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ANALYSIS OF REINFORCED CONCRETE DOUBLE-CANTILEVER BEAMS IN ROAD-BRIDGE SUPERSTRUCTURES USING NONLINEAR DEFORMATION MODEL

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ABSTRACT: In the analysis of reinforced concrete structures in general, and reinforced concrete road bridge structures in particular, using the limit state method with ultimate internal forces, according to the stress model, there are certain advantages compared to other previous methods. However, the limit state method with the stress model did not exhibit behavior close to the actual operation of the structure. In particular, the structural behavior of each working phase has not been described. Therefore, using the nonlinear analysis based on the nonlinear deformation model allows the description of the stress-strain state of the structure in any loading period, corresponding to the closer the actual behavior. This is a modern trend in many countries worldwide when applying this structural analysis model. This study was conducted based on the nonlinear deformation model in the technique codes of rules SP63.13330.2012, construction standards TCVN 5574:2018. In this study, a computational analysis was performed for reinforced concrete double-cantilever beams in road-bridge superstructures based on nonlinear deformational model to consider the nonlinear behavior of concrete and reinforcement. From the obtained results, we can clearly observe the effectiveness of the proposed method in evaluating the bearing capacity under a construction load. Therefore, the necessary conclusions and recommendations will be made for applying the nonlinear deformation model in analysis of this type of road-bridge superstructures.

Keywords: Nonlinear Analysis, Nonlinear Deformation Model, Reinforced Concrete Element, Road-Bridge Superstructure, Load- Carrying Capacity, Double-Cantilever Beams

1. INTRODUCTION

Currently, many operating reinforced concrete road-bridge superstructures with double cantilever beams have already been constructed on various roads in Vietnam and Russia. These road–bridge superstructures were designed using the model drawings of Issue 1947, which are typical Russian drawings. In the design process, these road-bridge superstructures are analyzed under live loads in the form of a reference load that is many times lower than the current load [1, 2]. The aforementioned superstructures operate normally and are still in a good state. However, it is sometimes necessary to evaluate the current condition of structures in situations in which experimental tests cannot be performed. Therefore, a nonlinear analysis was performed by applying nonlinear deformation models to evaluate the stress-strain state in each loading stage to verify the reserve load-carrying capacity of the road-bridge superstructures.

In addition, further development of the theory in the analysis of reinforced concrete structures involves the use of a nonlinear deformation model to investigate the behavior of structural reinforced concrete elements. Many studies have been conducted on the use of nonlinear deformational models with various concerns. In [3-8] the authors developed a methodology for analyzing reinforced concrete structures using a nonlinear deformation model. The results obtained from these studies showed that using a nonlinear deformation model significantly enhanced the carrying capacity of the structures and showed convergence between technical construction standards [9-11]. The nonlinear analysis always showed effectiveness in comparison with the elastic analysis. In [12], the authors conducted a nonlinear analysis of tapered reinforced concrete columns. The results from this study demonstrated that the nonlinear analysis showed accuracy in predicting the structural behavior matching with practical reality and increased the load resistance of the member by 11%.

In [13], the characteristics of nonlinear deformation and constitutive models of cemented tailings backfills were studied. The authors concluded that the deformation characteristics of the cemented tailings backfill significantly influenced the stability of the mine stope and surface subsidence. In addition, nonlinear analyses have been performed in many studies for road bridge structures. For example, a study [14] presented the application of a nonlinear model for a T-beam structure to calculate the influence of the shear strength. From the results obtained in previous studies [15-17], it is concluded that if nonlinearity is considered, the analysis results for bridge structures are relatively consistent with the practical behavior of structures, and the economic factor is significantly improved.

Furthermore, in [18-20], the authors applied a nonlinear deformation model to different structures, such as building structures, reinforced concrete, and pre-stressed reinforced concrete road-bridge superstructures. The results of these studies demonstrate the effectiveness of the nonlinear deformation model in improving the load-carrying capacity. In addition, the authors suggested suitable criteria for the limit state for the analysis of these structures to explain the reserve load-carrying capacity of the road-bridge superstructure. From the results obtained in [18-20], the load-carrying capacity of road-bridge superstructures can be warned when experimental tests are lacking.

Based on the aforementioned reasons, in this study, the authors proposed a calculation procedure and established an effective algorithm using a nonlinear deformation model. In addition, based on the proposed approach, the authors analyzed double-cantilever beams of road-bridge superstructures that operate in many areas of Vietnam and Russia. Comments and recommendations are provided from the results obtained in the conclusion.

2. RESEARCH SIGNIFICANCE

In this study, a nonlinear deformation model was used to analyze double-cantilever beams in road – bridge superstructures. The proposed approach has important implications for determining vehicle classes that operate on roads. From this, it is clear that the vehicle classes can be operated when an experimental test cannot be performed. This has important implications from the perspective of social economics. In addition, the results obtained in this study could explain the reserve load-carrying capacity of road bridge superstructures with double cantilever beams subjected to a current load higher than that used in the design process.

3. ANALYSIS METHOD

3.1 Working stress and limit state methods

Road-bridge superstructures with double cantilever beams were built before 1962, and their analysis was performed using the working stress design method. With the release of specifications for the design of railways, roads, and urban bridges and pipes (SN 200-62), there has been a transition to the limit-state method. The main differences between the working stress design method and limit state method are as follows: When calculating strength of structures using the working stress design method, the internal forces from standard loads with dynamic coefficients were first determined without multiplying by reliability coefficients, then using these forces, the stresses were calculated and compared with the “allowable stresses” which are results of dividing the strength characteristics of materials by safety factors. In the limit state method, instead of one safety factor, three groups of reliability coefficients (for loads γ_f, for material γ_m, and responsibility of the structure γ_n), coefficients of operating conditions, and load combinations are included in the analysis. According to the limit state, the durability of the structure is calculated based on the limit stresses of the concrete and reinforcement. For flexural members, it is calculated to ensure that the plastic failure condition, that is, the reinforcement yields plastically before the concrete in the compressive zone is broken. The analysis was based on the assumption that the stress in the tensile reinforcement reached the design tensile strength, the stress in the compressive concrete reached the design compressive strength, the stress-strain diagram of the concrete was rectangular, and the tensile concrete area was not involved in the structural bearing capacity.

In addition, applying the limit state method, the load-carrying capacity of road-bridge superstructures is calculated as follows: Determine the calculated values of internal forces as bending moments, shear forces and axial forces M_c, Q_c, N_c in beams-elements and compare the calculated and critical values of internal forces M_{cr}, Q_{cr}, N_{cr} in the most loaded cross-sections of the elements.

Table 1 presents several parameters of the beams of road-bridge superstructures with double-cantilever beams of the two schemes of the typical drawing in Issue 47 under the reference lane of moving loads AK and HK. Table 1 also presents an approach for calculating the vehicle classes of the reference lane for the moving loads AK and HK.

From Table 1, it can be seen the comparison between two methods, using the limit state method and working stress method in the analysis of the road-bridge superstructures with double-cantilever beams of two schemes 5.375+13.3+5.375m and 6.9+17.4+6.9m. From the obtained results of analysis that presented in Table 1, we can see that the carrying load capacity in the form of calculated vehicle classes increased significantly by approximately in 1.5 times for AK and 2 times for HK reference lane of moving loads.

The modern method of calculating the strength of reinforced concrete elements presented in the code of rules [9] and [10] using a nonlinear deformation model allows us to illustrate the stress-strain state of structures at any stage of loading. The use of a nonlinear deformation model provides the required level of structural safety and the ability to utilize better material reserves. In addition, by applying a nonlinear deformation model, structural materials behave as closely as possible to reality.

Table 1 Example of load-carrying capacity of typical road-bridge superstructures with double cantilever beams

Parameters	Symbol	Unit	Scheme 5.375+13.3+5.375		Scheme 6.9+17.4+6.9	
			Section at middle of span	Section at the beam support	Section at middle of span	Section at the beam support
Gabarit			G7+2·0.75		G7+2·0.75	
Critical value of bending moment (Limit state method - LS)	M_{cr}	kNm	2623	3020	3775	4062
Allowable bending moment (Working stress method – WS)	M_{allow}	kNm	1534	1837	2215	2473
Bending moment of dead load - LS method - WS method	M_{dead_LS} M_{dead_WS}	kNm kNm	343 423	684 798	709 829	1202 1405
Bending moment of moving load - A11	$\frac{M_{A11\_LS}}{M_{A11\_WS}}$		$\frac{1252}{1661}$	$\frac{1698}{2287}$	$\frac{1739}{2244}$	$\frac{2250}{2944}$
- HK80	$\frac{M_{HK80\_LS}}{M_{HK80\_WS}}$		$\frac{1775}{1775}$	$\frac{2328}{2328}$	$\frac{2637}{2637}$	$\frac{3320}{3320}$
Carrying calculated vehicle classes using WS method - AK=[(M_{cr}–$M_{dead\text{-}LS}$)/$M_{A11\text{-}LS}$]×11 - HK=[(M_{cr} – $M_{dead\text{-}LS}$)/$M_{HK80\text{-}LS}$]×80			AK=10.5 HK=53.7	AK=7.5 HK=40	AK=9.5 HK=45.6	AK=6.2 HK=30.6
Carrying calculated vehicle classes using LS method - AK=[(M_{cr}–$M_{dead\text{-}LS}$)/$M_{A11\text{-}LS}$]×11 - HK=[(M_{cr} – $M_{dead\text{-}LS}$)/$M_{HK80\text{-}LS}$]×80			AK=14.6 HK=99.2	AK=10.7 HK=76.3	AK=14.4 HK=89.4	AK=10 HK=64

3.2 Analysis Based on Nonlinear Deformation Model

3.2.1 Theoretical Background

When Russian codes [9] were issued, Vietnamese construction codes were later released [10], and the analysis of reinforced concrete structures in these countries could be performed based on the nonlinear deformation model. Applying the regulations in these documents, the stress-strain state of the structures at any stage of loading is described in a nonlinear analysis. The results of the nonlinear analysis can be applied to consider the decrease in section stiffness when the load increases.

For nonlinear analysis of double-cantilever beams of road-bridge superstructures, the authors formulated the relationships of various factors, such as strains in the compressive zone of concrete ε_c, bending moment M, bending curvature of cross section ρ, and stiffness of the cross section. The stiffness of the cross-section is defined as the ratio between the bending moment and bending curvature of the cross-section $B=M/(1/\rho)$. The relationship between the bending moment M raised in the beams and the stiffness of the cross-section is important when using it in the analysis of the entire superstructure.

To build the relationship between above-mention parameters, it needs to determine the strains ε_c, ε_s, ε_{sc} which are strain in compressive concrete, reinforcement, relatively. The relations between the strains ε_c, ε_s, ε_c sand corresponding stresses σ_c, σ_s, σ_{sc} are defined according to the described lines in Fig.1 and Fig.2.

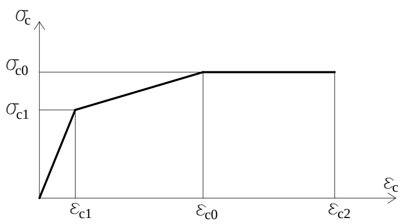


Fig.1 State diagram of compressive concrete in deformation model analysis

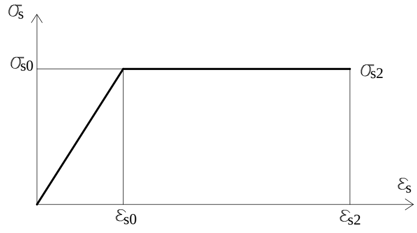


Fig.2 State diagram of reinforcement in deformation model analysis

It means that:

For compressive concrete, the relation as follows:

If $0 \leq \varepsilon_c \leq \varepsilon_{c1}$, then $\sigma_c = E_c \cdot \varepsilon_c$ (1)

If $\varepsilon_{c1} \leq \varepsilon_c \leq \varepsilon_{c0}$:

$$\sigma_c = \left[(1 - \frac{\sigma_{c1}}{R_c}) \frac{\varepsilon_c - \varepsilon_{c1}}{\varepsilon_{c0} - \varepsilon_{c1}} + \frac{\sigma_{c1}}{R_c} \right] R_c \quad (2)$$

If $\varepsilon_{c0} \leq \varepsilon_c \leq \varepsilon_{c2}$, then $\sigma_c = R_c$ (3)

Where $\sigma_{c1}=0.6 \cdot R_c$; $\varepsilon_{c1}= \sigma_{c1}/E_c$; $\varepsilon_{c0}=0.002$; $\varepsilon_{c2}=0.0035$. In which, E_c, R_c – Modulus of elastic and design compressive strength of concrete.
And for tensile and compressive reinforcement:
$\sigma_{s0}=\sigma_{s2}=R_s$, $\varepsilon_{s0}=R_s/E_s$, $\varepsilon_{s2}=0{,}025$, where E_s, R_s – modulus of elastic and design compressive strength of reinforcement.

The following assumptions are accepted: the stresses and strains are distributed by the element height in accordance with the linear relation, as shown in Fig.3. Tensile concrete was not considered in the analysis [18-20].

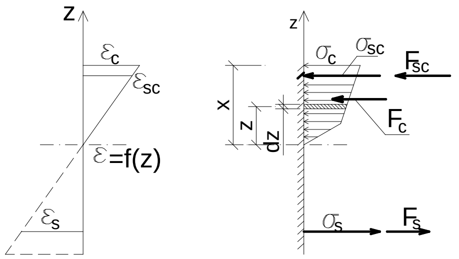


Fig.3 Scheme of distribution of strains and stresses of compressive concrete and reinforcement along the height of the beam section

From Fig.3, the internal forces of compressive concrete of tensile and compressive reinforcement are defined as follows [18,19, 20]:

$$F_c=\int_A \sigma_c dA;\ F_s=\int_A \sigma_s A_s;\ F_{sc}=\int_A \sigma_{sc} A_{sc} \quad (4)$$

Where A, dA are the area and infinitesimal area of compressive concrete.

The strain of compressive concrete is designated as variable $\varepsilon_{c,z=x}$. For each value of the variable, the bending moment M and height of the compressive zone of concrete x were determined from the equilibrium equation:

$$\sum F=F_c+F_s+F_{sc}=0 \quad (5)$$

The bending curvature of the cross-section was determined as follows:

$$1/\rho=\varepsilon_{c,z=x}/x \quad (6)$$

In this study, it is used MathCad programming software to perform the analysis. In the analysis, it is established the various relationships of three factors $\varepsilon_{c,z=x}$, M and x

However, it is necessary to note that the stiffness of cross section $B=M/(1/\rho)$ is determined in two stages of loading process.
- In first period of loading ($\varepsilon_{c,z=x} \leq \varepsilon_{c1}$), corresponding to the Eq.(1), the stiffness $B=M/(1/\rho)$ is unchanged and to be the value of $E_c I_{red}$, where I_{red} is the equivalent moment of cross-section inertia, and the tensile concrete is not considered.
- The second stage corresponds to the point $|\varepsilon_{c,z=x}|=\varepsilon_{c1}$, $\sigma_{c1}=0.6R_c$, corresponding to Eq. (2), the stiffness is determined to be $M/(1/\rho)< E_c I_{red}$. The load carrying capacity is decreased, and its loss is determined by the conditions under which the strains in the compressive concrete and reinforcement reach the values ε_{c2}, ε_{s2} as shown in Fig.1.

3.2.2 Procedure Analysis Based on Deformation Model

- Given all necessary parameters for the analysis. Example material parameters such as elastic modulus, strength of concrete, reinforcement E_c, E_s, E_{sc}, R_c, R_s, R_{sc}, and geometrical dimensions of the beam section b, b_f, h, h_f; parameters of reinforcement A_s, A_{sc}, a_s, a_{sc}, h_0.
- Calculate the characteristics of geometry of element section: Equivalent area A_{red}, equivalent first moment of area S_{red}, equivalent moment of inertia I_{red}
- Establish the equilibrium equation of forces to define the height of compressive zone x.
- Calculate the stresses $\sigma_c(\varepsilon_{c,z}(\varepsilon_c,x))$, $\sigma_{sc}(\varepsilon_{sc}(\varepsilon_c,x))$, $\sigma_s(\varepsilon_s(\varepsilon_c,x))$, in cross-section's height according to Eqs.(1) – (2).
- Calculate the forces as follows:

If $x \leq h_f$ $$F_c(\varepsilon_{c,z},x) = b_f \int_0^x \sigma_c(\varepsilon_{c,z})dz \quad (7)$$

If $h_f < x$ $$F_c(\varepsilon_{c,z},x) = b \int_0^{x-h_f} \sigma_c(\varepsilon_{c,z})dz + b_f \int_{x-h_f}^{x} \sigma_c(\varepsilon_{c,z})dz \quad (8)$$

$$F_{sc}(\varepsilon_{c,z},x)=\sigma_{sc}(\varepsilon_{c,z},x) \cdot A_{sc} \quad (9)$$

$$F_s(\varepsilon_{c,z},x)=\sigma_s(\varepsilon_{c,z},x) \cdot A_s \quad (10)$$

Where, $F_c(\varepsilon_{c,z},x)$ is force of compressive concrete corresponding to the compressive height x.
$F_{sc}(\varepsilon_{c,z},x)$ is force of compressive reinforcement corresponding to the compressive height x.
$F_s(\varepsilon_{c,z},x)$ is force of tensile reinforcement corresponding to the compressive height x.

- Calculate the bending moment of the forces at the neutral axis of the section:

If $x \le h_f$

$$M_c(\varepsilon_{c,z}, x) = b_f \int_0^x \sigma_c(\varepsilon_{c,z}) \times z \times dz \qquad (11)$$

If $h_f < x$

$$M_c(\varepsilon_{c,z}, x) = b \int_0^{x-h_f} \sigma_c(\varepsilon_{c,z}) \times z \times dz + b_f \int_{x-h_f}^{x} \sigma_c(\varepsilon_{c,z}) \times z \times dz \qquad (12)$$

$$M_{sc}(\varepsilon_{c,z},x)=F_{sc}(\varepsilon_{c,z},x)\cdot(x-a_{sc}) \qquad (13)$$

$$M_s(\varepsilon_{c,z},x)= M_s(\varepsilon_{c,z},x)\cdot(x+a_s-h) \qquad (14)$$

$$M=\sum M(\varepsilon_{c,z},x)=M_c(\varepsilon_{c,z},x)+M_s(\varepsilon_{c,z},x)+M_{sc}(\varepsilon_{c,z},x) \qquad (15)$$

- Calculate the bending curvature $1/\rho$ and the stiffness $B=M/(1/\rho)$ of particle of beam-element with length dl:

$$\frac{1}{\rho\left(\varepsilon_{c,z=x}, x\right)} = \left|\frac{\varepsilon_{c,z=x}}{x}\right| \qquad (16)$$

$$B\left(\varepsilon_{c,z=x}, x\right) = \frac{M}{1/\rho\left(\varepsilon_{c,z=x}, x\right)} \qquad (17)$$

In the last step of calculation, it is built a representation of the relationship between the above-calculated factors (strains of compressive concrete, bending curvature, and section stiffness, etc.): $M=f(\varepsilon_{c,z})$, $1/\rho=f(\varepsilon_{c,z})$, $B=f(\varepsilon_{c,z})$, $B=f(M)$.

In this study, the authors applied this algorithm, procedure, and recommended approach of nonlinear analysis for double-cantilever beams of a road-bridge superstructure. In addition, an algorithm was built, and the programming routine was written in MathCad software for reinforced concrete beams.

The results of this analysis can be applied to the nonlinear analysis of entire road- bridge superstructures. The decrease in section stiffness can be considered according to the change in the bending moment.

4. NUMERICAL EXAMPLE

In this section, the authors performed the nonlinear analysis for double cantilever beams of road-bridge superstructure with scheme 6.9+17.4+6.9m of typical drawing based on nonlinear deformation model. Figs.4, 5, 6 illustrate the facade and along section, cross section of the superstructure, and the beam's cross-section. The parameters of dimensions and geometry characteristics of the cross-section are presented in Table 2.

Design characteristics of materials as follows: Elastic modulus of concrete E_c=18900 MPa (M140), reinforcement (class A-I) E_s=206000 MPa; design strength of concrete R_c=6.4MPa, reinforcement R_s=210 MPa.

Table 2 Dimension of cross section, geometrical characteristics

Cross section *a*, m	b cm	b_f cm	h cm	h_f cm	A_s cm^2	a_s cm	A'_s cm^2	a' cm	h_0 cm	x_0 cm	$\varepsilon_{b0}\times10^4$
0 (1-1)	60	260	140	14	204.1	12.4	45.4	4.9	127.6	62.4	–2.032
8,7 (2-2)	60	260	115	14	181.4	10	45.4	6.1	105	34.2	–2.032

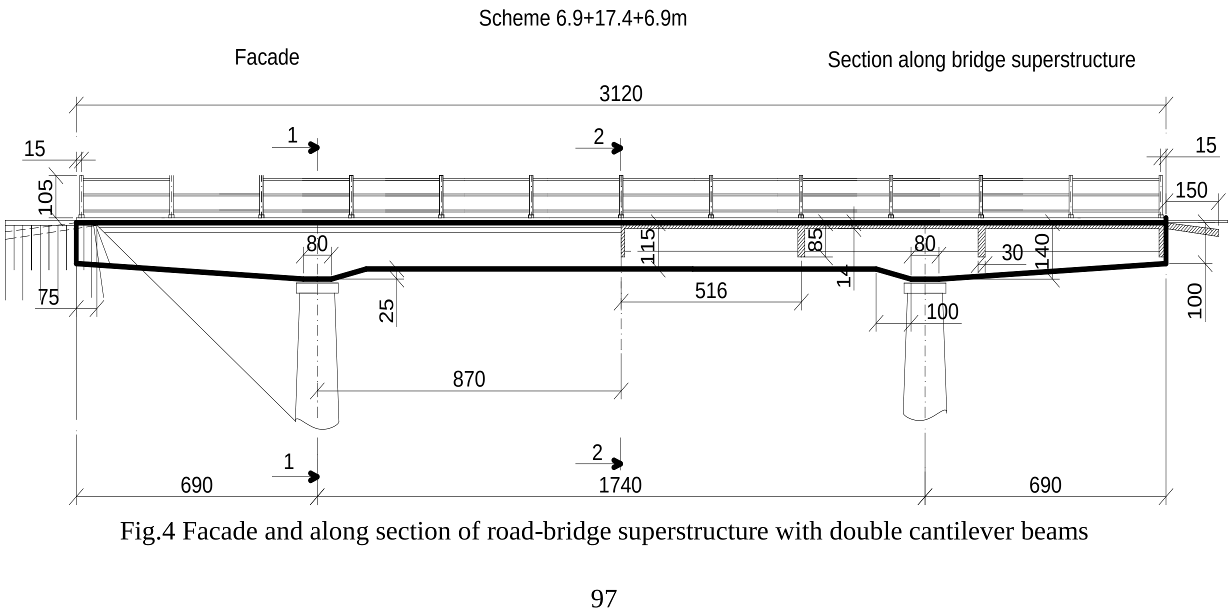


Fig.4 Facade and along section of road-bridge superstructure with double cantilever beams

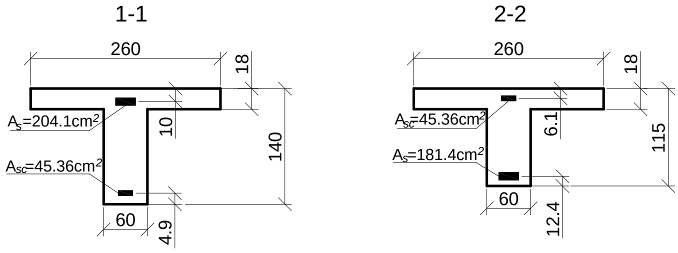


Fig.5 Cross section of double cantilever beams

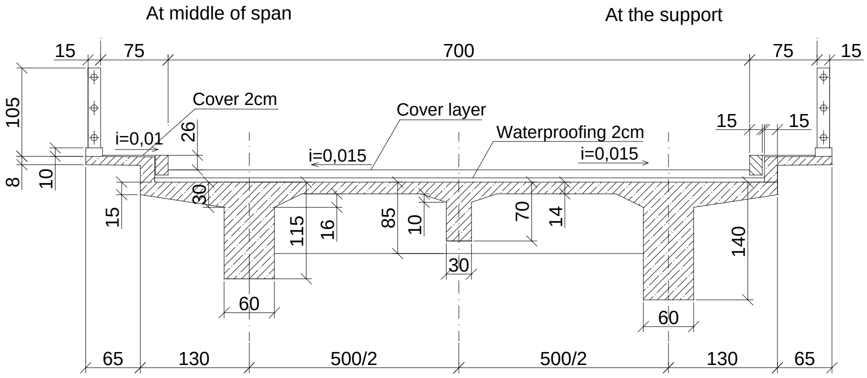


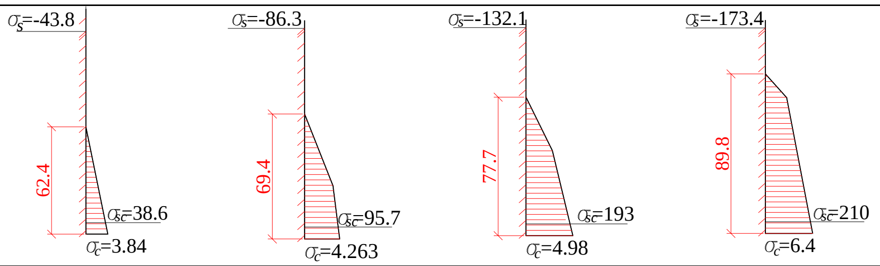
Fig.6 Cross section of road-bridge superstructure

Table 3 Results of nonlinear analysis in cross section at support and at middle of span

Cross section at support x=0

$\varepsilon_c \times 10^{-4}$	-2.032	-5	-10	-20
x, cm	62.4	69.4	77.7	89.8
$\varepsilon_s \times 10^{-4}$	2.13	4.2	6.41	8.41
$\varepsilon_{sc} \times 10^{-4}$	-1.87	-4.65	-9.37	-18.9
M, kNm	982	1858	2789	3461
$(1/\rho) \times 10^4$, m^{-1}	3.26	7.2	12.86	22.27
$B=M/(1/\rho)$, MNm^2	3014	2580	2168	1554

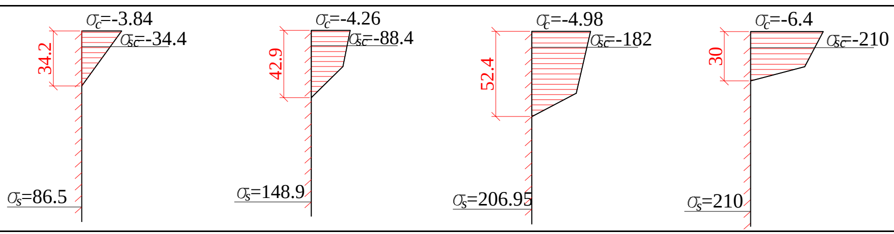
Diagrams σc, σs, σsc, (MPa)



Cross section at middle of span x=8.7m

$\varepsilon_c \times 10^{-4}$	-2.032	-5	-10	-20
x, cm	34.2	42.9	52.4	30
$\varepsilon_s \times 10^{-4}$	4.2	7.23	10.1	50.1
$\varepsilon_{sc} \times 10^{-4}$	-1.67	-4.29	-8.84	-15.93
M, kNm	1245	2037	2724	3233
$(1/\rho) \times 10^4$, m^{-1}	5.94	11.65	19.1	66.81
$B=M/(1/\rho)$, MNm^2	2100	1750	1427	484

Diagrams σc, σs, σsc, (MPa)



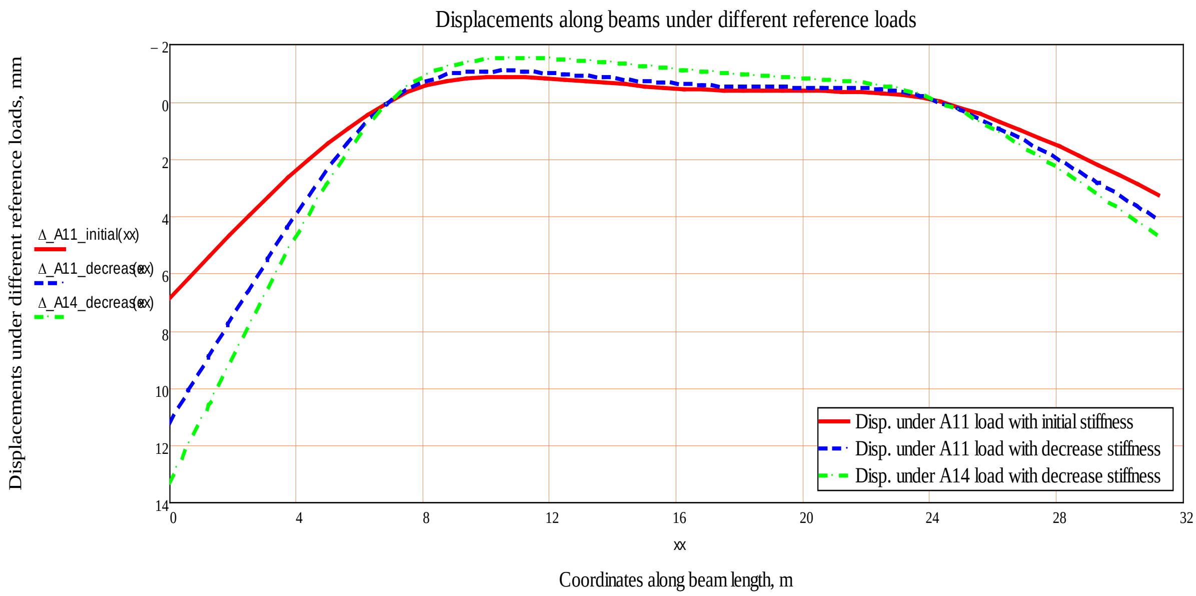


Fig.7 Displacements in beams under reference loads A11 and A14 with initial and decrease stiffness

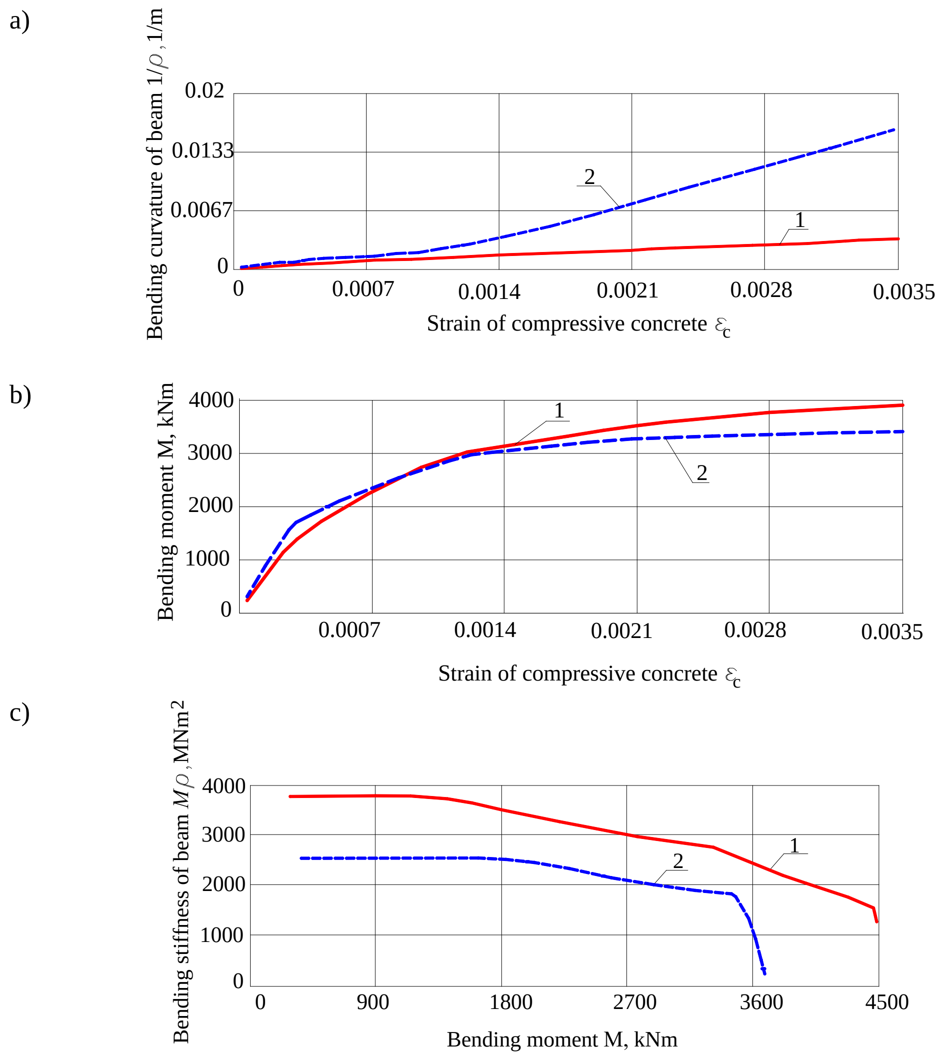


Fig.8 Diagrams of different relationships of nonlinear analysis of road-bridge superstructure with double cantilevered beams of scheme 6.9+17.4+6.9m: a $-1/\rho=f(\varepsilon_{c,z=x})$; b – $M=f(\varepsilon_{c,z=x})$, c – $M/(1/\rho)=f(M)$; 1 – for cross section at support, 2 – for cross section at middle of span

Fig.7 shows the results of the analysis using the deformation model in the form of the displacement distribution when the beams were subjected to reference loads A11 and A14 with initial and decreased stiffness. Fig. 8 presents diagrams of the relationships between the strain of the compressive concrete, bending curvature of the beam, bending moment, and bending stiffness of the beam for the cross-section at the support and middle of the road-bridge superstructure span.

Comments:

Fig.7 shows the results of the analysis using the nonlinear deformation model in the form of the distribution of displacement when the beams were subjected to reference loads A11 and A14 with initial and decreased stiffness. The displacements in the beams with decreased stiffness were higher than those in the beams with initial stiffness under the same loading. This verifies the correctness of the proposed approach using the nonlinear deformation model.

From Table 3, it can be seen that by applying the proposed analysis approach using the nonlinear deformation model, the stress-strain state in each stage of loading was observed, and the distribution of stresses in the cross-section of the beams was changed.

Fig.8 illustrates the diagrams of different relationships in the nonlinear analysis of road-bridge superstructures with double cantilever beams using the deformation model. From these diagrams, it can be observed that the bending curvature and internal forces changed at different stages of loading. Fig.8c shows the relationship between the internal forces and the section stiffness. The horizontal line segment in Fig. 8c corresponds to the first and second periods of change in the stress-strain state, indicating that the section stiffness is constant. After “break point” which corresponds to the value of strain in compressive concrete ε_{c0}=0.002, the section stiffness began to decrease when the bending moment reached a specific value gradually. Thus, it can be applied to the spatial nonlinear analysis of whole systems of beams in superstructures. When the decrease in section stiffness is changed, the distribution of internal forces occurs, and the load-carrying capacity of the superstructure can be improved.

5. CONCLUSION

In this study, the authors recommended an approach for the nonlinear analysis of reinforced concrete beams of road bridge superstructures using nonlinear deformation models of materials in different construction standards. Based on the recommended approach, the authors established an algorithm, analysis procedure, and calculation routine based on Mathcad software for reinforced concrete double cantilevered beams of road-bridge superstructures. From the established procedure, a numerical example was performed, and the relationships among the strains of the compressive concrete, bending curvature, internal forces, and section stiffness were determined. These relationships are meaningful in the nonlinear analysis of entire superstructures to estimate the load-carrying capacity in cases where an experimental test cannot be performed.

The results of the analysis allow a systematic demonstration of the development of the stress-strain state of the beams at all the loading stages. The relationship between internal forces and beam stiffness can be applied in the analysis of entire road-bridge superstructures to consider the decrease in stiffness with a gradual increase in internal forces. In addition, in the analysis considering the decrease in the section stiffness, the internal forces were redistributed in the superstructure. Therefore, it helps to increase the load-carrying capacity of the superstructure. Based on the obtained results, the reserve of the load-carrying capacity of the modern road-bridge superstructure can be explained because they are currently subjected to a much greater load than the load used in the designed process. In addition, the results can be applied in the analysis of entire road-bridge superstructures to estimate the current load-carrying capacity of superstructures and provide a warning of limit level loads when it is difficult to perform experiments.

6. REFERENCES

[1] Shapiro D.M., Agarkov A.V., Tran T.T.V., Spatial non-linear deformational analysis of road bridge multi-beam superstructures, Scientific Journal of Voronezh State University of Architecture and Civil Engineering, Series of Construction and Architecture, 2008, pp. 29-37.

[2] Shapiro D. M., Agarkov A.V., Deformative non–linear calculation of ferroconcrete T-section beams, Scientific Journal of the Voronezh State Architecture and Civil Engineering, Series of Construction and Architecture, 2009, pp. 105-110.

[3] Murashkin G.V., Murashkin V.G., Modeling of the deformation concrete chart, News of OrelGTY, Construction and Transport, Vol.2, Issue 14, 2007, pp. 86-88.

[4] Murashkin G.V., Pishulev A.A., Using deformation models to determine the bearing capacity of reinforced concrete flexural members with corrosion damages of concrete compressed zone, News of OrelGTY, Construction and Reconstruction, Vol. 6, 2009, pp. 36-42.

[5] Denis A. P., Alexander A. P., The Methodology for Calculating Deflections of Reinforced Concrete Beams Exposed to Short Duration

Uniform Loading (Based on Nonlinear Deformation Model), XXIII R-S-P seminar, Theoretical Foundation of Civil Engineering, Procedia Engineering 91, 2014, pp.188 -193.

[6] Denis A. P., Alexander A. P., Vyacheslav V. R., The Methodology for Calculating Deflections of Statically Indeterminate Reinforced Concrete Beams (Based on Nonlinear Deformation Model, XXV R-S-P Seminar, Theoretical Foundation of Civil Engineering, Procedia Engineering 153, 2016, pp.531-536.

[7] Al-Maliki H.N.G., Mohammad M.A. and Jasim J.A., Simulation Nonlinear of Structural Behavior of Hollow Reinforced Concrete Deep Beams Strengthened By CFRP, IOP Conference Series: Materials Science and Engineering, Vol. 928, 2020, pp. 01-20.

[8] Radim C., Kamil B., Zdenka N., Petr M. and David B., Experimental Measurement of The Load-Bearing Capacity of Wire Hooks and Bends Used in Gabion Retaining Walls, International Journal of GEOMATE, Vol. 25, Issue 111, 2023, pp.170-176.

[9] Ministry of Regional Development of the Russian Federation, SP 63.1330.2012 Set of rules: Concrete and Reinforced concrete structures, Russia, 2012, pp. 01-171.

[10] Ministry of Science and Technology, TCVN 5574:2018 Design of concrete and reinforced concrete structures, Vietnam, 2018, pp. 01-194.

[11] European Committee for Standardization, British Standard: Design of concrete structures. Part 1-1 General rules and rules for buildings, Eurocode2 BS EN 1992-1-1:2004+A1:2014, 2014, pp. 1-277.

[12] Al-Maliki H.N.G., Alshimmeri A.J.H., Ali A.M., Madhloom H.M., Gamil Y., Nonlinear Simulation Analysis of Tapered Reinforced Concrete Column (Solid and Hollow) Behavior Under Axial Load. International Journal of GEOMATE, Vol. 21, Issue 86, 2021, pp.131-146.

[13] Aiping C., Chengsong Z., Shibing H., Yushan Z., Mingsong P., Journal of Materials Research and Technology, Study on the nonlinear deformation characteristics and constitutive model of cemented tailings backfills considering compaction hardening and strain softening, Vol. 19, 2022, pp. 4627-4644.

[14] Ahmed A.K., Hala A., Kareem G.N., Ibrahim A. E., Nonlinear Analysis of Reinforced Concrete T-Beam, Al-Azhar University Civil Engineering Research Magazine (CERM), Vol. 2, 2021, pp. 168-185.

[15] Ali K., Ralph P. D., Thomas B. P.E., A Computer Model for Nonlinear Analysis of Bridge Structures, Studies in Applied Mechanics, Vol.35, 1994, pp. 423-432.

[16] Kubilay K., Non-linear analysis of bridge structures, Trakya University Journal of Engineering Sciences, Vol.18, Issue.1, 2017, pp. 17-29.

[17] Chung C. Fu and Mohamed S. A., Nonlinearity in bridge structural analysis, 2013, pp. 01-25.

[18] Tran T.T. V., Shapiro D.M., Nonlinear deformation analysis for precast pre-stressed concrete beam systems, E3S Web of Conferences, Russia: EDP Sciences, 2019, pp. 01-13.

[19] Tran T.T.V, Vu T.B.Q., Nonlinear deformational analysis of reinforced concrete frame, Lecture Notes in Civil Engineering 54, Innovation for Sustainable Infrastructure, 2019, pp. 317-326.

[20] Tran T.T. V, Vu T.B.Q., Nonlinear analysis for proposing limit state criteria of reinforced concrete road bridge superstructures, Archives of Civil Engineering, Vol. 69, Issue 1, 2023, pp. 495-512.