DE GRUYTER
OPEN

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

ISSN 2080-5187 CEER 2015; 16 (1): 51-68
DOI: 10.1515/ceer-2015-0004

EXAMPLES OF SOLUTIONS FOR STEEL-CONCRETE COMPOSITE STRUCTURES IN BRIDGE ENGINEERING

Kazimierz FLAGA[1], Kazimierz FURTAK
Cracow Uninersity of Technology, Institute of Building Engineering, Poland

Abstract

The aim of the article [1] was to discuss the application of steel-concrete composite structures in bridge engineering in the aspect of structural design, analysis and execution. It was pointed out that the concept of steel-concrete structural composition is far from exhausted and new solutions interesting from the engineering, scientific and aesthetic points of view of are constantly emerging. These latest trends are presented against the background of the solutions executed in Poland and abroad. Particular attention is focused on structures of double composition and steel-concrete structures. Concrete filled steel tubular (CFST) structures are highlighted.

Keywords: structures of double composition, steel-concrete structures, concrete filled steel tubular members

1. INTRODUCTION

The high efficiency of steel-concrete composite structures makes them a fundamental solution for girder bridges of medium and long spans, of which there are numerous examples in both Poland and the world. While the majority of design and execution problems in bridges of simple composition have been solved, the search for new structural forms by the application of the so-called double or triple composition as well as the use of favourable properties of CFST members is of great interest. These members offer advantageous utilisation of steel due to the elimination of the phenomenon of local stability loss in compression. They also allow the assembly of a lighter bridge from steel tubes

---

[1] Corresponding author: Cracow Uninersity of Technology, Institute of Building Engineering, Warszawska St. 24, 31-155 Kraków, Poland, e-mail:kflaga@pk.edu.pl, tel.+48126282241

and an improvement of the bridge bearing capacity, after the assembly, by filling the tubes with concrete. The article presents the successful attempts at such solutions in the world.

2. EXAMPLES OF POLISH COMPOSITE BRIDGES

In recent years in Poland a number of interesting composite steel-concrete bridges have been built. Three such realisations have been presented below

2.1. Bridge over the Bug river in Brok (Fig. 1) is a six-span structure of span arrangement 58,00+3x69,00+88,00+49,00 m (Fig. 2).

The overall length of the bridge is 402,00 m, the overall width (Fig. 3) 13,12 m, including the roadway of 8,00 m in width, and footpaths on both sides 2,56 m each. In the cross section there are two main girders. In the zones by the piers truss girders were used while in the span zones and by the abutments they are transformed into two-web plate girders. The trusses of type W have variable height (after parabola 2^o), in the range of 1500÷4900 mm. The deck slab (form concrete class B35) has the mean thickness of 0,24 m (in the cantilever part it decreases to 0,185 m). It is prestressed longitudinally in the by-pier zones. Pretensioning was performed by vertical displacements of the structure (in the assembly stage) and (also in the assembly stage) tendons (7 L 15,5)

Fig. 1. Bridge over the Bug river in Brok (Poland)

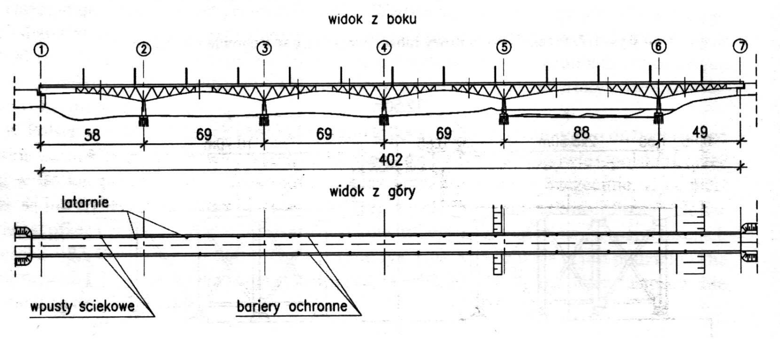


Fig. 2. Side view and top view of the bridge in Brok (Poland)

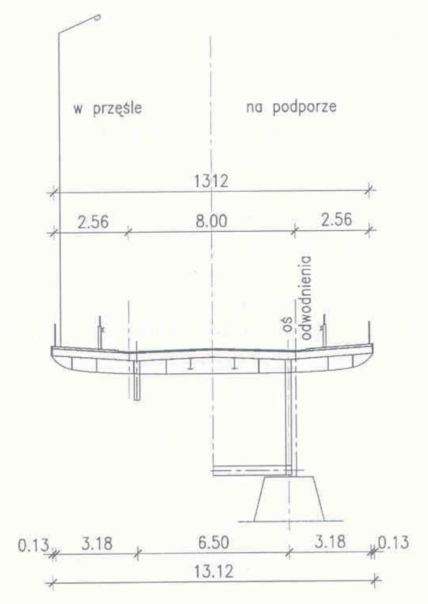


Fig. 3. Cross section of the bridge in Brok (Poland)

2.2. Bridge over the Oder river in Rogów Opolski (Fig. 4) is a five-span structure of span arrangement 2x72,40+72,24+92,00+72,24 m (Fig. 5).

It is composed of two parts two- and three-span parts with expansion joints in-between. The overall length of the bridge is 420,88 m. The bridge has two separate component structures (motorway cross section) placed on common supports. Each of the load carrying structures is composed of four composite girders of spacing of 2,55 m. The steel girder (plate girders) have a constant height of 3150 mm. The Web thickness is 12 mm (by the piers □ 20 mm). The RC deck slab is 0,21 m thick between the girders, and 0,26 and 0,31 m above the girders. The overall width of the bridge is 10,70 m. The roadway has two traffic lanes 3,50 m each, two safety lanes 1,00 m each and two kerbs with parapets with handrails of width 0,85 m each (Fig. 6).

Fig. 4. Bridge over the Oder river in Rogów Opolski (Poland)

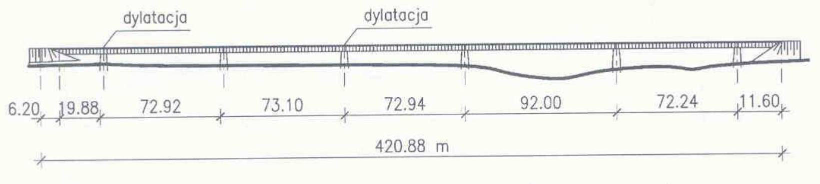


Fig. 5. Side view of the bridge in Rogów Opolski (Poland)

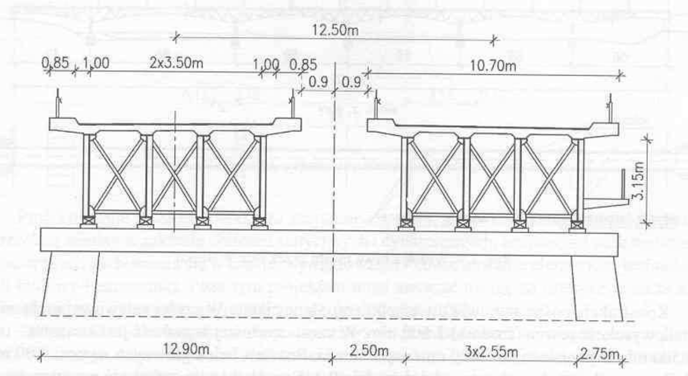


Fig. 6. Cross section of the bridge in Rogów Opolski (Poland)

2.3. Bridge over the Vistula river in Wyszogród (Fig. 7) is composed of two parts with expansion joints in-between. One part (over a floodplain) consists of eleven spans of arrangement 50,00+10x60,00 = 650,00 m. The other part (over the river) consists of six spans of arrangement 75,00+4x100,00+75,00 = 550,00 m (1200,00 m in total, which makes it the longest bridge in Poland (Fig. 8). The load carrying structure is made from two continuous composite beams (plate girders). In the floodplain part they are of constant height (webs) of 2500 mm. In the river part the height ranges from 2500 mm in the spans to 5400 mm above the piers. The main beams are spaced at 7,00 m. The RC deck slab has the mean thickness of 0,285 m. The overall width of the bridge is 12,37 m, including the roadway of the width of 8,70 m (Fig. 9). The steel structure of the bridge was slid on longitudinally. To obtain the rectilinearity of the slip trajectory - due to the variable depth of the girders - the trajectory structure was made from two plate girders placed in the axes of the bridge main girders and posts of variable height (Fig. 10).

Fig. 7. Bridge over the Vistula river in Wyszogród (Poland)

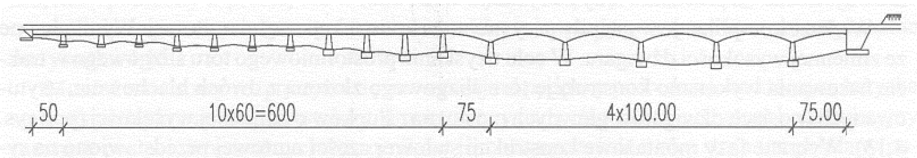


Fig. 8. Longitudinal section of the bridge in Wyszogród (Poland)

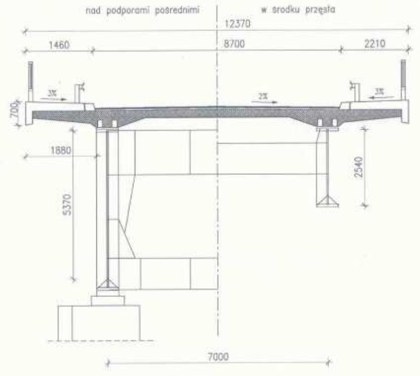


Fig. 9. Cross section of the bridge in Wyszogród (Poland)

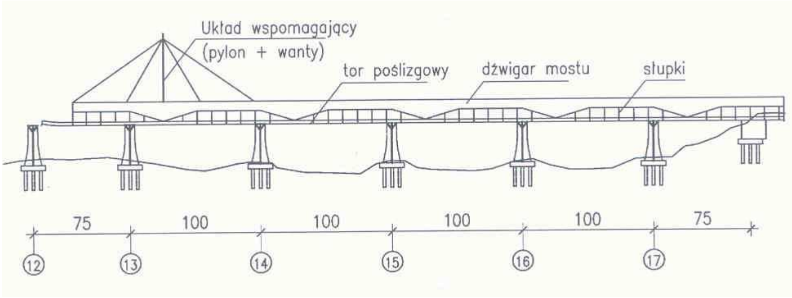


Fig. 10. Structural arrangement of assembly block of the river part of the bridge in Wyszogród

3. DOUBLE COMPOSITE BRIDGES

3.1 The basic idea of double composite is to assist the steel section in transferring the compressive force in the zones of negative bending moments. This effect is achieved by making in the lower parts of the cross section the concrete slab interacting with the steel of the bottom fibres of the section. The concrete bottom slab perfectly protects the bottom chords against buckling, it also permits considerable savings of the steel amount in the section in compression.

There is a modified version of the above solution, i.e. structures with specially shaped support areas in which the steel section is replaced partly (the part in compression) or completely by concrete section. The bottom slabs are used chiefly in bridges of long span. The thickness of the bottom slab is variable along the bridge length. This results from an increase of the compressive force towards the pillar. Since the bottom slab (Fig. 11) is not given along the whole length of the span, its appearance on the whole width, in one section, would be a structural notch. The variable thickness permits mitigating the effect of notch. The main step, however, is making openings at the end of the slab in the parts between the girders, which will ensure its gradual appearance in the section (ills 11 and 12).

Bridge structures in which the idea of double composite was used appeared in the 1970 s. In particular, the idea was developed by a Spanish design engineer professor Julio Martinez Calzon, whose design will be presented further on.

From the aesthetics point of view, the idea of double composite is the idea of building a form whose beauty lies in the active interaction of two different materials. These materials manifest themselves through structural solutions exposing their texture and colour. Their surface areas, then, require a special care. Steel girders are often fabricated from rustproof steel of CORTON type, which ensures their dark brown colour, well setting it in contrast with grey (and often white) shade of concrete. Below, several most interesting structural solutions of this type of bridges have been presented.

Fig. 11. View from below the RC slab in girder bridge of double composition over the Oder river in Stary Bohumin (The Czech Republic)

Fig. 12. Girder bridge of double composition over the Regalica river in Szczecin (Poland)

3.2 Bridges with bottom plate in regions at the supports

This type of bridge is well illustrated by the “Pioneers’” bridge over the Regalica river in Szczecin (Fig. 12), the first realisation of this type of bridge in Poland (2002). The structure of the bridge is composed of a six-span continuous beam consisting of two plate girders combined with an RC deck slab of the span arrangement 59,25+90,00+2x116,25+90,19+63,75 = 535,69 m. The girders have variable height webs ranging from 3,00 m to 6,50 m in the southern beam (upstream face) and from 3,16 m to 6,66 m in the northern beam. In the regions at pier box sections with the bottom chord as an RC slab combined with the main girders was employed. The slab has constant thickness across the bridge width and variable lengthwise.

Fig. 13 shows an interesting double composite bridge built over the Santa Lucia river in Montevideo province, Uruguay, in 2004. It is a thirteen span girder bridge of the constant depth of the box, of length of 780 m and width of 200 m, with the centre sail spans 64,0 m in span. The composite bottom plate above the piers “goes out of” the bridge steel box and can be seen outside. Moreover, the projecting concrete overhang brackets are supported by rakers from rust resisting steel, which enhances the spatial effect of the composite structure itself. The light and shade effect achieved in this manner gives the object unique aesthetic qualities (Fig. 13).

Fig. 13. Girder bridge of double composition over the Santa Lucia in Uruguay

3.3 Bridges with specially shaped region in compression above intermediate piers

An example of a structure shaped in this way is a bridge over the Turia river (1991) in Valencia (ills 14 and 15). It is a frame structure (with girders elastically fixed on intermediate piers), with three spans of arrangement 53,0+103,0+53,0 m = 209,0 m. The main girder is a composite box single cell girder of double (one might even say triple) composition in the region above the piers. The cross section area in compression was made as reinforced prestressed. The steel and concrete sections were joined as a prestressed butt direct connection using screw anchors of high strength. Apart from high load carrying capacity and stiffness, the anchors provide good resistance to dynamic actions and cyclic loads. Owing to an unusual scheme of contrasting colours - dark brown box girders from CORTEN steel and piers against the specially formed region in compression of white concrete above the piers□ a very interesting visual effect was obtained.

Figures 16 and 17 show an example of a similar structure of the “del Arenal” bridge over the Guadalquivir river in Cordoba (Spain).

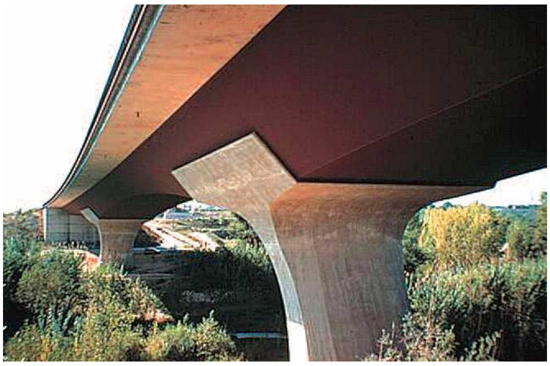


Fig. 14. Julio M. Calzon, bridge over the Turia river,Valencia, 1991 (103m)

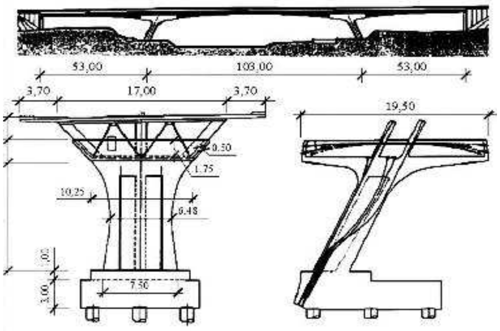


Fig. 15. Julio M. Calzon, bridge over the Turia, Valencia - longitudinal and cross sections

Fig. 16. Julio M. Calzon, “del Arenal” bridge over the Guadalquiwir rivier, Cordoba, 1993 (110 m)

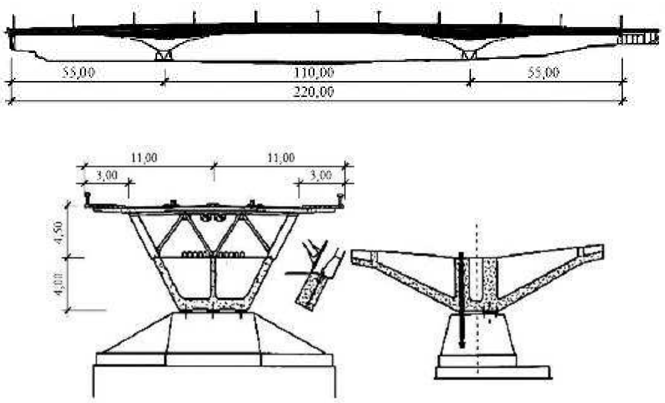


Fig. 17. Longitudinal and cross sections of “del Arenal” bridge in Cordoba

3.4 Bridges with specially formed concrete intermediate piers

These are objects in which the concrete section appearing in the zone of negative bending moments occurs not only in the girder part in compression but on its entire height. The steel girders are then employed only in the zone of positive moments. The connection of sections is placed in the area of the change of moments. It is executed as a prestressed butt direct connection. The anchor bolts are additionally prestressed in the zones where there is a hazard of tensile stress.

Fig. 18. Julio M. Calzon, “del Diabolo” bridge over the Llobregat river, Martorell (Barcelona), 1975 (100 m)

Examples of this kind of structure are “del Diabolo” bridge over the Llobregat bridge (1975) in Martorell (Barcelona) (ills 18 and 19), “del Milenario” bridge over the Ebro river (1987) in Tortosa (Tarragona) (ills 20 and 21) as well as “de

Mengibar" bridge over the Guadalquivir river (1995) in Mengibar (Jaén) (Fig. 22). These structures are continuous frame structures. In the case of the first two bridges above the main girders are composite box single cell cross-sections. The girder of "de Mengibar" is a composite box four cell cross-section.

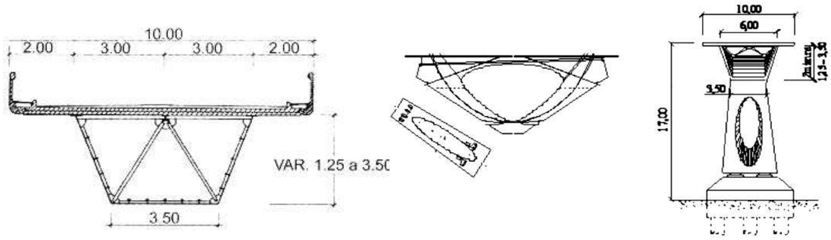


Fig. 19. Sections through the girder and pier of "del Diabolo" bridge

Fig. 20. Julio M. Calzon, "del Milenario" bridge over the Ebro river, Tortosa (Tarragona), Spain, 1987 (180 m)

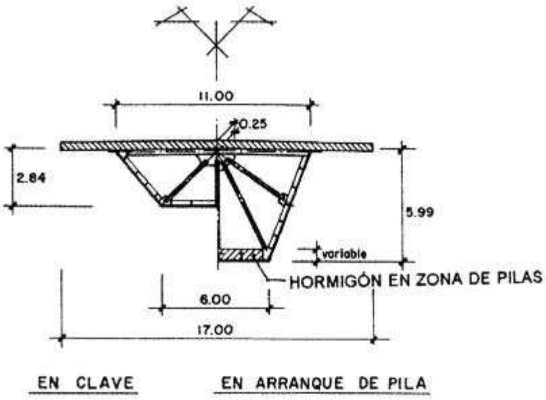


Fig. 21. “Del Milenario” bridge - cross and longitudinal sections

The main girder of “del Diabolo” bridge makes a continuous three span beam of span arrangement 50,0+100,0+50,0 m. The characteristic intermediate piers of the bridge are prestressed RC structures supported on foundation blocks in jointed manner. The bridge, combining beauty and an innovative construction solution, was a source of inspiration for the creation of equally outstanding works, using double composite ideas.

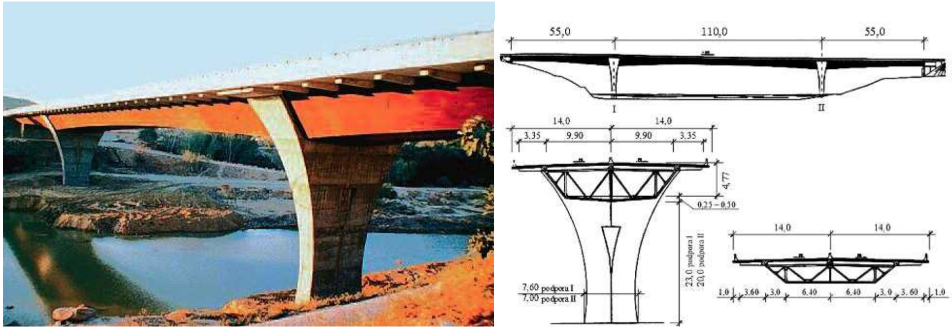
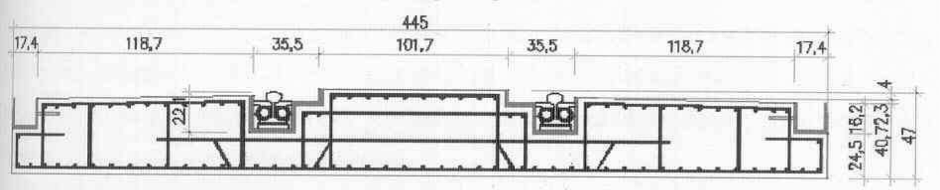


Fig. 22. “De Mengibar” bridge over the Guadalquivir river, Mengibar (Jaén), Spain, 1995: a) view of the bridge, b) longitudinal and cross sections

4. STEEL-CONCRETE BRIDGES

Steel-concrete structures cover two groups of solutions: steel members encased in concrete and steel tubes filled with concrete. The former ones have been sporadically employed in the Polish bridge engineering, particularly in single span railway plate bridges (Fig. 23). They also include structures with rigid reinforcement used in arch bridges especially road bridges of long span, constructed in unfavourable site conditions (Fig. 24). In Hundwilertobel bridge applied in arcs self-supporting rigid reinforcements in the form of light truss-girders made of rolled shapes. The latter - advisable in compressed members - are practically not built in Poland.



Rys. 1.1.1-1 *Przekrój poprzeczny płyty wewnętrznej z widocznym zbrojeniem.*

Fig. 23. Cross section of a railway plate girder steel-concrete bridge

Steel-concrete structures belong to composite structures due to considerable similarity: the same fundamental materials: concrete and steel, connectors joining the concrete and steel parts (if necessary). However, there are significant differences the most important of which is the mutual position of the concrete and steel parts which decide of the separate character of combined steel-concrete elements in the class of composite structures.

Steel-concrete structures under bending are economically unfavourable. In the two-symmetry steel section employed most frequently the steel girder part in compression is generally not fully utilised. Similarly, the concrete near the neutral axis and the region in tension is not fully utilised. On the other hand, they are easy to make but their undeniable advantage is the elimination of scaffolding during placing concrete. They are calculated in the same way as the classical composite girders.

Steel-concrete elements in compression, in the form of steel tubes encased in concrete, called CFST elements (concrete filled steel tubular), are characterised by high load carrying capacity and deformability and high failure energy. These properties are particularly advantageous in seismic and paraseismic conditions and where pillars or columns are affected by unpredictable strong horizontal forces (e.g. during earthquakes). They are also more resistant to fire temperatures than RC pillars.

In CFST elements in compression in high effort states there is a very good interaction between concrete and steel coating. This results from the fact that due to the steel coating restricting transverse strain triaxial stress takes place in the concrete, which increases its strength. Also in the steel coating triaxial stress is observed: compression in the direction of compressive force, radial compression from concrete thrust and circumferential tension. Due to the interaction between the steel coating and the concrete core the tube loses its local stability only immediately before the element's carrying capacity is exhausted.

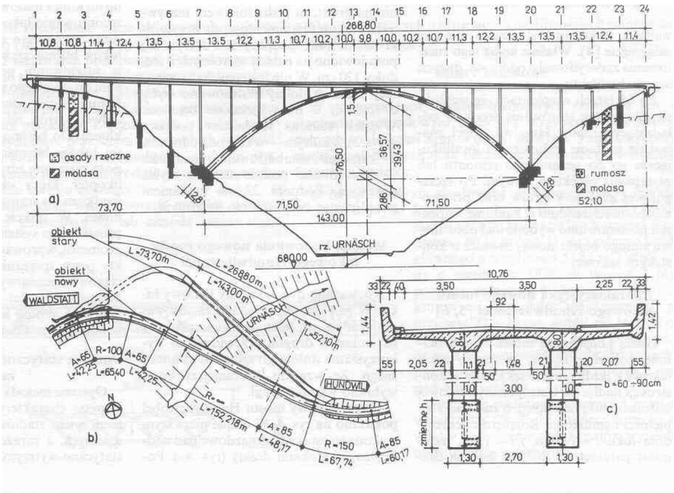


Fig. 24. New bridge Hundwilertobel (Switzerland): a - general scheme of the structure; b - location; c - cross section

The advantages of CFST members also include:

- high flexural rigidity,
- reduction of cross-section compared with steel and RC structures,
- ease of shaping welded connections,
- natural protection of concrete against corrosion.

The drawbacks include:

- higher steel consumption in RC elements,
- difficulties in placing concrete particularly at small cross-section dimensions,
- possibility of formation of gaps between the concrete core and the steel coating due to concrete shrinkage, especially at low effort of the members.

Over the last twenty years structures from CFST members have become increasingly popular in bridge engineering, especially in China. They are employed in the construction of arch bridges and trussed arch bridges of long span, e.g. the Wushan bridge over the Yangtze river (2005) of span length of 460 m (Fig. 25). Also the Wanxian bridge over the Yangtze (Fig. 26), a concrete arch deck bridge with a record length of 420 m was erected using CFST elements. In cross-section (Fig. 27) the arch is a three cell huge RC box 16,0 m in width and 7,0 m in depth. A structural member of such little pleasing shape, owing to its shape of a slender arch becomes a masterpiece. The stiff frame of five trussed arches composed of CFST elements (steel tubes filled with concrete class (C60) was “sunk” in the RC box of the bridge, also serving for suspending the mobile scaffolds, this RC box girder.

In the majority of arch bridges from CFST elements in China, the first to be assembled is - as the lighter one - the steel arch, which is next filled with concrete. After concrete hardening the tubes' carrying capacity increases about two times compared with the tubes with no concrete. The illustrations show views of the arch bridge from CFST elements on the route to Jungbo (Fig. 28) and two trussed arch bridges from CFST elements near a place called Gruilin (ill 29) as well as the Quinghuan bridge in Wuhan (Fig. 30). In further illustrations the cross-sections of the arches of the "Mo-Zi-Wan" (Fig. 31) and "Da-Du" bridges (Fig. 32), composed of CFST elements have been shown.

Fig. 25. Tubular concrete structure (CFST) of arch road bridge over the Yangtze river, Wushan, China, 2005 (460 m)

Fig. 26. Wanxian bridge, China, 1997 (420 m)

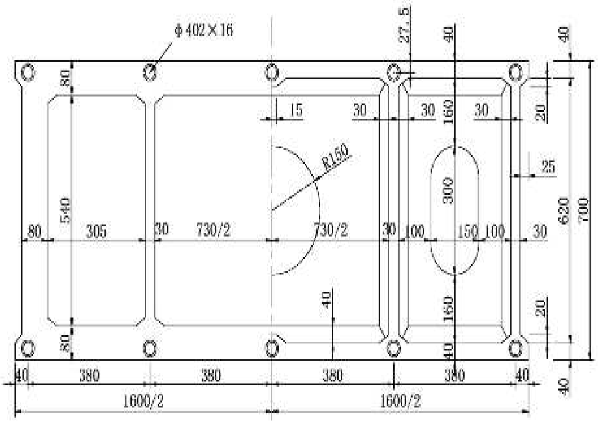


Fig. 27. Cross section of structural arch of Wanxian bridge

Fig. 28. Arch bridge from CFST elements along the route to Ningbo (China)

Fig. 29. Truss concrete filled steel tubular (CFST) through bridge of 200 m span, near Quilin (China)

Fig. 30. Quinghuan bridge over the Han river in Wuhan (China)

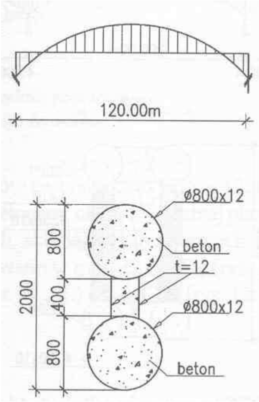


Fig. 31. Static scheme and cross section of load bearing arch structure of Mo-Zi-Wan bridge

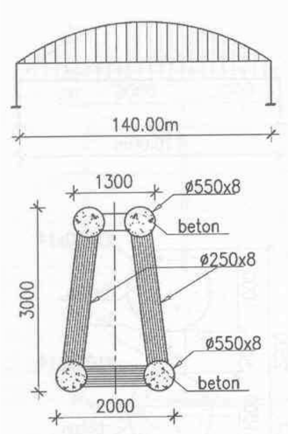


Fig. 32. Static scheme and cross section of load bearing arch structure of Da-Du bridge

5. SUMMARY

The article describes successful examples of the applications of steel-concrete composite structures in Poland and abroad. Particular attention is given to structures of double composition and steel-concrete structures from CFST compressed members. They offer hope to their wider application in the Polish conditions.

REFERENCES

1. Flaga K., Furtak K.: *Application of Composite Structures in Bridge Engineering. Problems of Construction Process and Strength Analysis.* Civil and Environmental Engineering Reports. CEER 2014; 14(3): 57-85.
2. Furtak K.: *Mosty zespolone.* Wydawnictwo PWN, Warszawa-Kraków 1999.
3. Flaga K., Kumaniecka A., Rudnicki A., Sołowczuk B.: *Mosty Świata - Chiny 2009.* Wydawnictwo Politechniki Krakowskiej. Kraków, 2010.
4. Flaga K., Januszkiewicz K.: *Piękno konstrukcji mostowych.* Wydawnictwo Politechniki Krakowskiej. Kraków, 2012 .

PRZYKŁADY KONSTRUKCJI ZESPOLONYCH W BUDOWNICTWIE MOSTOWYM

Streszczenie

W artykule [1] omówiono problemy konstrukcyjne, obliczeniowe i realizacyjne, związane z zastosowaniem konstrukcji zespolonych stal-beton w mostownictwie. Wskazano tam, że idea konstrukcyjnego zespolenia stali z betonem jest jeszcze daleka do wyczerpania i że wciąż pojawiają się nowe rozwiązania interesujące z inżynierskiego, naukowego i estetycznego punktu widzenia. W artykule niniejszym pokazano te nowoczesne trendy na tle rozwiązań zrealizowanych w Polsce i na świecie. Szczególną uwagę poświęcono konstrukcjom podwójnie zespolonym oraz konstrukcjom stalowo-betonowym. Wyeksponowano tu szczególnie konstrukcje z rur stalowych wypełnionych betonem, typu CFST. Dają one nadzieję na ich szersze zastosowanie w warunkach polskich.

Słowa kluczowe: konstrukcje podwójnie zespolone, konstrukcje stalowo-betonowe, elementy rurobetonowe

Editor received the manuscript: 15.10.2014