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PIOTR GWOŹDZIEWICZ*, ŁUKASZ JARNO **, JERZY PAMIN**

ACCOUNTING FOR TIME-DEPENDENT EFFECTS IN THE CONSTRUCTION STAGE FEM ANALYSIS OF COMPOSITE PRE-STRESSED BRIDGE GIRDERS

ZNACZENIE EFEKTÓW DŁUGOTRWAŁYCH W ANALIZIE ETAPOWANIA KONSTRUKCJI MES ZESPOLONYCH, SPRĘŻONYCH DŹWIGARÓW MOSTOWYCH

Abstract

In this paper, the results of the numerical analysis of pre-stressed concrete girders made of a high-strength concrete composite with a slab made of normal concrete are presented. A FEM analysis of the construction stage considering the influence of rheological effects on the behaviour of the structure was performed. Results of the analysis are presented in the work and are compared with the results of numerical analysis of the same elements, in which the time-dependent effects are not included. On the basis of these results, appropriate conclusions are proposed.

Keywords: *construction stages, finite elements method, prestressed concrete, rheology*

Streszczenie

W niniejszym artykule przedstawione zostały wyniki analizy numerycznej dźwigarów strunobetonowych wykonanych z betonu wysokiej wytrzymałości zespolonych z płytą pomostu wykonaną z betonu zwykłego. Przeprowadzono analizę etapowania budowy MES, uwzględniając wpływ efektów reologicznych na zachowanie się konstrukcji. Wyniki analizy przedstawione w pracy porównane zostały z wynikami analizy numerycznej tych samych elementów, w której efekty zależne od czasu nie zostały uwzględnione. Na podstawie otrzymanych wyników sformułowano odpowiednie wnioski.

Słowa kluczowe: *beton sprężony, etapowanie budowy, reologia, metoda elementów skończonych*

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[*] Ph.D. Eng. Piotr Gwoździewicz, Institute of Materials and Civil Structures, Faculty of Civil Engineering, Cracow University of Technology.

[**] M.Sc. Eng. Łukasz Jarno, Ph.D. D.Sc. Jerzy Pamin, Institute for Computational Civil Engineering, Faculty of Civil Engineering, Cracow University of Technology.

1. Introduction

Nowadays, due to environmental issues and the forms of structures that architects design, there is a requirement for engineers to make greater efforts to analyse and design more sophisticated structural and material solutions. In the modern world of civil engineering, it is more often required to combine advanced concepts like composition, pre-stressing, high strength materials etc. with one another in order to meet high requirements for structures [1, 2]. Additionally, modern engineering pushes engineers to meet the requirements of durability and long-term serviceability in the structure. This is the reason why time dependent effects of concrete structures such as creep, shrinkage and the evolution of compression strength cannot be neglected and should be carefully considered at every stage of the design process.

The aim of this paper is to present a numerical model of a composite pre-stressed bridge girder. The prefabricated girder model is based on a slab model and two cases of construction stage analysis are considered in order to examine the influence of creep on the results. The model was calibrated and validated based on experimental studies carried out by Wonchang Choi (State University of North Carolina, Raleigh) [3], see Section 2. The basic parameters of the model such as geometry, strands configuration, boundary conditions and loads are described in Section 3. The results of the two analysis cases are shown in Section 4.

2. Experimental study

To evaluate the flexural behaviour of pre-stressed composite girders composed of high and normal strength concrete, nine twelve-meter long specimens were designed and tested. The concrete used for these girders was designed to have compressive strengths of 69, 97 and 127 MPa. All girders were designed based on the AASHTO LRFD codes, but some details were modified in order to prevent premature failure in shear or bond slip during flexural response. The tests were carried out for three girder types: first girder with 1.5 m wide NSC deck, second girder with 0.3 m cast deck and third girder without any deck cast on it. The deck was 200 mm thick and made from normal strength (28 MPa) concrete. The girders which were taken as a reference for the numerical approach were pre-stressed with sixteen straight 12.7 mm strands (1860 MPa low relaxation pre-stressing steel), material parameters of the pre-stressing strands were provided by the supplier with an average ultimate breaking strength of 194.6 kN. Fourteen strands were placed at the bottom flange and two were placed at the top. Each strand was tensioned up to 75% of its ultimate strength. All of the given results were divided into: material properties obtained from the experimental study; measured pre-stressing losses by using internal welded strain gauges; measured end slip used to determine transfer length; flexural response of the girders – flexural strength, cracking strength, load-deflection relationships, failure modes etc., for more details see [4].

For this kind of structure, taking into account the construction process (staging) and rheological behaviour of the material seems to be one of the most important aspects, especially when two different concretes (with different ages) are connected and are expected to work together in one composite section. In this numerical approach, a FEM model is built and construction stage analysis is performed to evaluate the influence of the rheological behaviour of concrete during the staging process of the described structural member.

3. FEM numerical model

3.1. Geometry, material, loads and boundary conditions

The specimen is made of concrete with a compressive strength of 69 MPa and a modulus of elasticity of 36.9 GPa, represented in the computations by an elastic constitutive model. The girder is modelled using 8-node hexahedron solid elements with linear shape functions. The composite deck is made of concrete with 28 MPa compressive strength and 18.5 GPa modulus of elasticity. The rheological effects in the two different concretes are evaluated using CEB-FIP time-dependent material model [5]. The girder with a total length of 12.5 meters and distance between supports (span) of 12.2 meters is connected at the final stage to a slab with a 152.4 cm width and a 20.3 cm thickness. The connection of these two parts of composite girder for the preliminary test was assumed as rigid. The modelled girder has an ‘I’ shape cross-section with a 91.4 cm height, a 45.7 cm bottom flange width and a 30.5 cm top flange width (Fig. 1).

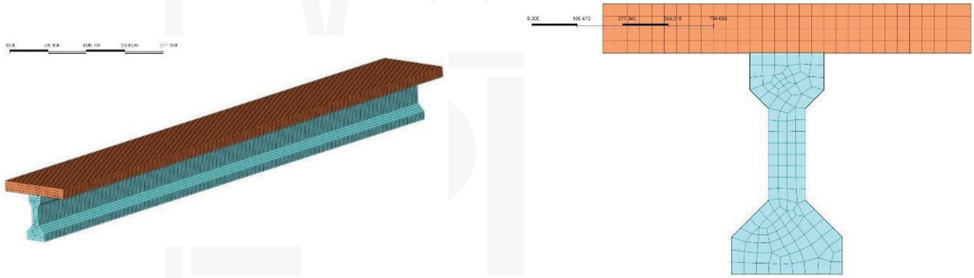

Fig. 1. Geometry of the modelled girder

Each tested girder contains Φ 4 mm stirrups with a spacing of 7.6 cm near the end blocks and 15.2 cm along the entire length of the girder. The longitudinal reinforcement is neglected due its negligible influence on the behaviour of the structure and lack of relevant data in the references. The stirrups are modelled as discrete bars embedded in the solid elements with full bond conditions between concrete and steel (Fig. 2).

The pre-stressing reinforcement of the girder contains sixteen straight strands, fourteen in the bottom flange and two in the top flange. Each particular strand is modelled separately using a bar in solid discrete reinforcement elements and a uniform pre-stressing force is applied. The girder is a simply supported beam. The supports with spacing of 12.2 meters were made of a steel plate above a neoprene pad. In the numerical approach, the supports were defined as rigid in a vertical direction which can have an influence on the results as the model is stiffer than the real specimen. The load was applied to the girder with a MTS closed-loop actuator. The girder was loaded up to the yielding of pre-stressing strands and then to the point of failure. To examine the accuracy of the model, the cracking load obtained from experimental results is applied to the model as a pressure load according to the test set-up shown in Fig. 2. The total value of the load is 573.82 kN.

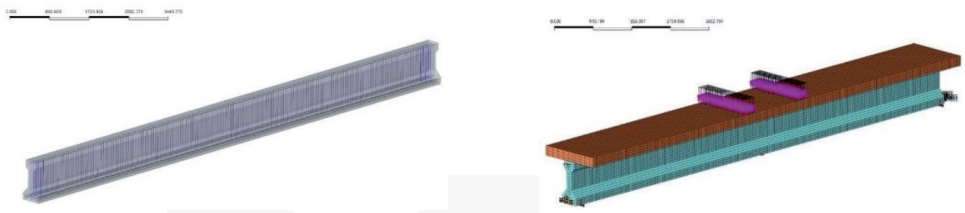

Fig. 2. Reinforcement, load and boundary conditions

3.2. Analysis cases

Construction stage analysis – the building process is divided into five stages: creation of the simply supported girder with reinforcement, pre-stressing of the girder, application of the wet concrete load, adding the newly cast slab to the composite girder, application of the external load. The staging analysis is performed with assumption of null time progress for a particular stage (stage duration time equals to zero), this means that no time-dependent effects are taken into account. This kind of analysis allows one to evaluate the influence of the building process divided in stages only in terms of the changing geometry and deformed shape from one stage to another.

Construction stage analysis with time-dependent effects – this type of analysis is performed to simulate the influence of the creep of concrete; however, the shrinkage phenomenon and compressive strength evolution in time are neglected in order to distinguish pure creep

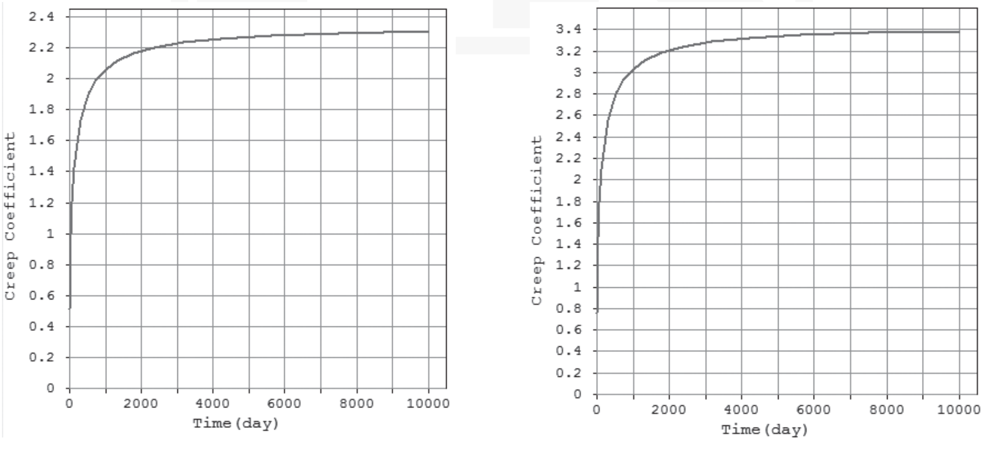

Fig. 3. HSC (a) and NSC (b) creep function

behaviour. Two different creep functions based on the CEB-FIP code recommendations [5] are introduced for HSC and NSC concretes (Fig. 3).

It is assumed that each stage has a seven-day duration and an additional sixth stage to reach the 10,000 days duration time of the whole process is introduced to show the long term behaviour.

4. Construction stage analysis results

The structure is completed in a number of construction stages. The configuration of the structure, loading, boundary conditions and physical properties of structural members change during the construction stages, especially when speaking about composite and additionally pre-stressed structures. If the structural system changes as the construction progresses, the real behaviour of the structure in the final stage may be different from that analysed without considering the staging. The analysis of the model is divided into 5 construction stages.

4.1. First stage – concrete girder with reinforcement

The first stage of constructing the modelled girder is treated as a 'virtual stage' to see the behaviour before pre-stressing. In reality, the strands are tensioned on the stressing bed and then concrete is cast – in the numerical simulation, it is not possible to model the strands first, but in the case of linear analysis, the Boltzmann superposition principle holds. In the first stage, only the self-weight load of the girder and steel stirrups is active. Fig. 4 shows the deflection of the girder with a maximum mid-span value of 2.5 mm.

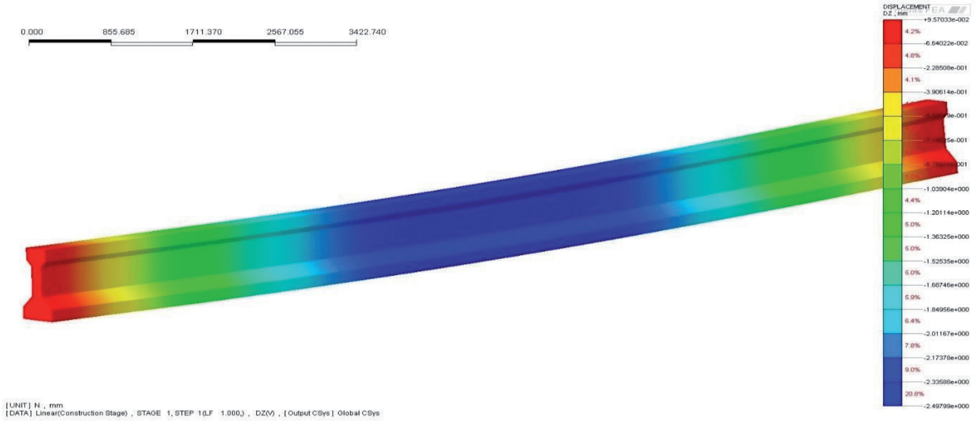

Fig. 4. Deflection of the girder in 'virtual' stage 1

In this stage, the maximum tension stress in the direction defined by the longitudinal axis of the girder is calculated as 2.38 MPa and the maximum compressive stress is 3.03 MPa.

4.2. Second stage – pre-stressing of the girder

In the second stage, pre-stressing is applied to the girder, a camber is observed. In Fig. 5, the camber is shown with a maximum negative deflection of almost –8 mm.

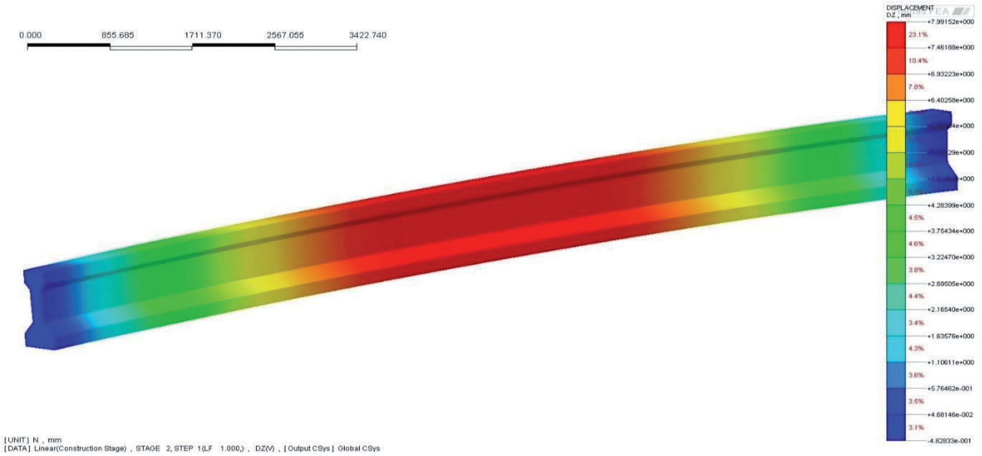

Fig. 5. Displacement due to pre-stressing

4.3. Third stage – casting the slab – wet concrete load

In the third stage, casting of the normal strength concrete deck is simulated. To represent wet concrete with 2316 kg/m^3 density, an equivalent uniform pressure load is applied to the top surface of the girder (Fig. 6).

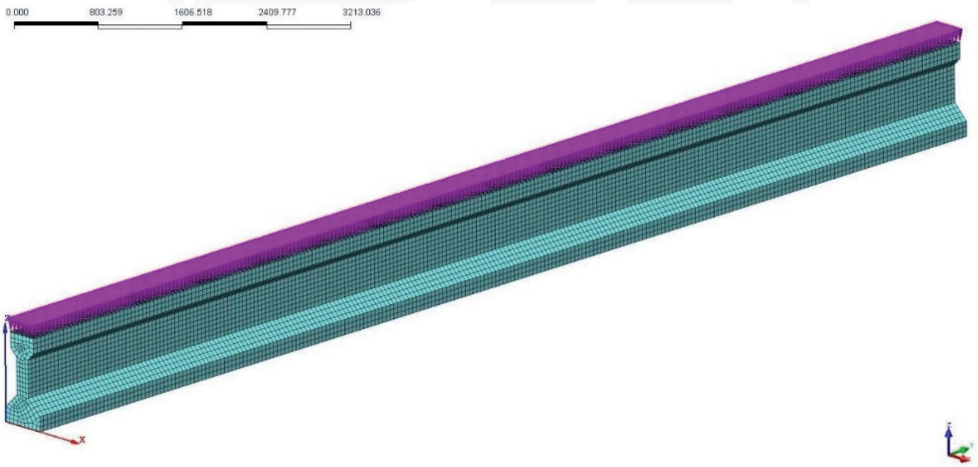

Fig. 6. Representation of wet-concrete load

In this stage, applying a wet concrete load decreases the maximum camber reached in stage two when the pre-stressing forces were applied from –7.99 mm to –5.48 mm (Fig. 7).

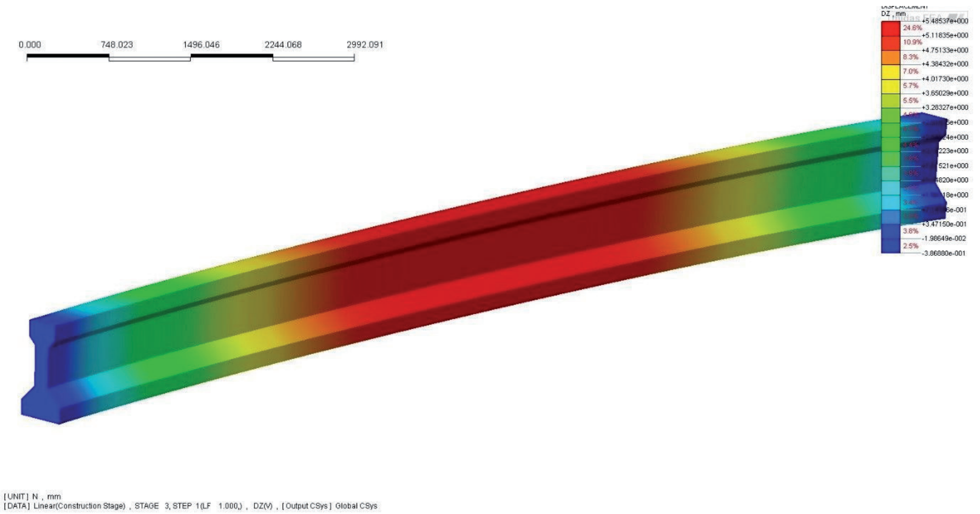

Fig. 7. Displacement after application of wet-concrete load

4.4. Fourth stage – composite girder

In the fourth stage, the cross-section of the girder becomes composite, the wet-concrete load in this stage is deactivated and the slab member becomes active. The cross-section of the girder consists of two parts – the girder and the slab with a rigid connection between them.

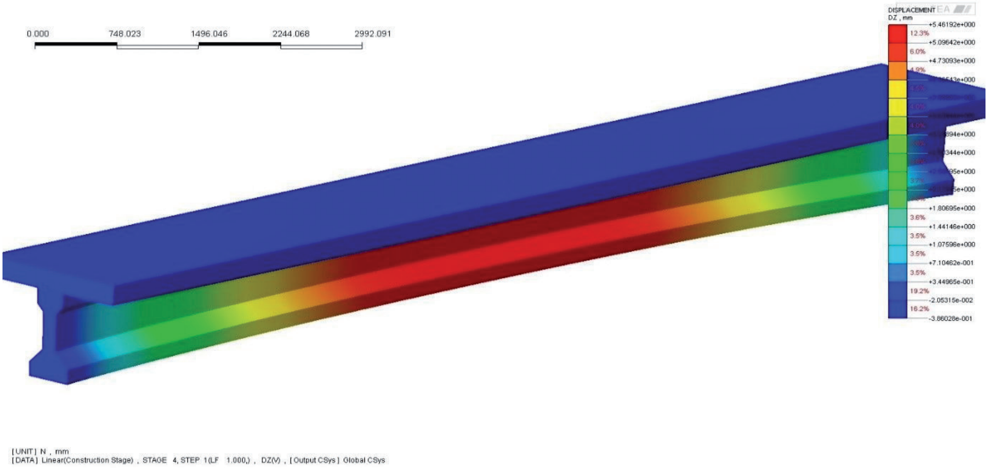

Fig. 8. Displacement of composite girder (due to a graphics malfunction, the curvature of the deck is not represented)

Comparing the results from stage 3 and 4, no significant differences are expected since the slab is connected to the girder with negative deflection. This is shown in Fig. 8. where the slab initial shape is not properly represented.

The maximum vertical displacement at the mid-span of the composite girder is –5.46 mm, this is almost the same as in stage 3, which was expected. The changes to self-weight due to evaporation of water during the hardening of concrete have been neglected.

4.5. Fifth stage – external load

In the last stage, the external load is applied, the value of the load is adopted according to the experimental results as described in [3]. The maximum displacement caused by the cracking load is 4.6 mm with L/250 [6] condition of 5 mm (Fig. 9). The maximum tension stress at the mid-span of the girder is calculated as 3.7 MPa which compares well with the tension strength of concrete used in the experiment described in [3].

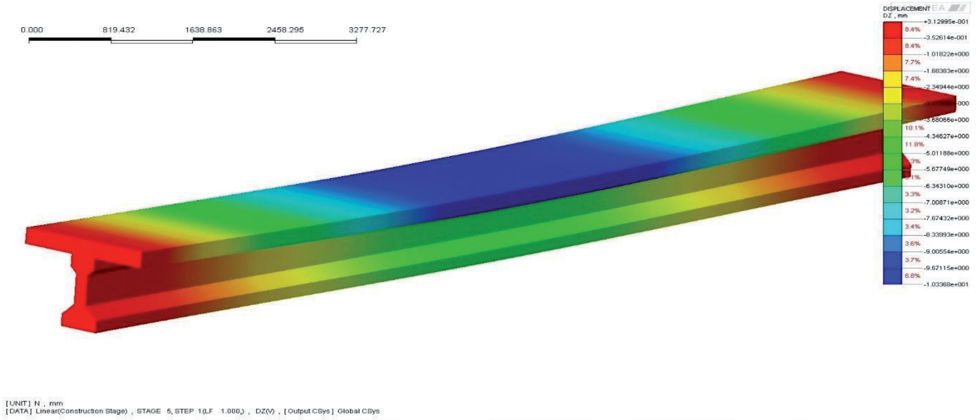

Fig. 9. Displacement after external cracking load application

5. Construction stage analysis with time-dependent effects

5.1. Third stage – casting the slab – wet concrete load

The first and the second stages do not change because there is no creep influence on the deformations and the stress distribution. The results from the construction stage analysis with or without taking the creep phenomenon into account are the same for these stages. In the third stage, after the pre-stressing and wet concrete load is applied, there is a mid-span deflection (camber) of –12.7 mm (Fig. 10) compared with –5.48 mm when creep is not taken into account. This difference occurs due to creep deformation occurring within 14 days of pre-stressing of the girder.

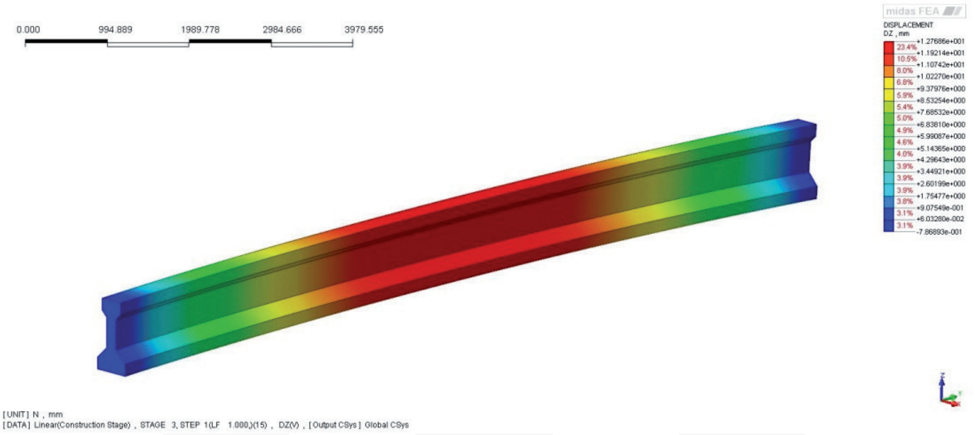

Fig. 10. Displacement due to wet-concrete load with time effects

5.2. Fourth stage – composite girder

In this stage, after forming the composite section, the negative mid-span deflection increased slightly from –12.7 mm to –13.2 mm (Fig. 11). The low increment of the deformation is due to creep of concrete which is limited by the self-weight load of the slab. The stresses in the girder in this stage are slightly lower compared to the third stage (the difference is about 0.5 to 1.0 MPa), this is because of the creep which results in a decrease of the pre-stressing force (Fig. 12).

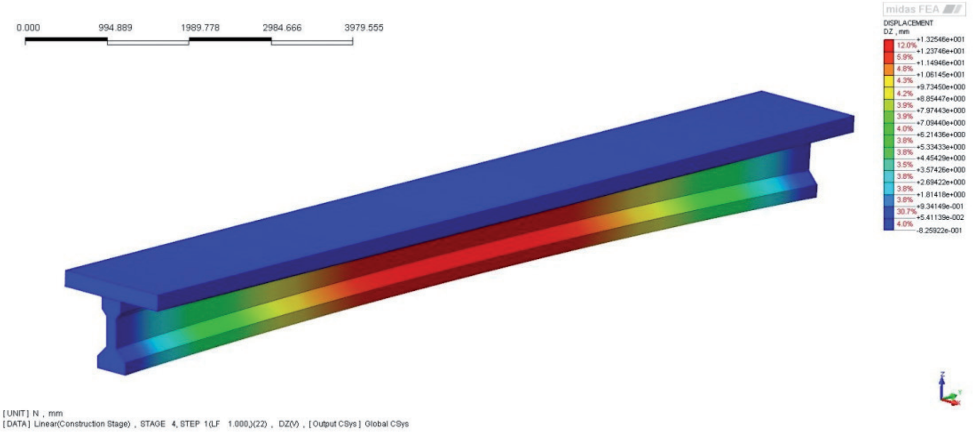

Fig. 11. Displacement of composite girder with the creep behaviour (due to graphics malfunction, the curvature of the deck is not represented)

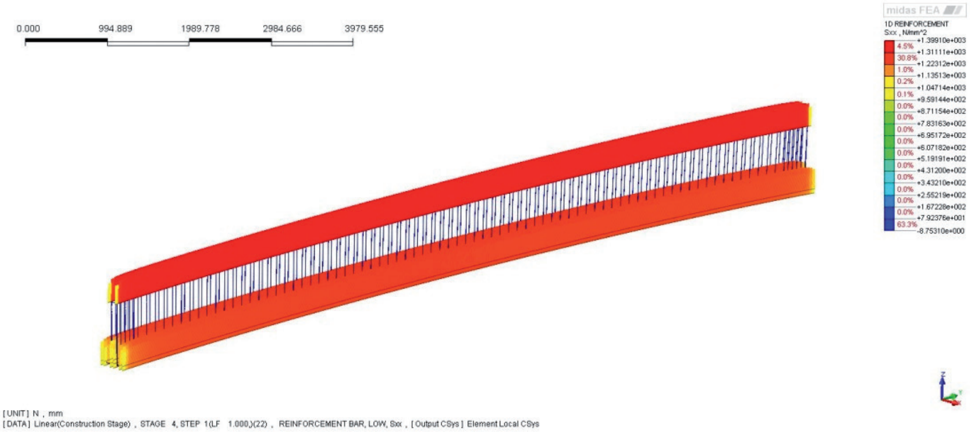

Fig. 12. Stress distribution along the pre-stressing strands

5.3. Fifth stage – external load

After the cracking load is applied, one can observe change in the girder deflection (camber) from –13.2 mm to –3.42 mm which means that the deflection of the composite girder is 9.6 mm (Fig. 13). The deflection of the slab is approximately the same as the deflection in the construction stage analysis without time dependent behaviour in the fifth stage. This is because the creep phenomenon for the NSC (slab) begins in the stage when the external load is applied to the slab. In a short time period, creep has a positive influence on the girder deflection which is smaller and positive. The maximum tensile stress at the mid-span on the bottom surface is now 4.28 MPa compared with 3.7 MPa when the creep is not taken into account.

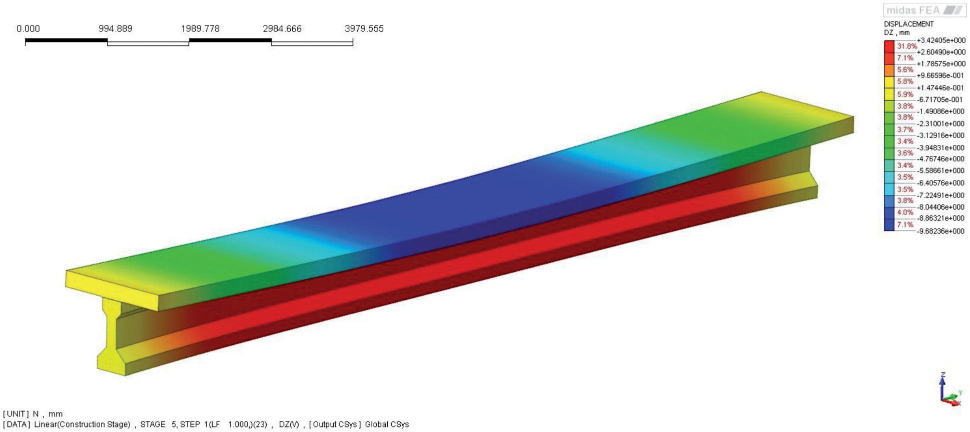

Fig. 13. Deflection of composite girder with creep

5.4. Sixth stage – long term behaviour (10,000 days)

Sixth stage is an additional stage which represents the long-time behaviour of the concrete and it lasts for 10,000 days. The deflection of the girder increases from negative –3.54 mm to positive 8.0 mm and from 9.6 mm to 21 mm for the slab (Fig. 14). The increase of the maximum tensile stress at the mid-span on the bottom surface of the girder due to creep is observed with a value of 7.68 MPa which exceeds the tensile strength of the concrete used.

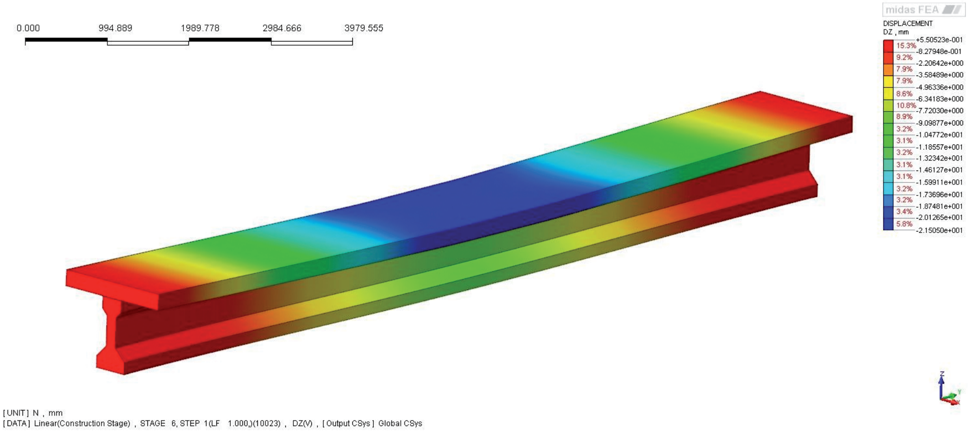

Fig. 14. Deflection of composite girder for long-term behaviour (10,000 days)

The longitudinal stress distribution along the pre-stressing strands after 10,000 days is shown in Fig. 15. The maximum stress in the strands is 1316 MPa and long-term loss of the pre-stressing force due to creep is observed (7% loss).

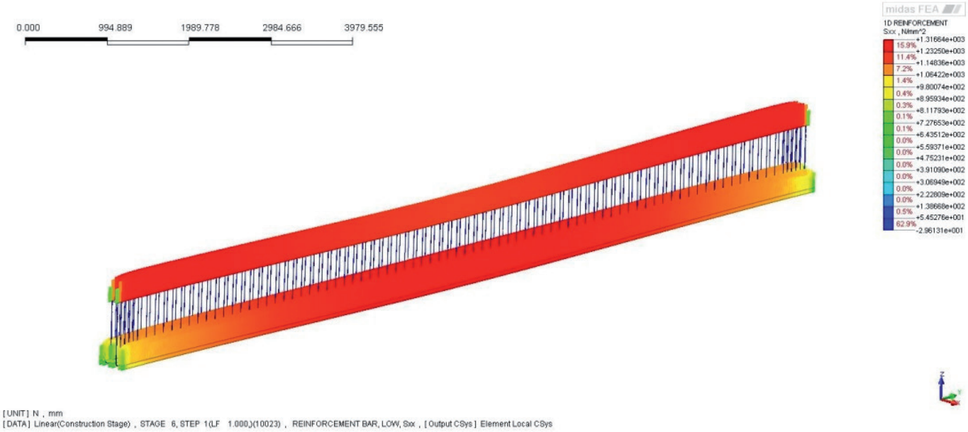

Fig. 15. Stress distribution along pre-stressing strands after 10,000 days

6. Conclusions

The study shows a significant influence of creep in the modelling of the bending behaviour of the concrete-concrete composite girder with construction stages taken into account. The conclusion can be inferred that in structures built in stages, such as composite and additionally pre-stressed, rheological effects cannot be ignored. Not taking into account the time-dependent effects causes a significant underestimation of the level of stress in the structure relating to long-term behaviour – this could even lead to exceeding the strength of the materials. Based on the literature review and experimental research performed by Choi [4], future work is proposed. The main purpose of the research is to implement a new concrete visco-elastic model to account for rheological effects. Using a generalised Maxwell spring-dashpot model [7], an incremental formulation of the linear viscoelasticity model for ageing materials was derived [8]. The model is based on the superposition principle for the visco-elastic behaviour of concrete under continuous loading and profits from the spectral form of the characteristic function for the material. In the further plans the model will be programmed in the 3D FEM software package. The results will be compared with existing models which are based on the CEB-FIP, ACI, AASHTO and EC recommendations for creep and shrinkage functions.

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