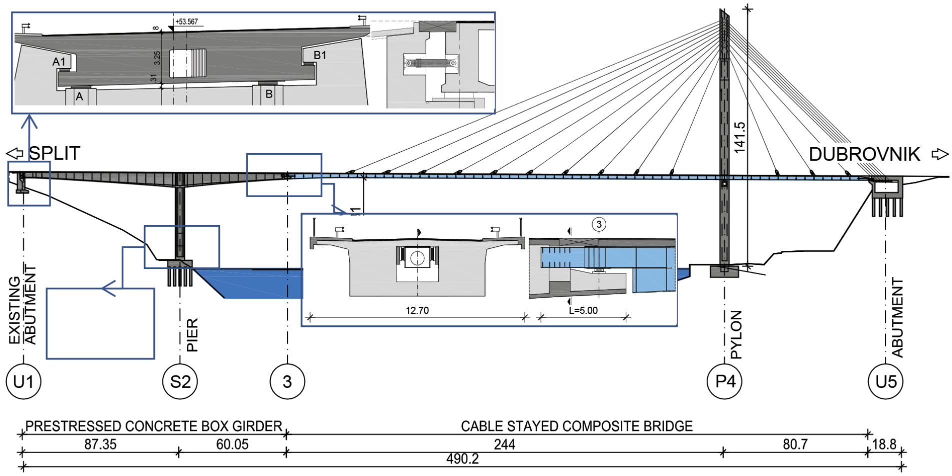


Figure 1. Dubrovnik Bridge: Layout and specific details

Two units with a load capacity of 2.000 kN in the longitudinal direction were placed, which should reduce the displacement and pier bending moment by 50 %. The damping coefficient of these devices is up to ξ = 0,61 (for comparison the damping of the concrete bridge is ξ = 0,05). On the abutment U1 two pot bearings (A and B) are installed for vertical reactions. However, as seismic calculations have shown that large tensile (uplift) reactions can occur, two more neoprene bearings (A1 and B1) have been added (Fig. 1). The adequate overlap length was adopted to ensure that the function of the PC superstructure support on the abutment is maintained under extreme seismic displacements. An even larger overlap (seat) length was needed at the connection of the cable stayed superstructure and the PC box girder to prevent the separation of the two span assemblies due to seismic action. The cable stayed girder is supported on the PC box girder by two vertical pot bearings and by two lateral neoprene bearings to absorb horizontal forces transversely to the bridge (Fig. 1). There are also a total of four bearings on the pylon P4, two pot bearings for taking over the vertical reaction and two side bearings between the structure and the pylon for taking over the transverse horizontal forces.

3.2 Jasenovac Bridge

The original main bridge superstructure (1973) over the Sava River was a three-span PC continuous box type girder, destroyed in 1990 during the Independence War, designed without consideration of seismic actions. The superstructure and two piers were completely destroyed, while two piers and all foundations were in good condition and could be utilized to support the new superstructure. The bridge lies in seismic zone VIII and the design ground acceleration is 0,2g. An analysis was performed for the conditions of different technical solutions for the reconstruction of the bridge. The basic parameter of the analysis was the acceptability of a particular solution regarding the seismic behaviour. The reference peak ground acceleration for the bridge location seismic zone is a_{gR}=0,20g for the return period of 475 years and the adopted importance factor amounts to γ_I = 1,0. The ground type is C. The Response Spectrum Analysis was utilized to calculate the response of the bridge to seismic action, based on ENV 1998-2 [2]. The performed analyses revealed that the best solution, technically and economically, is a steel superstructure on existing foundations, which do not need to be strengthened [7]. A continuous steel box girder with spans L=60,55+120,0+55,35=235,9 m was designed and built (Fig. 2). No special anti-seismic devices were necessary, because the steel superstructure has small weight and piers are relatively high, so that stability under seismic actions is assured. The longitudinally fixed bearing is positioned on the pier S7 near the left Sava Riverbank (Fig 2.). The longitudinal horizontal force due to the seismic action amounts to H_x=3,7 MN.

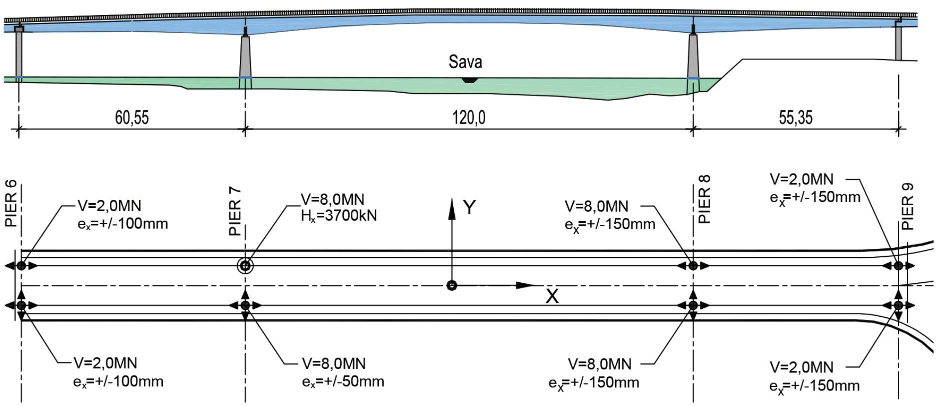


Figure 2. Jasenovac Bridge: Longitudinal layout and layout of bearings

3.3 Krka Bridge

A concrete arch bridge with 204 m span was constructed across the Krka River canyon on the section Skradin–Šibenik of the Adriatic highway. The superstructure is continuous with spans L=3x32+3x28+3x32+28+24=360 m, comprising two main steel box-type beams spaced at 7,6 m, strong steel cross beams and a concrete deck plate in composite action with both main and cross beams [8]. The adopted system of structural bearings allows the bridge structure to respond differently to normal working conditions (permanent and live loading, temperature and wind) and to seismic events. Bearings and seismic devices comprise the following (Fig. 3): permanent fixed bearings on piers S3, S4, S5, S10, S11 and S12 (pot type with vertical capacity of 9.000 kN and horizontal capacity of 940 kN); special device in pier S8 northbound, fixed under normal working conditions and longitudinally sliding for large seismic event (pot type with vertical capacity of 7.000 kN), special device in pier S8 southbound, transverse sliding under normal working conditions and free sliding for large seismic event (pot type with vertical capacity of 9.000 kN); permanent longitudinally guided bearings in all other positions except U1, S6, S7, S9 and U14 southbound where free sliding bearings are installed (pot type with vertical capacity varying from 3.550 kN to 7.500 kN); viscous dampers seismic protection devices at both abutments. Since the concrete arch is the stiffest bridge element, practically the whole longitudinal horizontal force is resisted by the two bearings in pier S8, but up to the maximum value of 1.000 kN each [9].

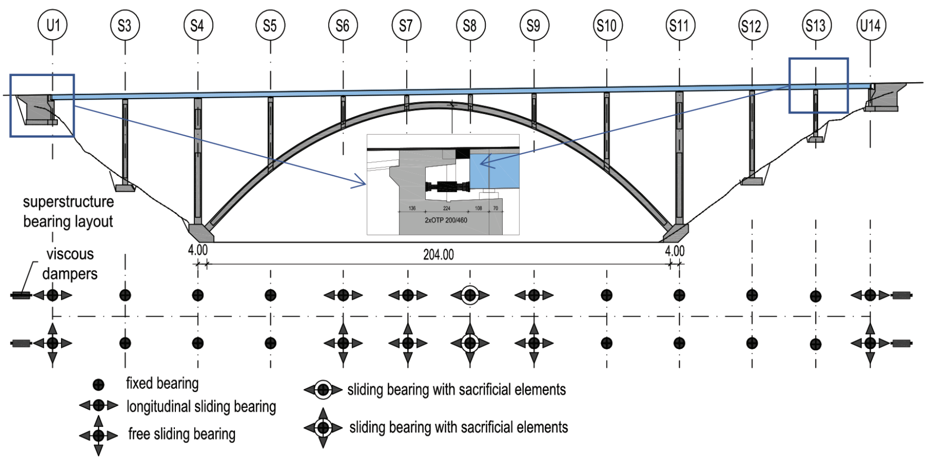


Figure 3. Krka Bridge: Longitudinal layout and bearings and dampers device layout

The calibrated pins (sacrificial elements) on pier S8 bearings allow the transmission of the longitudinal horizontal forces only up to this predefined value, so that the arch resistance only needs to be designed up to this threshold. All other fixed bearings take up only small horizontal forces in the direction of the bridge axis due to relatively large flexibility of piers S3, S4, S5, S10, S11 and S12. When the horizontal longitudinal force exceeds the value of 1.000 kN, the special fixed and transverse sliding bearings in pier S8 become free to move in longitudinal direction, thus activating the seismic viscous dampers at both abutments. Due to flexibility of piers with longitudinally fixed bearings, the bridge can almost freely move longitudinally. Thus, for normal working conditions the bridge is fixed at pier S8 and is free to contract/expand for thermal variations in all other positions due to flexibility of tall arch piers or presence of sliding bearings (short piers), while for seismic events the fixed bearings in S8 become movable and the whole bridge is free to displace longitudinally. So, base isolation is achieved, and the longitudinal movements are controlled by means of viscous dampers at the abutments, which dissipate seismic energy. The dampers installed at both abutments (2 each) are of type OTP 200/460 and have been designed to accommodate the maximum seismic force of 2.000 kN and allow the total longitudinal movements of ± 230 mm [9].

3.4 Mirna Viaduct

The Mirna Viaduct crosses the Mirna River valley on Nova Vas – Višnjan section of the Istrian "Y" west leg state road. The overall viaduct length is 1.378,03 m, with spans L= 51 + 15x66,5 + 70 + 2x50 + 63 + 42,5 + 30,5 = 1354,5 m (Fig. 4). The relatively slender continuous superstructure comprises two main steel plate girders spaced, cross beams in frame action and a concrete deck plate in composite action with main girders [10]. A relatively unusual structural bearing layout was adopted, made possible by the low horizontal stiffness of friction steel pile foundations in adverse soil conditions. On piers P5 to P17 pairs of longitudinally fixed structural bearings were installed with one of them movable in the transverse direction and the other fixed. The fixity of both bearings on a particular pier in the bridge axis direction was necessary to limit torsional effects on torsional weak piers of H shaped cross section. One of structural bearings on both abutments C0 and C22, and piers P1 to P4 and P18 to P21 is free sliding and the other longitudinally guided (Fig. 4). The superstructure is longitudinally restrained at both abutments by two installed viscous dampers of 1.000 kN allowable capacity each [10].

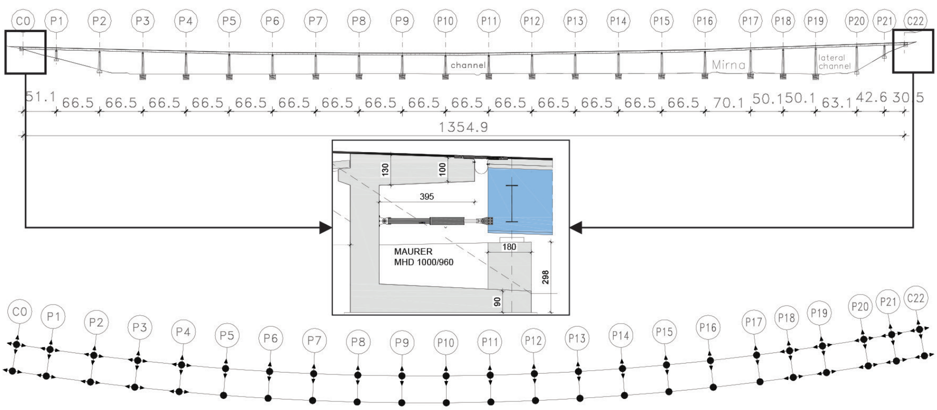


Figure 4. Mirna Bridge: Longitudinal layout and bearings and dampers device layout

3.5 Rječina Bridge

A new southern bridge has been completed parallel to the existing (1984) northern Rječina Bridge of the Rijeka city beltway. The new Rječina Bridge is a PC rigid strut frame structure with the box type superstructure. The superstructure is continuous over three spans, with the main span of 108,5 m and with two identical side spans of 50 m each [11].

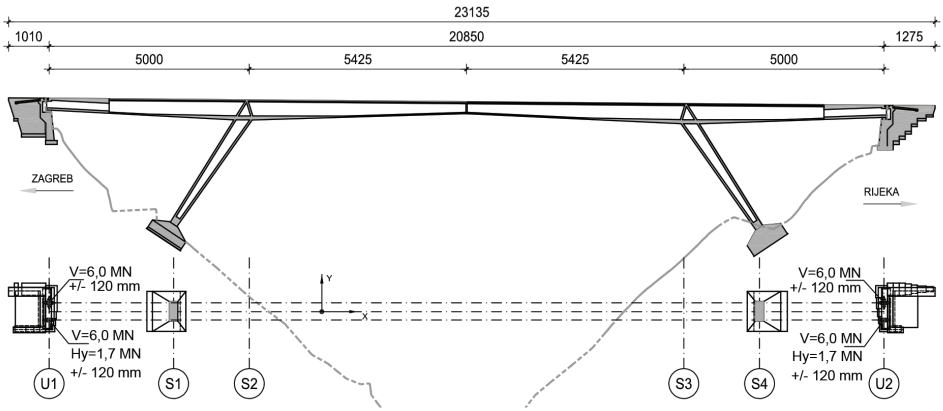


Figure 5. Rječina bridge: longitudinal layout and bearings layout

Its new design exemplifies more stringent requirements on bridge structures, incorporated in current structural standards in comparison to standards valid about thirty years ago for the old bridge. Seismic actions on the old bridge were accounted for by applying 7 % of the dead load horizontally, while for the new bridge the Response Spectrum Analysis, according to pre-standard Eurocode 8 was conducted with the peak ground acceleration of 0,2g and the behaviour factor of 1,2. Also, the total dead weight of the new bridge is significantly larger of the existing bridge dead weight, while outer dimensions of all structural elements were kept the same. Due to the frame action and appropriately conceived bridge structure, no special devices were necessary to take over seismic actions, except that one structural bearing on each abutment had to be designed for large horizontal force in the transverse direction (V=6,0 MN, H_y=1,7 MN) (Fig. 5).

3.6 Trogir Bridge

The first part of the Trogir - Čiovo Island bridge from the Mainland to the bascule bridge is continuous over nine spans with the total length L=20,58+28,0+32,0+5*40,0+34,8 =315,38 m. The second part comprises the bascule bridge with a 41,2 m span, and the third part is continuous bridge over 4 spans L=34,8+2*40,0+32,0=146,8 m, extending from the bascule bridge to the Čiovo Island (Fig. 6).
The superstructure cross-section is a three-cell steel box with vertical webs and curved intrados [12]. The seismic action was based on design ground acceleration a_g=0,25g and soil type A. Seismic effects were obtained by using linear dynamical modal response spectrum analysis with sufficient number of modes, so that the active mass was more than 95 % of total mass of the bridge. Fixed bridges are supported on special elastomeric laminated bearings adapted for large seismic movements, i.e. seismic isolators (Fig. 5.). Bearings are designed for maximum vertical force of 4.200 kN (SLS) and maximum movements of ±91 mm for persistent design situations and ±202 mm for seismic design situations [12]. These bearings enable re-centering of the superstructure after

and during seismic actions. Additional bearings are installed at all ends of fixed bridges to carry over transverse horizontal forces due to wind and earthquake. Elastomeric expansion joints reinforced with metal plates fixed on both sides are installed at all ends of fixed bridges, designed to accommodate movements of ±100 mm [12].

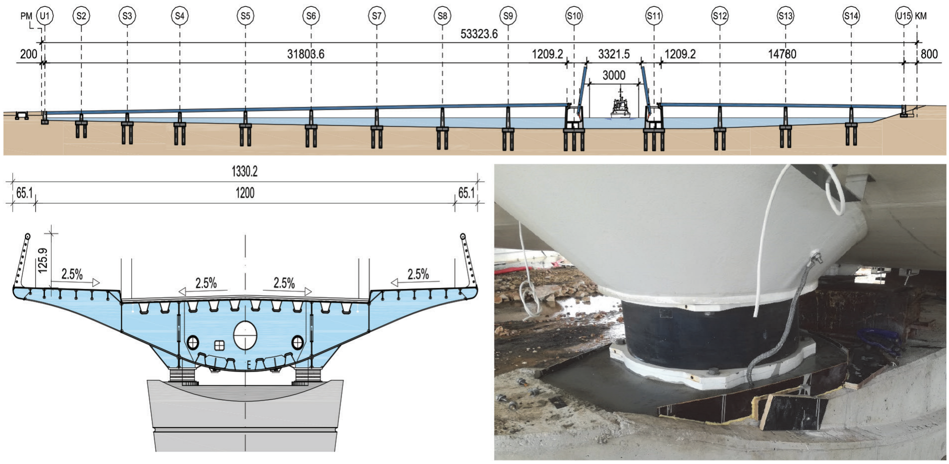
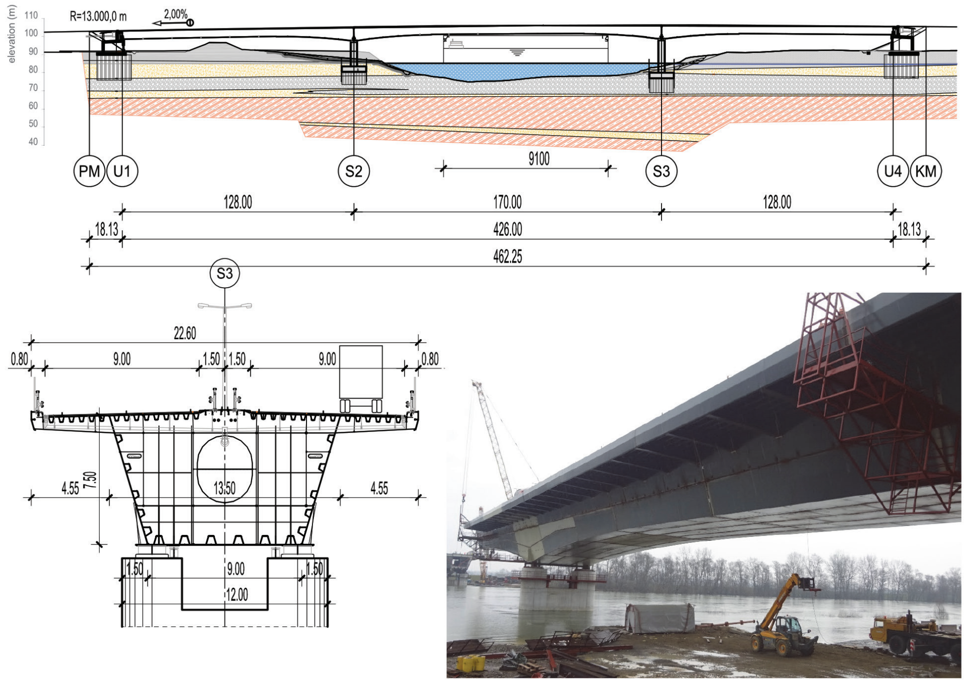


Figure 6. Trogir Bridge: Longitudinal layout, cross section and seismic isolator

3.7 Gradiška Bridge

The latest bridge currently being built is a continuous steel box girder with orthotropic deck plate across three spans: L = 128 + 170 + 128 = 426 m (Fig. 7) [13]. The reference peak ground acceleration for the bridge location seismic zone is a_{gR}=0,20g and the adopted importance factor amounts to γ_I = 1,3, both as specified in the Croatian National Annex HRN EN 1998-1/NA. The ground type is C. The Response Spectrum Analysis was utilized to calculate the response of the bridge to seismic action. In order to mitigate seismic effects, the following elastomeric bearings were designed: HDN=Ø*Te*H*Kr*Rz*dX=1600*256*498*6,3*51.200,0*520 (mm, kN) on piers S2 and S3 and HDH=Ø*Te*H*Kr*Rz*dX=1100*220*458*6,0*25.600,0*440 (mm, kN) on abutments U1 and U4. Their damping is ξ =14-16 %. The maximum design seismic displacement amounts to d_E=375 mm [14]. Transverse horizontal forces are carried by seismic blocks at abut-



ments.

Figure 8. Gradiška Bridge: Longitudinal layout (above), cross section (bottom left) and current progress in construction (bottom right)

5 Conclusion

Over the last 20 years requirements for earthquake design have significantly changed. Bridges designed by teams of the Bridge Chair of Zagreb University Faculty of Civil Engineering have fulfilled these requirements by employing modern solutions comprising resourceful conceptual design, including seismic isolation, increased damping, seismic dissipation by plastic joint formation, and sometimes soil strengthening. In seismic design the Response Spectrum Analysis method was mostly utilized. Only when nonlinear devices, such as fluid viscous dampers were employed, did we have to resort to nonlinear methods.

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