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MODEL OF STRESS-STRAIN STATE OF THREE-LAYERED REINFORCED CONCRETE STRUCTURE BY THE FINITE ELEMENT METHODS

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Abstract. The object of the study is multi-layer reinforced concrete structures of concrete with various physical and mechanical characteristics of materials - concrete and reinforcement under the influence of loading. Analysis of the stress state of multilayer reinforced concrete beams by using different materials is a complex problem due to the different mechanical and physical characteristics of materials and the cracking behavior of concrete. This article presents an analysis of the stress-strain state of three-layered reinforced concrete structures using the finite element method in the program ANSYS Mechanical. Numerical modeling allows on ANSYS allows combining different combinations of loads, the variability of the strength and deformation characteristics of materials and various types of reinforcement in multilayer reinforced concrete beams. Comparison is made between the experimental results, numerical results and finite element analyses with respect to initial crack formation and the ultimate load capacity of beams. The results of the study were shown that as the grade of concrete in the external layer increases from B15 to B20 and the grade of lightweight concrete in the internal layer increases from B0.75 to B1.5, the crack resistance can be increased by 59.7% and the bearing capacity of the test beam is increased by 16.4%. When the thickness of the external layers varies from 40mm to 80mm, making the crack resistance increased by 47.5% and the bearing capacity of three-layer concrete beams greatly increased by 6.7%. The obtained scientific results enable to determine rational parameters for modeling various structural solutions of multilayer reinforced concrete structures.

Keywords: concrete buildings; reinforced concrete; multilayer structures; three-layer structures; contact interlayer; heat-insulating materials; stress analysis; ANSYS Mechanical.

МОДЕЛИРОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ТРЕХСЛОЙНОЙ ЖЕЛЕЗОБЕТОННОЙ КОНСТРУКЦИИ МЕТОДАМИ КОНЕЧНЫХ ЭЛЕМЕНТОВ

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Аннотация: Объектом исследования являются многослойные железобетонные конструкции из бетона с различными физико-механическими характеристиками материалов - бетона и арматуры под воздействием нагрузки. Анализ напряженного состояния многослойных железобетонных балок с использованием различных материалов представляет собой сложную проблему из-за различных механических и физических характеристик материалов и растрескивания бетона. В данной статье представлен анализ напряженно-деформированного состояния трехслойных армированных строительных конструкций с использованием метода конечных элементов в программе ANSYS Mechanical. Численное моделирование позволяет на ANSYS комбинировать различные комбинации нагрузок, изменчивость прочностных и деформационных характеристик материалов и различных типов арматуры в многослойных железобетонных балках. Проводится сравнение между экспериментальными результатами, численными результатами и анализом методом конечных элементов в отношении начального образования трещин и предельной несущей способности балок. Результаты исследования показали, что по мере увеличения марки бетона во внешнем слое с B15 до B20 и сорт легкого бетона во внутреннем слое увеличивается с B0,75 до B1,5, трещиностойкость может быть увеличена на 59,7%, а несущая способность теста луч увеличен на 16,4%. При толщине наружных слоев от 40 мм до 80 мм трещиностойкость увеличивается на 47,5%, а несущая способность трехслойных бетонных балок значительно увеличивается на 6,7%. Полученные научные результаты позволяют определить рациональные параметры для моделирования различных конструктивных решений многослойных железобетонных конструкций.

Ключевые слова: бетонные здания; железобетон; многослойные конструкции; трехслойные конструкции; контактная прослойка; теплоизоляционные материалы; анализ напряжений; ANSYS Mechanical.

INSTRUCTION

Today, the development of technologies new materials from concrete has helped create many kinds of enclosing structures for civil and industrial buildings. Enclosing structures not only meet the requirements for bearing capacity but also meet other requirements such as thermal insulation, sound insulation, fire resistance, corrosion resistance, ... One of the effective solutions to solving this problem is the use of multilayer reinforced concrete structures with a middle layer of low thermal conductivity concrete, that consists of: the external layers made mainly of structural concrete to provide the load-bearing of elements such as: heavy concrete [1, 2], fine-grained concrete [3] or clay concrete [4, 5]; The internal layer of heat insulation and sound insulation is used by light concrete of low strength, such as foam concrete [6, 7], coarse-pored concrete [8], polystyrene concrete [1, 9], etc.

In this type of construction, made of non-uniform materials, under loadings, stress and strain distribution is a rather complex process, so the ratio between the modulus of elasticity of the middle and outer layers haves a strong influence on the stress and strain distribution. Various methods are used to calculate multilayer reinforced concrete structures. For calculating strength and deformation, the authors [10, 11] proposed to bring a three-layer reinforced concrete cross-section with a monolithic bond to an I-beam, based on the ratios of the initial elastic modulus of concrete of the layers using the hypothesis of flat sections. In the literature [12-14] a method for calculating a multilayer structure using a contact layer based on the Kirchhoff-Love hypothesis was used.

It was found that the stress–strain state of multilayer reinforced concrete structures was influenced by many factors. The influence of the physical and mechanical properties of concrete and the geometrical parameters of the layers was analyzed in references [15– 16]. The influence of geometric and physical nonlinearity, plastic and geological properties of concrete on the stress–strain state of multi-layer structures was studied in references [17, 18].

At present, the development of science and technology has allowed to perform a wide variety of researches using the finite element method and pro-vide results close to full-scale experiments. Meth-ods of debonding evaluation in FRP strengthened concrete beams based on finite element model (FEM)-modeling proposed in References [19–20]. In this study, the authors propose a solution to analyze the stress-strain state of three-layer reinforced concrete by using a finite element model (FEM) with the help of the program ANSYS.

1. MATERIALS AND METHODS

1.1 Model of tested samples and material properties

This article considers three-layered beams with a width of 160 mm, a height of 250 mm and a length of 3000 mm. For external layers, concrete of class B15, B20 and B25 (Table 1) is commonly used, with a thickness from 40mm to 80mm. For the middle layer, lightweight concrete with low thermal conductivity is used, with polystyrene concrete class B0.75, B1 and B1.5, and with the thickness from 170mm to 90mm.

In the tested beam, armature is obtained with 2 rebars with a diameter of 8 mm (A-500), σ_y = 475.2 MPa, σ_u = 660.5 MPa, modulus of elasticity of the armature E_s = 206,000 MPa.

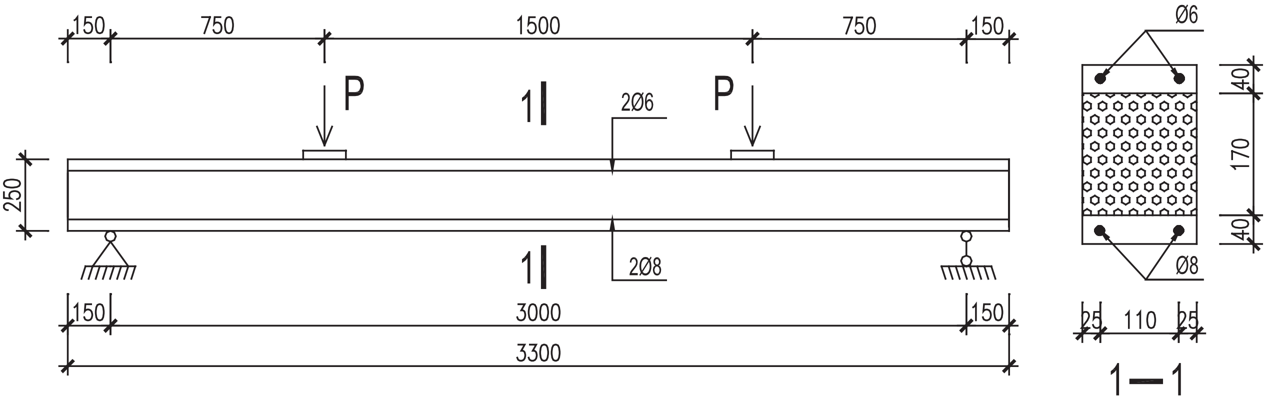


Figure 1. Three-layer concrete beam model of test

Table 1. Parameters and characteristics of concrete in tested beams

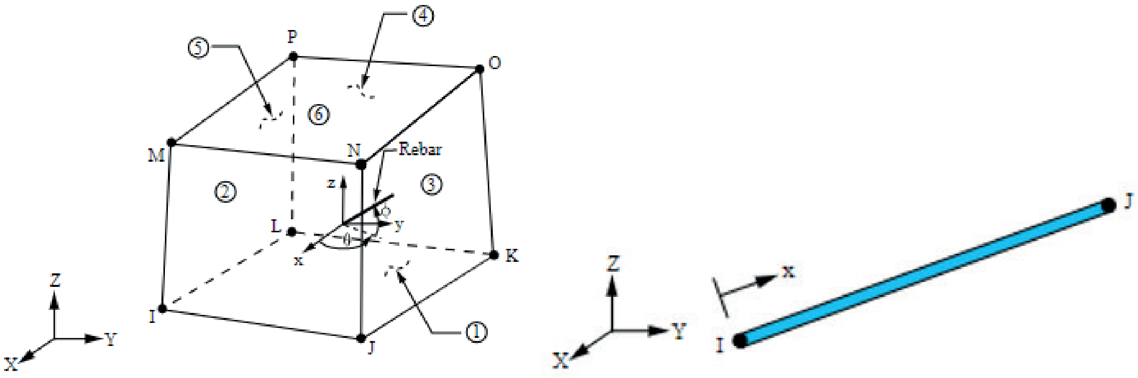
	External layer			Internal layer		
	B15	B20	B25	B0,75	B1	B1,5
R_b, (MPa)	11	15	18.5	0.84	1.1	1.61
R_{bt}, (MPa)	1.15	1.4	1.6	0.44	0.51	0.61
E_b, (MPa)	23000	27000	30000	650	850	1100
v	0.2	0.2	0.2	0.2	0.2	0.2

1.2 Finite element modeling for three-layers reinforced concrete beam on ANSYS

The research methods are based on numerical simulation of stresses and strains of multilayer reinforced concrete elements under the action of various load combinations. The use of modern software systems enables to carry out numerous variable studies, combining a different combination of loads and variability

of strength and deformation characteristics of materials – structural concrete, low-strength concrete for the middle layer, as well as to compare the results obtained from PC ANSYS with the theoretical results of the calculation. One of the most modern, universal software complexes ANSYS, based on finite element method was used in the article as well as volumetric eight-node finite elements of type SOLID65 and rod elements LINK180 [21].

The element Solid65 is used to model the concrete. This element has eight nodes with three degrees of freedom at each node –translations in the nodal x, y and z directions. This element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. A schematic of the element is shown in Figure. 2 (a). The element Link8 is used to model steel reinforcement. This element is a 3D spar element and it has two nodes with three degrees of freedom – translations in the nodal x, y, and z directions. This element is also capable of plastic deformation. This element is shown in Figure. 2 (b).



(a) *(b)*

Figure 2. (a) Solid65 Element and (b)Link8 element

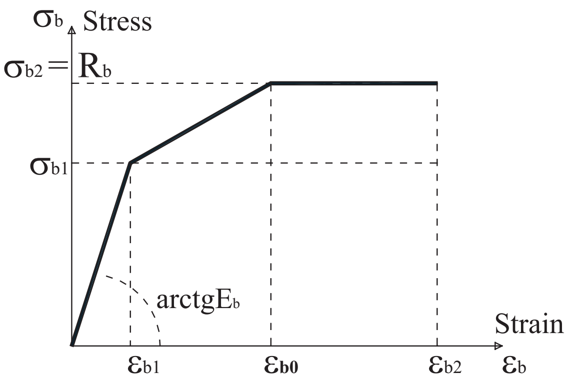


Figure 3. Stress-strain relationship for concrete

Where: σ_b - compressive stresses of concrete;
R_b - prismatic strength of concrete;
ε_b - the deformation of concrete;
ε_{b1}; ε_{b0}; ε_{b2} - the deformation of concrete corresponding to the stress $\sigma_{b1}= 0.6*R_b$; $\sigma_{b0}= R_b = \sigma_{b2}$

Figure. 3 shows the stress- strain relation of concrete [22]. Following equations are used to compute the multilinear isotropic stress-strain curve for the concrete (Figure. 3):

When $0\leq \varepsilon \leq \varepsilon_{b1}$, with $\sigma_b=E_b.\varepsilon_b$ (1)

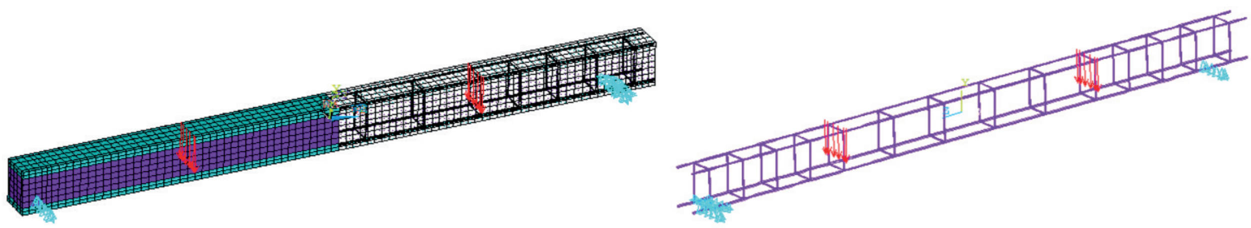
When $\varepsilon_{b1}\leq \varepsilon \leq \varepsilon_{b0}$, with

$$\sigma_b = [\left(1-\frac{\sigma_{b1}}{R_b}\right)\frac{\varepsilon_b-\varepsilon_{b1}}{\varepsilon_{b0}-\varepsilon_{b1}}+\frac{\sigma_{b1}}{R_b}]R_b \quad (2)$$

When $\varepsilon_{b0}\leq \varepsilon \leq \varepsilon_{b2}$, with $\sigma_b= R_b$

The values of the stress σ_{b1} are determined by the following formula: $\sigma_{b1}= 0.6R_b$

$$\text{with } \varepsilon_{b1}=\frac{\sigma_{b1}}{E_b} \quad (3)$$



(a) (b)

Figure 4. Three-layers concrete beam model in ANSYS. a) Model of three-layer concrete beam b) Modeling of steel bars in concrete beams

2. RESULTS AND DISCUSSION

2.1 The results and analysis the stress-strain state of three- layered reinforced concrete structures of experiment and on ANSYS

The analysis and comparison of stress and deformation of the three-layer beam under the effect of load between finite element method with using software complexes ANSYS, numerical method and experiment is done on three-layer beams in Figure. 1. The parameters and properties of materials are shown in Table. 2.

The analysis results of moment (M) and deflection (f) of three-layer beam on ANSYS are shown in Figure 5 and Table 3.

Beam start to crack and to be damaged, are shown in Figure. 6 and Figure. 7.

Table 2. Parameters and characteristics of concrete in tested beams

The layers of beam	External layer	Internal layer
The thickness of the layers h, cm	0.04	0.17
Prismatic strength of concrete R_b, (MPa)	21.5	1.54
Tensile strength of concrete R_{bt}, (MPa)	1.8	0.36
The initial modulus of elasticity E_b, (MPa)	12100	1310
Coefficient Poisson $v = 0.00189\ \lvert R_b \rvert + 0.12$	0.16	0.122
Shear modulus $G = E_0/(2(1 + v))$, MPa	5216	346
The average density of concrete, kg/m^3	1800	440

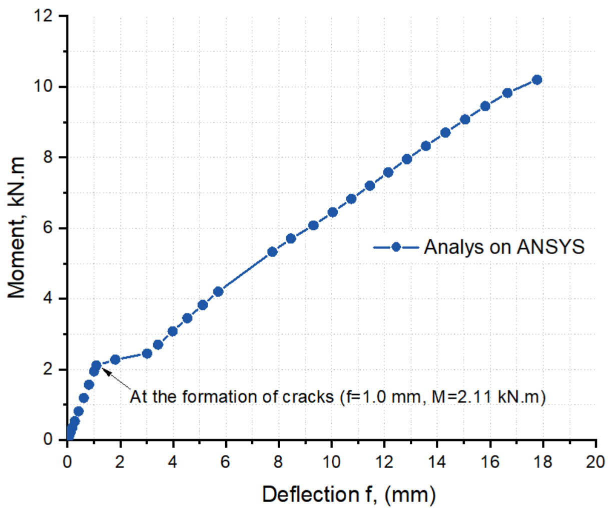


Figure 5. Load-Displacement curve for tested beam

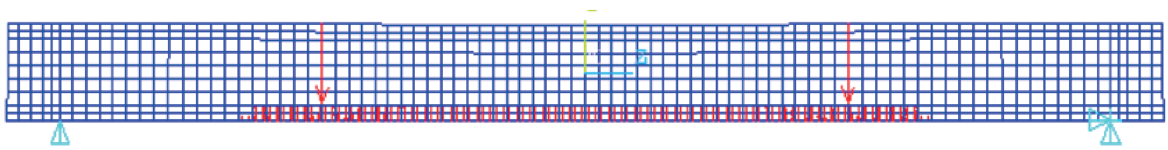


Figure 6. Beam start to crack, at moment M_{crc} = 2.11 kN.m

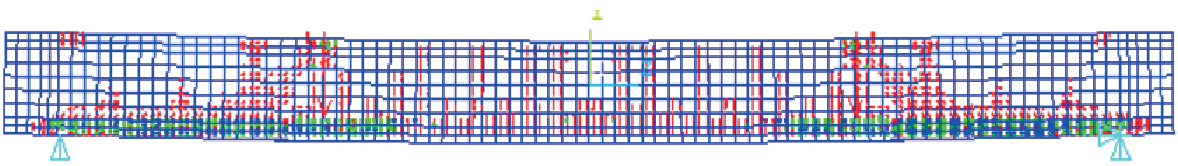


Figure 7. Beam is damaged, at moment M_{ult} = 10.20 kN.m

Table 3. Comparation of the results of analysis

Model	At the formation of cracks		At failure of beam	
	Moment M_{crc} (kN.m)	Deflection f, (mm)	Moment M_{ult} (kN.m)	Deflection f, (mm)
On ANSYS	2.11	1.10	10.20	17.7
Experimental study [1]	2.23	1.12	9.6	8.30
Numerical study based on the monolith converter of cross-section [1]	2.09	1.20	11.1	17.96

The analysis results in Table. 3 are shown that moment (M) and deflection (f) of the three-layer beam at the crack's formation and at the beam's failure on ANSYS near experimental results than results by using numerical models. The difference of the results of the beam bearing capacity analysis between the ANSYS model and experiment is 1% at the crack's formation and 5.8% at the beam's failure. This difference between the numerical and experimental models respectively is 6.3% và 13.5%.

The analysis results of stress and deformation of three-layer beams on ANSYS are close to the experimental results, it allows to use this method in the research and evaluation of bearing capacity of the three-layer beam under the effect of load.

2.2 Effect of concrete grade changes in external and internal layers on the bearing capacity of three-layer concrete beams

The three-layer reinforced concrete beams in Figure. 1 are used to analyze the effect of concrete grade changes in external and internal layers on the bearing capacity of three-layer concrete beams. The heavy concrete class B15, B20 and B25 are used in external layers thickness 40mm. The lightweight concrete class B0.75, B1 and B1.5 are used in internal layers thickness 170mm.

Table 4 presents the cases of investigating changes in concrete grades in the external and internal layers:

Table 4. Concrete grade in cases investigated

Case	Layer 1: NC layer	Layer 2: LW layer	Layer 3: NC layer
1	B15	B0.75	B15
2	B15	B1	B15
3	B15	B1.5	B15
4	B20	B0.75	B20
5	B20	B1	B20
6	B20	B1.5	B20
7	B25	B0.75	B25
8	B25	B1	B25
9	B25	B1.5	B25

Where: The normal concrete layer below is layer 1; the lightweight concrete layer in the middle is layer 2; the normal concrete layer above is layer 3.

For three-layer concrete beams, the vertical displacement spectrum and moment at the formation of cracks and at the failure of the beam are shown in Table. 5, Figure. 8 and Figure. 9.

Table 5. Comparation of the results of analysis

Model	At the formation of cracks		At failure of beam	
	Moment M_{crc} (kN.m)	Deflection f, (mm)	Moment M_{crc} (kN.m)	Deflection f, (mm)
Case-1	1.16	0.43	9.07	22.06
Case-2	1.18	0.41	9.82	19.96
Case-3	1.19	0.39	10.19	17.36
Case-4	1.52	0.57	9.44	23.07
Case-5	1.54	0.54	10.19	18.85
Case-6	1.57	0.51	10.37	16.26
Case-7	1.74	0.52	9.65	23.24
Case-8	1.81	0.51	10.48	18.67
Case-9	1.90	0.51	10.55	17.13

For three-layer reinforced concrete beams, as the grade of concrete in the external layer increases from B15 to B20, the bearing capacity of the test beam is increased. The moment at the crack's formation increased from 1.16 kN.m to 1.74 kN.m (increase by 50%), on the beams using lightweight concrete B0.75 in the internal layer; and increased from 1.19 kN.m to 1.9 kN.m (increase by 59.7%), on beams using lightweight concrete B1.5 in the internal layer (in Figure.8). The moment at the beam's failure can be increased from 9.07 kN.m to 10.55 kN.m (increase by 16.4%), is shown in Table.5 and Figure. 9.

When the concrete grade in the external layers is the same, the grade of lightweight concrete in the internal layer increases from B0.75 to B1.5, the moment at the beam's failure can be increased from 9.07 kN.m to 10.19 kN.m (increase by 12.4%) (in Figure.9).

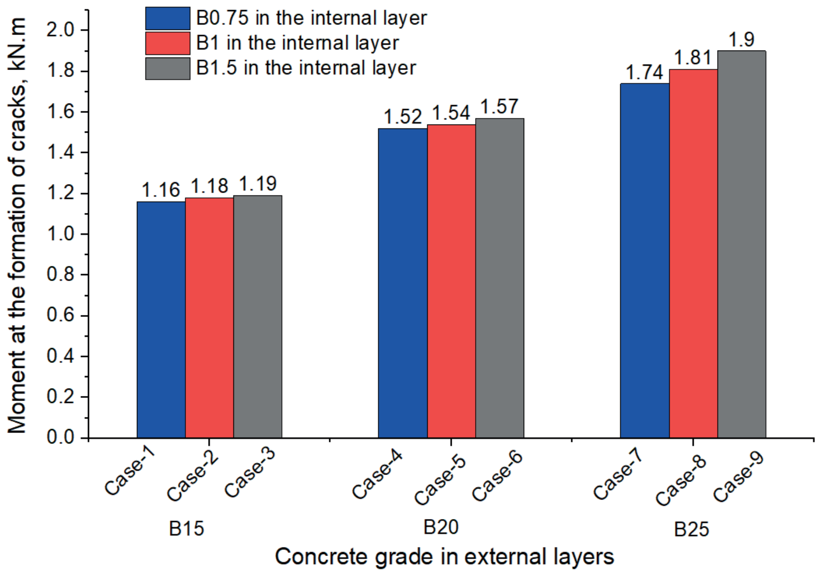


Figure 8. Chart of the relationship between crack's moment and concrete grade in external layers

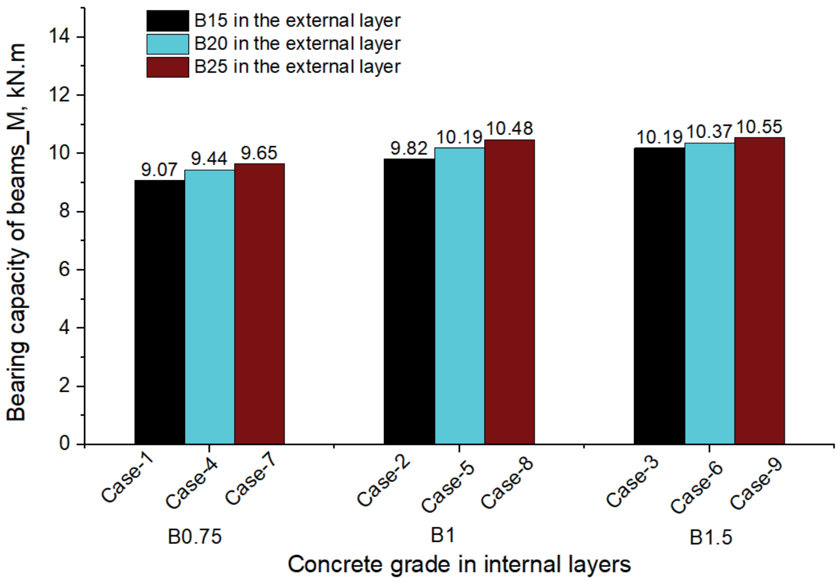


Figure 9. Chart of the relationship between bearing capacity of beams and concrete grade in internal layers

2.3 Effect of thickness of the external and internal layers on the bearing capacity of three-layer concrete beams.

In this case, three-layered beams with width 160mm, height 250mm and length 3000 mm, shown in Figure1, are studied. The external layers of tested beams made by heavy concrete (normal concrete) grade B15, with changes of thickness from 40mm to 80mm and the
internal layers of tested beams made by lightweight concrete grade B1, with changes of thickness from 170mm to 90mm.

Table 6 presents the cases of investigating changes of thickness of the external and internal layers on bearing capacity of three-layer reinforced concrete beams.

The results of the analysis the stress and deformation state on the beams are shown in Table. 7 and Figure.10.

Table 6. Thickness of layers in cases investigated

Case	Layer 1: NC layer	Layer 2: LW layer	Layer 3: NC layer
10	40 mm	170 mm	40 mm
11	60 mm	130 mm	60 mm
12	80 mm	90 mm	80 mm

Where: The normal concrete (B15) layer below is layer 1; the lightweight concrete (B1) in the middle is layer 2; the normal concrete (B15) layer above is layer 3.

Table 7. Comparation of the results of analysis

Model	At the formation of cracks		At failure of beam	
	Moment M_{crc} (kN.m)	Deflection f, (mm)	Moment M_{crc} (kN.m)	Deflection f, (mm)
Case-10	1.18	0.41	9.82	19.96
Case-11	1.57	0.44	10.19	20.26
Case-12	1.74	0.46	10.46	19.15

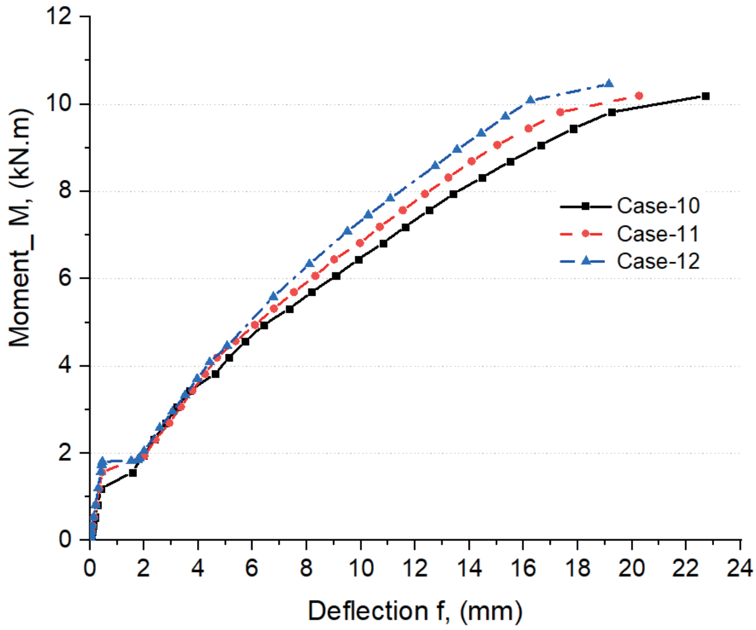


Figure 10. Load-displacement curve for tested beams

In the beam samples case-10; 11 and case-12, the material used by the external and internal layers of the three-layered beams remains constants, when thickness of the external layers varies from 40mm to 80mm, making the crack resistance and the bearing capacity of three-layer concrete beams greatly changed. The moment at the crack's formation increased from 1.18 kN.m to 1.74 kN.m (increase by 47.5%), the bearing capacity of tested beams increased from 9.82 kN.m to 10.46 kN.m (increase by 6.7%).

3. CONCLUSION

The obtained experimental and theoretical results lead to the following conclusions:
(1) The final analysis shows similar results obtained by numerical methods using the ANSYS PC, compared to experimental studies and theoretical calculations. The results of analysis of moments and deflections of multilayer reinforced concrete beams of ANSYS are usually lower compared to the result of moments and deflections when calculated according to the theory scheme (from 1 to 5.8%).
(2) The analysis of concrete grade changes in the layers shows that as the grade of concrete in the external layer increases from B15 to B20, the crack resistance can be increased in 59.7% and the bearing capacity of the test beam is increased in 16.4%. When the concrete grade in the external layers is the same, the grade of lightweight concrete in the internal layer increases from B0.75 to B1.5, the moment at the beam's failure can be increased in 12.4%.
(3) The analysis of changes thickness of the external and internal layers shows that when the thickness of the external layer varies from 40mm to 80mm, making the crack resistance increased in 47.5% and the bearing capacity of three-layer concrete beams greatly increased 6.7%.

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