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SELECTED ASPECTS OF COMPOSITE STEEL AND CONCRETE BRIDGE SUPERSTRUCTURE DESIGN IN ACCORDANCE WITH PN-EN 1994-2

WYBRANE PROBLEMY PROJEKTOWANIA USTROJU NOŚNEGO MOSTÓW ZESPOLONYCH STALOWO-BETONOWYCH W UJĘCIU PN-EN 1994-2

Abstract

The paper presents the chosen issues dealing with the design of composite steel and concrete bridges in accordance with PN-EN 1994-2 and with reference to hitherto Polish standards and rules. Particularly problems of global analysis, classification of composite cross-sections and verification of Ultimate and Serviceability Limit States were considered.

Keywords: composite steel and concrete bridges, Eurocode 1994-2

Streszczenie

W artykule przedstawiono wybrane zagadnienia związane z projektowaniem ustroju nośnego mostów zespolonych stalowo-betonowych w ujęciu PN-EN 1994-2 na tle dotychczas obowiązujących norm i zasad. W szczególności skupiono się na problemach analizy globalnej konstrukcji, klasyfikacji przekrojów, a także weryfikacji stanów granicznych nośności i użytkowalności.

Słowa kluczowe: mosty zespolone stalowo-betonowe, Eurokod 1994-2

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1. Introduction

Although composite steel and concrete superstructures are found to be widely and willingly applied in Poland, especially for small and medium span bridges, there has been no instituted standard for composite bridge designs in our country till the Eurocode 4 being now introduced. Until now designers have based their calculations on Polish standards concerning steel bridges [8], concrete bridges [9] and technical literature or manuals such as [2], [4] or [5]. For the first time PN-EN 1994-2 (EC4-2) – [10], which includes general rules dealing with the design of composite steel and concrete bridges, came out in 2006. Polish-language version of EC4-2 appeared only in March this year, thus it is relatively a new publication. In certain cases Eurocode methods and approach differ to some extent from former tradition of calculations.

Both Eurocodes and former Polish Standards distinguish between two kinds of designed construction verification: Ultimate Limit States and Serviceability Limit States. Fulfillment of conditions of the former guarantees safety of the structure and its users, whereas the latter ensures the proper functioning of the structure under normal use, comfort of people and pleasing appearance of the construction [11]. The classification is closely connected with the values of loads and material properties and also combinations of actions. There are however, differences in these standards connected with the range of construction work at Ultimate Limit State or required verifications for Serviceability Limit States.

Hitherto, calculations of composite bridge structures were based on a stress convention. For each phase of construction stresses in steel and concrete were determined on the assumption of the linear stress distribution for a cross-section (figure 1). Rheological influences as creep and shrinkage of concrete had to be taken into account as well as thermal action. Ultimate Limit State was then accomplished when stress in any fibre of composite cross-section caused by design loads was equal to design strength.

EC4-2, in contrast to the bridge structure verification methods used so far, allows for plastic range in analysis, introduces an idea of composite cross-section classification and presents the methods of dealing with global analysis issues. In this paper only chosen problems of design in accordance with Eurocodes are brought up.

2. Chosen problems of composite superstructure bridge design

2.1. Structural analysis

As it was mentioned above, traditional analysis of bridges allows for only elastic range in response to both global analysis and stress distribution for cross-section, whereas EC4-2 introduces three types of examination which might be used for Ultimate Limit States of composite bridges. Apart from the linear elastic analysis, with or without corrections for cracking of concrete, EC4 allows also for non-linear scrutiny, yet the standard does not include specific rules. In practice, it is rarely used by designers, however, plastic analysis could be considered in accidental situations as vehicular impact on a bridge pier or impact on a parapet.

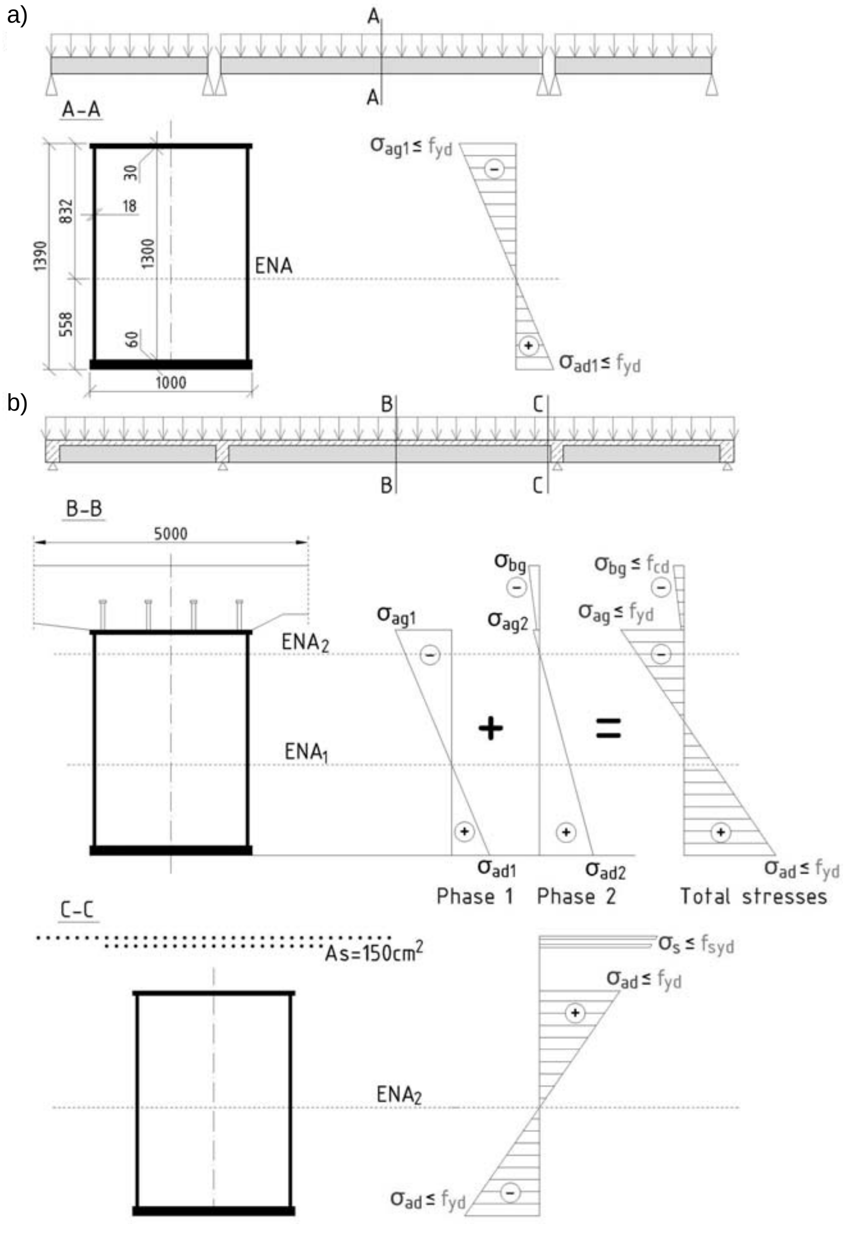

Fig. 1. Stress distribution and idea of ULS verification for: a) steel cross-section in the phase of erection (simple supported steel girders), b) composite cross-section in sagging and hogging bending moment zone (superstructure with reinforced concrete support cross beams)

Rys. 1. Rozkład naprężeń oraz zasada weryfikacji SGN dla: a) przekroju stalowego w fazie wznoszenia (stalowe belki wolnopodparte), b) przekroju zespolonego w strefie momentów dodatnich i ujemnych (ustrój nośny z żelbetowymi poprzecznicami podporowymi)

If the deformed geometry of a structure has an influence on the internal forces, second order analysis should be considered. EC4-2 includes the criterion for necessity of taking into account second order effects. However, in case of girder bridges the influence of deformed geometry is negligible, thus first order analysis is usually used [1].

2.2. Classification of a cross-section

Similarly to the Polish Standard for steel structures design (PN-90/B-3200) and the Eurocode 3, EC4-2 introduces the concept of classes for bent and compressed composite cross-sections. The classification is presented in the Eurocode as a method of considering effects of local buckling of plane steel elements in compression.

Cross-sections are classified on a scale of 1 to 4 depending on the dimensions of the compressed elements (precisely, depending on the slenderness of the elements expressed by the ratio width/thickness), the yield strength of steel, the stress distribution at Ultimate Limit States and the direction of the bending moment. The class of the whole cross-section corresponds to the largest class of all its elements (webs, flanges).

A cross-section in Class 4 is called thin-walled or slender and is susceptible to local buckling in opposite to Class 1, 2 and 3.

For the conventional composite bridge girder important role is played by the concrete slab which restrains the upper flange of the steel section from buckling even when yielded [3]. Due to that fact, in a sagging bending moment zone the steel top flange is in Class 1, providing that shear connectors fulfill the spacing required in Clause 6.6.5.5 of EC4-2. Usually the plastic neutral axis (PNA) is then located in the concrete deck or in the upper flange of the steel section. It follows that the web is in tension and the whole composite cross-section is finally classified as Class 1. On the other hand, in a negative bending moment zone the concrete in tension is neglected and the cross-section consists only of the steel girder and the deck reinforcement. For large bridges, a cross-section under hogging moment is often in Class 3/4 (figure 2).

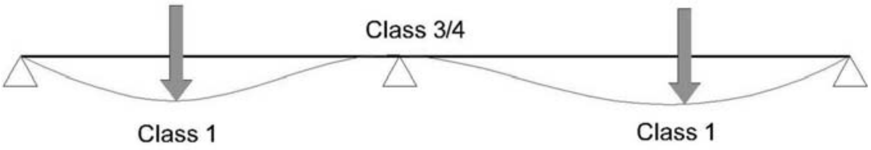

Fig. 2. Typical classification of cross-sections for long-span composite bridges [6]

Rys. 2. Typowa klasyfikacja przekrojów dla mostów zespolonych o dużych rozpiętościach [6]

The class of a cross-section might also differ at the selected stages of the construction. Illustrative example of such a situation is presented in figure 3. In the phase of the erection the simply supported steel box girder is in Class 3 (both the compressed upper flange and the web are assigned to that Class) and the verification of Ultimate Limit States for bending in that phase has to be performed with the elastic stress distribution. The same box girder combined with a concrete slab of the average depth of 30 cm and the effective width of 5 m is in Class 1 or 2 depending on the moment direction (figure 3) [7].

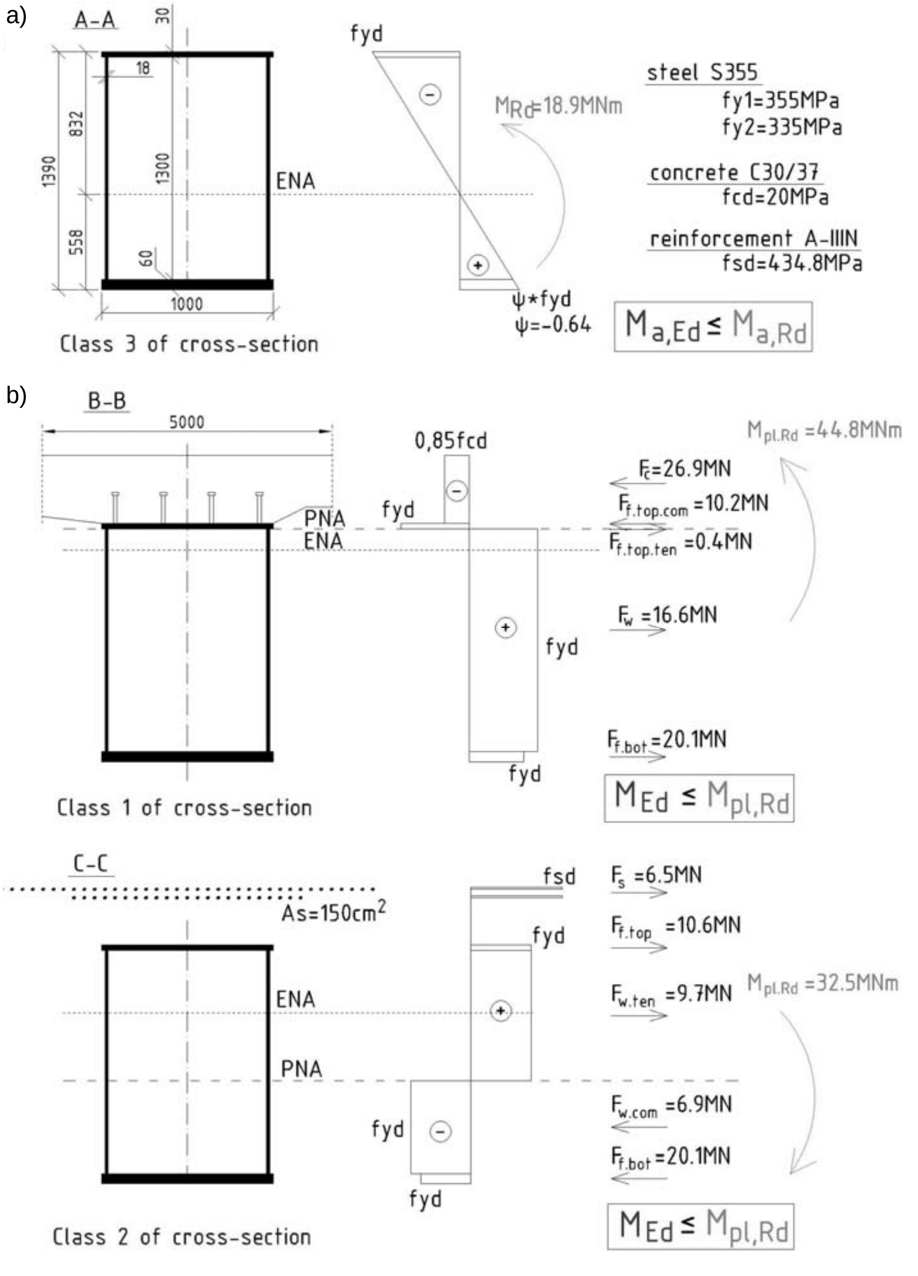

Fig. 3. The class of the cross-section, stress distribution and bending resistance in accordance with EC4-2 for cross-sections defined in figure 1 [7]

Rys. 3. Klasa przekroju poprzecznego, rozkład naprężeń oraz obliczeniowa nośność przekroju według EC4-2 dla przekrojów poprzecznych jak na rysunku 1 [7]

If under a negative bending moment the bottom flange of the steel section is in Class 1 or 2 and simultaneously the web is in Class 3, the whole cross-section might be concerned as a cross-section in Class 2 with an effective web [13]. The idea of the effective web application is presented in figure 4.

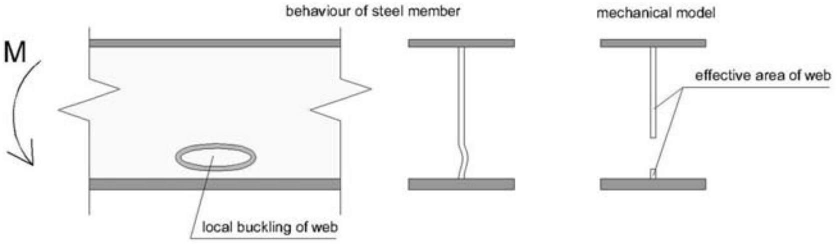

Fig. 4. The idea of an effective web [6]

Rys. 4. Idea efektywnego pola powierzchni środnika [6]

The cross-section presented in figure 5 is classified as Class 2 with an effective web. Its geometry is similar to the cross-section depicted in figure 3, yet it has thinner web plates (14 mm). It is assumed in accordance with [13] that the total compressive force in the web is limited to $40\varepsilon t_w f_{yd}$, where: ε is a coefficient taking into account the yield strength of steel, t_w is a thickness of the web and f_{yd} is the design yield strength.

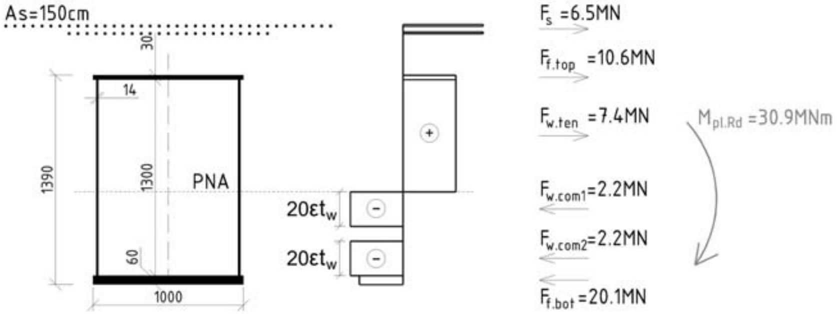

Fig. 5. Stress distribution and plastic resistance for a cross-section in Class 2 with an effective web

Rys. 5. Rozkład naprężeń i nośność plastyczna dla przekroju klasy 2 z efektywnym środnikiem

As it was mentioned above, the class of a cross-section takes into account local buckling, however, it has also other significant consequences, especially for verification of Ultimate Limit States.

Firstly, the classification determines methods of cross-section resistance calculation. For Class 3 and 4 the elastic stress distribution is considered (figure 3a) similarly to traditional approach, whereas for Class 1 and 2 the plastic range is allowed (figure 3b). Even though the elastic global analysis for the construction is taken into consideration, the plastic stress distribution for these cross-sections might be assumed. In other words, the internal forces received from the elastic model are compared to the plastic resistance of the composite cross-section.

Secondly, for composite elements which have all cross-sections in Class 1 or 2, the influence of a sequence of construction, temperature, shrinkage and creep of concrete might be neglected for the Ultimate Limit States verification. There is also one accompanying requirement in EC4-2: no allowance for lateral torsional buckling is necessary. This condition can be understood that the enumerated effects might be neglected if there is no threat of lateral torsional buckling owing to geometry of the girder cross-section and the bridge structural system.

For designers being used to traditional methods of calculation, neglecting the influences mentioned above might be surprising. So far determination and summing of stresses for each phase of erection was essential for the verification of Ultimate Limit States. Adding of bending moments acting on different cross-sections, for instance, on a steel beam in the erection phase and on a composite girder in the phase of use, was pointless. What is more, reological effects were taken into account in a basic load system, thus they were leveled with self weight and traffic actions.

However, all of these influences have to be considered for the verification of Serviceability Limit States, hence the designer is not entirely excused from analyzing thermal and rheological effects. Calculations might be simplified only for Ultimate Limit States.

2.3. Cracking of concrete in support zones

For a multispan composite bridge a concrete slab in hogging bending moment regions is assumed to be cracked. Due to that fact, the flexural stiffness in the support zone is reduced and the redistribution of internal forces occurs. That change of the stiffness significantly influences the results of the global analysis. Hence it has to be thoroughly taken into consideration.

Before the Eurocodes, the redistribution of internal forces due to cracking of a concrete slab might have been taken into account by means of a simplified method introduced for example in [4]. The idea of the method is to reduce hogging bending moments and simultaneously increase sagging bending moments. Global analysis of the superstructure is then performed for the structural model without reduction of the stiffness and afterwards established reduction factor was applied to the analysis results (figure 6). The factor *p* is given in [4] and depends on kind of verification and type of a concrete deck (pre-stressed or not).

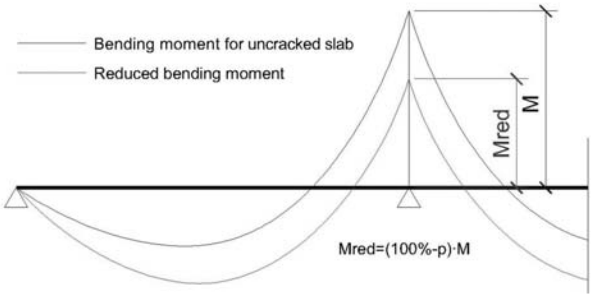

Fig. 6. Scheme of hogging bending moment reduction due to cracking of concrete deck in accordance with [4]

Rys. 6. Schemat redukcji momentu podporowego w wyniku zarysowania płyty pomostu wg [4]

EC4-2 introduces another approach for taking cracking of concrete into account. The general method (clause 5.4.2.3(2)) requires two successive global analyses. The first scrutiny performed with assumption of uncracked structure is used to designate regions of expected cracks. An envelope of internal forces has to be determined for the characteristic combination of actions which includes effects of concrete rheology (creep and shrinkage) as well. In the regions where tensile stress in a top fibre of concrete exceeds twice the mean value of axial tensile strength of concrete ($\sigma_c > 2f_{ctm}$) cracked zones have to be assumed. This criterion defines the reduced stiffness zones of the cross-section on both sides of the intermediate supports. The second analysis, called "cracked analysis", is based on a modified structural model: in the determined cracked sections the flexural rigidity is changed for E_aI_2, which is specified in clause 1.5.2.12 of EC4-2: in the cross-section concrete is neglected, however, the reinforcement of the deck is taken into account. The second analysis is designed for receiving internal forces and deflections which are used for the verification of Ultimate Limit States and Serviceability Limit States.

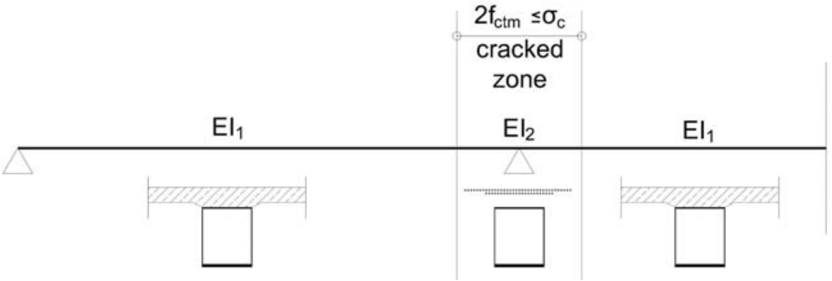

Fig. 7. Idea of general method for taking into account cracking of concrete in global analysis introduced in EC4-2

Rys. 7. Idea ogólnej metody uwzględnienia zarysowania betonu w analizie globalnej przedstawionej w EC4-2

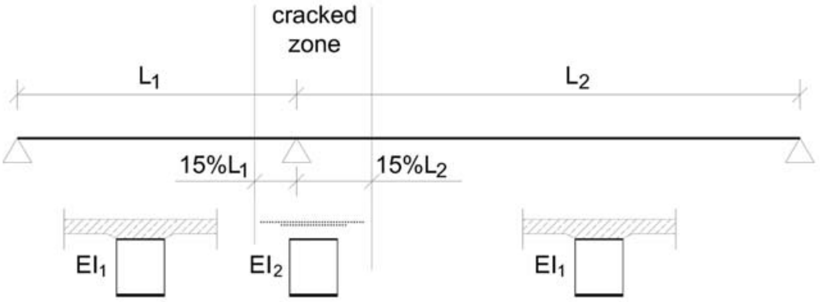

Fig. 8. Simplified method for considering cracking of concrete in global analysis introduced in EC4-2

Rys. 8. Uproszczona metoda uwzględnienia zarysowania betonu w analizie globalnej przedstawiona w EC4-2

The clause 5.4.2.3(3) of EC4-2 provides simplified method which application is limited to specific superstructures: conventional bridges with not pre-stressed concrete flange above steel section with all ratios of adjacent span lengths equal at least 0.6 (for instance, three-span bridge 20 + 40 + 20 m is not classified to this group). The method is non-iterative and assumes that the cracked sections are situated on both sides of all internal supports and their length is equal to 15% of span lengths.

For a bar or a grid model of a composite superstructure, the change of the main girders stiffness is uncomplicated, however, for more elaborated models such as three dimensional models including shell or plate elements, application of flexural stiffness reduction should be carefully considered.

The uncracked model is considered merely for the calculations of shear connections between a concrete slab and a steel girder, even if the concrete is in tension.

2.4. Verification of Ultimate Limit States

A detailed list of conditions which should be verificated for Ultimate Limit States of the composite cross-section is included in Chapter 6 of EC4-2. In general, the requirements are parallel to the requirements of the former Polish standards, however, methods of the verification in some cases are different.

According to EC4-2 the bending resistance of the cross-section for Ultimate Limit States could be determined by means of the plastic, elastic or non-linear analysis.

The application of the rigid-plastic theory is allowed for the design bending resistance calculation for cross-sections in Class 1 or 2 on the condition that pre-stressing of the concrete deck is not used. An illustrative example of the stress distribution at Ultimate Limit State for Class 1/2 under both sagging and hogging bending moment is depicted in Figure 3. Ultimate Limit State is achieved when a whole cross-section is plastified: normal stresses for all fibres reach the design yield strengths. For the composite cross-section presented in Figure 3 (cross-section B-B) the plastic resistance $M_{pl,Rd}$ is equal to 44.8 MNm, whereas elastic $M_{el,Rd}$ reaches a value of 34.8 MNm, which is equal to 78% of $M_{pl,Rd}$. What is more, for bridges with all cross-sections in Class 1 or 2, thermal and rheological influences might be neglected, which causes decrease in the total moment M_{Ed} acting on the structure. In this situation, the verification of stress limitation at Serviceability Limit States might be a governing condition.

If under a sagging bending moment the cross-section is in Class 1 or 2 and the plastic resistance is considered, the possible yielding in the mid-span area influences the longitudinal moment distribution in the global analysis [6]. According to EC4-2 the influence might be neglected if at midspan cross-sections are in Class 1 or 2, on support they are in Class 3 or 4 and the ratio of lengths of the spans adjacent to one support (shorter/longer) is less than 0.6. Otherwise, the plastic resistance of a mid-span cross-section should be reduced to $0.9M_{pl,Rd}$ or non-linear analysis applied. Due to the moment reduction the non-linear scrutiny might be omitted and only cracked elastic global analysis considered.

The elastic analysis of the cross-section bending resistance is applied especially for Class 3 and 4, yet for Class 4 an effective cross-section, which takes into consideration reduction due to local buckling, should be used [13]. The verification with the elastic analysis is comparable to bending resistance checked in accordance with hitherto Polish standards: Ultimate Limit State is accomplished when stress in any fibre is equal to design strength.

EC4-2 also permits a non-linear analysis for a cross-section, irrespective of its Class. In this scrutiny the parabola-rectangle stress-strain diagram is considered for the concrete and the bi-linear diagram for the steel (for reinforcement acceptable is diagram with either horizontal or inclined top branch). EC4-2 provides also a simplified method for non-linear bending resistance determination for Class 1 and 2 which takes advantage of the compressive force in the concrete (EC4-2, Clause 6.2.1.4(6)).

The verification of shearing at Ultimate Limit States for a composite girder in accordance with the former tradition of the calculations was performed by means of the stress convention similarly to the bending resistance checking. For a cross-section the maximum shear stresses were determined and compared with the shear resistance. To examine the interaction between shearing and bending, for instance, in an intermediate support cross-section, equivalent stresses calculated on the basis of the Huber-Mises-Hencky theory were compared with the reduced design strength of structural steel.

EC4-2, irrespective of class of a cross-section, provides a criterion for shearing in another form: $V_{Ed} \leq V_{pl,a,Rd}$, where V_{Ed} is the shearing force acting on the analyzed cross-section and $V_{pl,a,Rd}$ is the plastic resistance of the structural steel section usually of the girder webs. For the slender webs which are subject to buckling, the verification of the shear buckling resistance should also be performed. The examination amounts also to the comparison of the suitably determined forces.

If V_{Ed} exceeds half of the shear resistance (or the shear buckling resistance), the bending and shearing interaction has to be taken into account. For cross-sections in Class 1 or 2 it might be considered by the reduction of the design yield strength for the web before calculations of plastic bending resistance $M_{pl,Rd}$ are done, whereas for Class 3 and 4 more elaborated method is presented in [13].

2.5. Verification of Serviceability Limit States

According to hitherto Polish standards, the verification of Serviceability Limit States for a composite superstructure should include deflection limitation, determination of precambering of the steel girder and crack width limitation. EC4-2, apart from these enumerated conditions, requires also limitation of stresses for each material (concrete, steel and reinforcement) and examination of the web breathing. The verification of Serviceability Limit States is performed for characteristic or frequent load combination (for deflection limitation) [11].

As it was aforementioned, although for bridges which have all cross-sections in Class 1 or 2, the influence of sequence of construction, temperature, creep and shrinkage of concrete might not be taken into account for Ultimate Limit States, for verification of stresses all of these effects have to be thoroughly considered. Shrinkage and creep might be taken into consideration by applying modular ratio for the concrete - the method introduced in Clause 5.4.2.2 of EC4-2.

Delimitation of the compressive stresses in concrete prevents from excessive creep and microcracks and is accurately specified in [12]. In the structural steel the limitation of stresses concerns normal stresses, shear stresses and a complex state of stress as well. Stresses in the reinforcing steel and the shear connectors have to be also verificated in accordance with Cause 7.2.2 of EC4-2.

Both Polish standards and EC4-2 demand the examination of crack width limitation, however, the requisite limits differ from each other (0.3 mm in EC4-2 and 0.2 mm in [9]). EC4-2 introduces a simplified method of the verification which assumes that the limitation is provided by required spacing of reinforcement bars and their diameters. If that method is not sufficient, the elaborated method included in the [12] should be considered.

Due to the concrete susceptibility to influence of time it is also important to verify conditions of Serviceability Limit States in cross-sections both at the age when the bridge first open and after all creep and shrinkage have taken place.

Web breathing is a term which is not encountered in Polish Standards or literature and means out-of-plane deformation of a plate caused by repeated application of in-plane loading [13]. The excessive web plates breathing might result in fatigue at or adjacent to the web-to-flange connections. Limitation of the breathing amounts to the restriction of the web slenderness. Limit of that slenderness depends on the span length and a kind of bridge and is more restrictive for railway bridges than for road.

3. Conclusions

In the European Union the tendency to standardize might be also observed in a field of the construction design. This trend manifests itself in the development of the Eurocodes which have been recently introduced in Poland. The Eurocode 4-2 includes guidelines for the design of the composite steel and concrete bridges, however they are not always compatible with the former tradition of the calculations.

In this paper only the selected problems of the composite bridge design have been considered, especially these, which differ from the former approach or introduce new aspects of the design. The methods of the global analysis of the construction, classification of cross-sections, taking cracking of concrete into consideration in the structural model and finally basic rules of Limit States verification have been discussed.

Surely the classification of the composite cross-sections and its consequences are a significant innovation with reference to the hitherto calculation methods. Although the sequence of construction, rheological effects and influence of temperature are not negated entirely for verification of superstructure with all cross-sections in Class 1 or 2, however they are considered only for Serviceability Limit States. This modification is a substantial and qualitative change with relation to former standards.

It should be also emphasized once again, that EC4-2 allows for assumption of plastic or non-linear stress distribution for Ultimate Limit States and verification of ULS conditions amount mainly to comparing of forces, not stresses as it was before.

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