

NON-LINEAR ANALYSIS OF HYBRID REINFORCED T-BEAM WITH PARTIAL SUBSTITUTION RECYCLED RUBBERIZED CONCRETE

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Abstract

At present, the need to make use of industrial waste materials is increasing due to their harmful effects on the environment. In the present work, the behavior of hybrid reinforced T-Beam by steel, and CFRP with rubber is studied. The finite element modeling by using ANSYS version 15 program. It contains also all the required steps needed to create the concrete models that were prepared to study the behavior of beams with rubber concrete. The reinforcement of beams was various combinations of polymer CFRP and steel bars. The crumb rubberized concrete mixes were prepared by partial substitution (5 %, 10 %, 15 %, 17.5 %, 20 %, 22.5 %, and 25 % replacements by volume). Due to the large number of parameters affecting the behavior of Hybrid Reinforced T- Beam with rubber concrete, an extensive parametric study was performed using ANSYS version 15 program. Three parameters were investigated namely: Bottom RFT, compressive strength of concrete, and the existence of opening. The analytical results agree well with the experimental results in terms of mode of failure and the failure load values. The results indicated that although the flexural capacity of the tested specimen decreased with the addition of Crumb Rubber and reduced its self-weight. The failure load of the beam increases with bottom reinforcement by the GFRP bar or CFRP bar. Also, reinforced beams by CFRP bars had a higher failure load than reinforced beams by GFRP bars. Having an opening in hybrid reinforced T-Beam with rubber concrete reduced the beam load capacity and maximum deflection. Also, using GFRP bars, and CFRP bars in the vicinity of openings in hybrid reinforced T-Beams increased the load capacity of these beams.

Keywords:

CFRP bars;
T-beams;
Crumb Rubber;
Finite element method;
Hybrid beams.

1 Introduction

With the advancement of industry and the increase in industrial waste, it was necessary to make positive use of waste by recycling it. Rubber is one of the most common waste materials. Directing civil and environmental engineering researchers to use of rubber in the concrete industry [1,2]. These researchers replaced different proportions of aggregates with rubber in the members' concrete mix. The results showed the addition of crumb-rubber aggregate has a significant effect on concrete mix apparent porosity which affects both the plastic state workability and hardened state mechanical properties [3].

Parth et al. [4] performed an experimental program to study the of Crumb Rubber in Concrete as a sand replacement in range of 0%, 2.5%, 5%, 7.5% and 10 % by weight for M-25 grade cement (OPC). Abhay et al. [5] studied effect of using Crumb Rubber in concrete. The results showed that the using Crumb Rubber produces low workability for concrete. Sabir et al. [6] replaced 5%, 10%, 15% of finely crushed sand with crumb rubber in the concrete mixture. The results showed that the use of crumb rubber reduces self-weight of concrete, and toughness. Roman et al. [7] investigated of the influence of the rubber powder on material characteristics and durability of crumb rubber concrete. The tests showed that workability, compressive strength and permeability decreased as the amount of rubber increased. Yang et al. [8] performed an experimental program to study the Mechanical Properties of Crumb Rubber

Concrete after Elevated Temperature. The results showed that using crumb rubber increases toughness rather than strength. Recently different types of FRPs have commonly been used for structural reinforcement of concrete member. Obaidat et al. [9] conducted an experimental program to study strengthening of reinforced concrete beams using composite laminates. The main variables considered were the internal reinforcement ratio, position of retrofitting and the length of CFRP. Chaallal and Shahawy [10] performed a series of experimental programs to study strengthening of concrete columns with fiber reinforced polymer-wrapped in combined axial-flexural loading. Prota et al [11] tested eleven 3700 mm long shallow reinforced concrete beams under static loading, seven strengthened with steel fibers, and two strengthened with CFRP. Hassan and Rizkalla [12] and Hassan [13] examined the flexural behavior of prestressed concrete bridge slabs strengthened with various CFRP systems. The half scale specimens were strengthened with near surface mounted (NSM) CFRP bars and strips as well as externally bonded CFRP strips and sheets. The flexural capacity of the slabs could be increased by as much as 50 percent using the CFRP strengthening, with the most cost effective solution being the CFRP sheets. Yahiya et al. [14] carried out a study on the strengthening of un-bonded post-tensioned reinforced concrete beams using near surface mounted NSM technique by carbon fiber reinforced polymers CFRP and high tensile strength HTS steel bars. Various code writing organizations around the world have proposed design guidelines for the repair or strengthening of concrete structures with FRP. The American Concrete Institute released a document in 2002 concerning design and construction of externally bonded FRP systems for strengthening concrete structures (ACI Committee 440, 2002) [15]. Many different aspects of using FRP are included, such as system installation guidelines, including various types of surface preparation techniques, inspection and field evaluation procedures, as well as guidelines for the repair of minor damage observed after CFRP installation.

Mohamad A Hasan et al. [16] investigated of performance of hybrid reinforced T-Beam. Eight specimens with 200X300 mm dimensions, 500 mm flange width, and 100 mm slab thickness were loaded to failure. The reinforcement of beams was polymer CFRP. Maciej et al. [17] performed an analytical program to study the reduction of dynamic impacts in block made of concrete – rubber composites. The results exhibit that using the embedded rubber pads increased the protection against the transversal dynamic load. Md. Shahjalal et al. [18] investigated of mechanical properties of fiber-reinforced rubberized recycled concrete. The results exhibit that The compressive strength decreased with an increase in crumb rubber percentage, but it increased by including fiber content. Sachinthan et al. [19] performed an experimental program to study the effect of recycled rubber aggregate size on fracture and other mechanical properties of structural concrete. The results showed that the toughness of concrete improved by using recycled aggregates at low percentages.

In a non-linear analysis of concrete structures, Sucharda et al [20] examined the behavior and performance of RC beams without shear reinforcement. For this purpose, the researcher used stochastic modelling (Valašik et al [21]; Strauss et al [22]; Wu, et al [23]). Kozielova et al [24] used Newton-Rapson method for modelling of interaction of a RC slab with subsoil. Newton-Rapson method shows the change of stiffness after the creation of cracks.

The current research aimed to reach a proposed analytical finite element model of hybrid reinforced T-beam structures to estimate the performance of these T-beams with variable compressive strength of concrete produced by Mohamad A Hasan et al. [16] by using Ansys 15 and to evaluate of the flexural ductility indices of T-beams with variable compressive strength of concrete.

The finite element model and the results of this research can be welfare in considering the performance of hybrid reinforced T-beams and the design of the structures.

2 Research significance

The objective of this study was to focus a more useful analytical understanding of the performance of hybrid reinforced Beam by CFRP with Crumb Rubber. Thereby, we must focus on obtaining the maximum strength of hybrid reinforced members due to using different types of concrete. Therefore, the main objective was the nonlinear finite element analysis (Ansys 15 software) of hybrid reinforced Beam with variable compressive strength of concrete. The specimens' behavior include: the ultimate load, the deflection, the cracking pattern, ductility and stiffness. The analytical results are compared with the previously investigated experimental models presented by Mohamad A Hasan et al. [16]. A parametric study was performed using nonlinear finite element analysis to investigate more variables affecting the behavior of the beams.

Mohamad A Hasan 's experimental program [16] includes testing of six hybrid reinforced Beam subjected to two line loads. Six tested beams with variable compressive strength of concrete. Table 1

shows the details of the tested beams. Dimensions and reinforcement details of the tested specimens are shown in Fig. 1.

Table 1: Details of tested beams [16].

Model	Tensile reinforcement (CFRP)	Compression reinforcement (CFRP)	Concrete Cube Strength [MPa]
G-GPC1	4Ø10	2Ø10	46
G-GPC2	4Ø16	2Ø10	42.3
G-GPC3	4Ø16	2Ø10	38.8
G-GPC4	6Ø16	2Ø10	53.5
G-GPC5	6Ø16	2Ø10	54.1
G-GPCC6	4Ø16	2Ø10	43.5

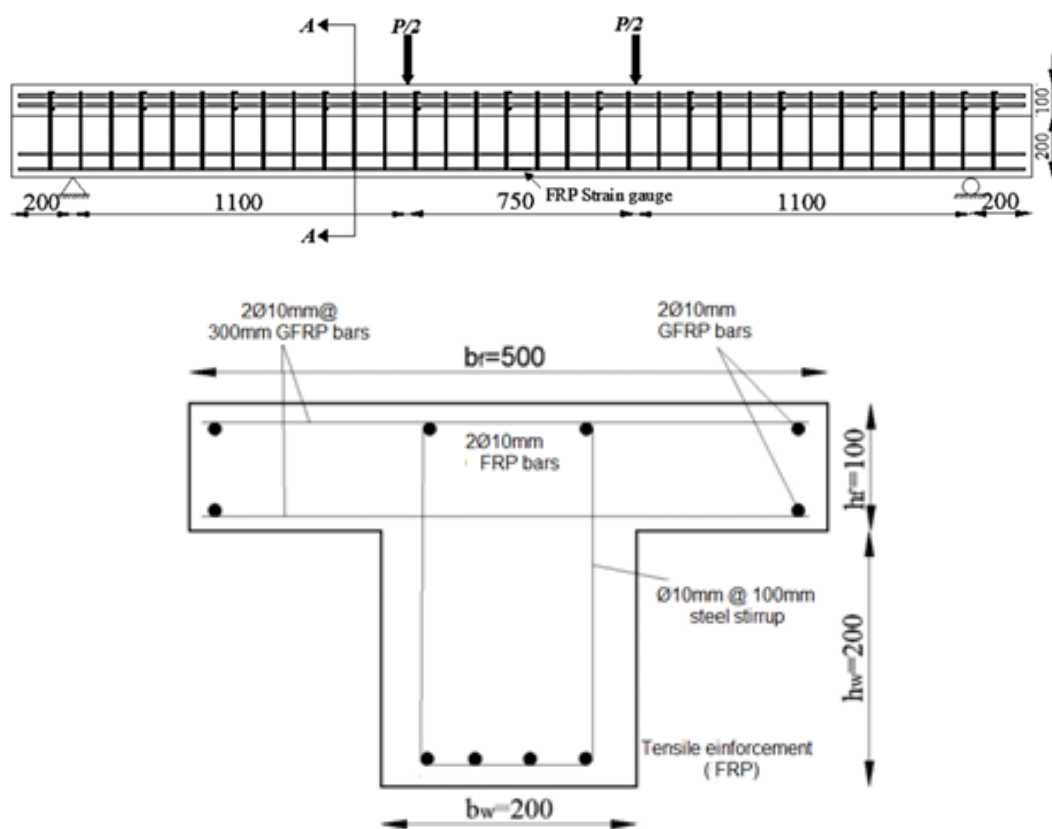


Fig. 1: Dimensions and reinforcement details of the tested specimens [16].

3 Methodology and analytical model

In order to validate the results of Mohamad A Hasan 's study [16] and give the opportunity to future parametric studies, the nineteen tested beams were analyzed by ANSYS version 15. Concrete is modeled by the SOLID 65 element, which has the ability to crack in tension and crush in compression.

The element is defined by six faces and eight nodes; each node has three degrees of freedom. The most important properties of this element is that it can behave nonlinearly. Fig. 2 shows a typical brick element in global Cartesian and local intrinsic coordinates. Concrete material is defined in ANSYS by its linear behavior with poisson's ratio of 0.2, and modulus of elasticity of $4400 (fcu)^{0.5}$. Moreover, the non-linear behavior is defined by open shear coefficient of 0.3 and closed shear coefficient of 0.8. Also, the tensile strength of concrete was defined as $0.6 (fcu)^{0.5}$. The actual values of compressive strength fcu obtained from cube testing were used as input which change with changing percentage of recycled rubber used in the concrete mix.

Rubber material is defined in ANSYS by its multi-linear behavior. The model used in this analysis of relation between stress-strain curve of rubber concrete obtained from cube testing were used as input, Table 2.

Table 2: The material properties of concrete used in ANSYS program.

Material	Element Type	Material Properties	
Concrete	Solid65	Linear Isotropic	
		Modulus of elasticity (EX) [N/mm ²]	4400 (fcu) ^{0.5}
		Passion ratio (PRXY)	0.26
		Concrete Properties	
		Open Shear-Coefficient	0.3
		Closed Shear-Coefficient	0.8
		Uniaxial Cracking Stress (fctr) [N/mm ²]	0.6 (fcu) ^{0.5}
		Uniaxial Crushing Stress (f'c) [N/mm ²]	0.8 fcu
		Multi-Linear Isotropic	
		Strain	Stress [MPa]
		from cube testing	from cube testing

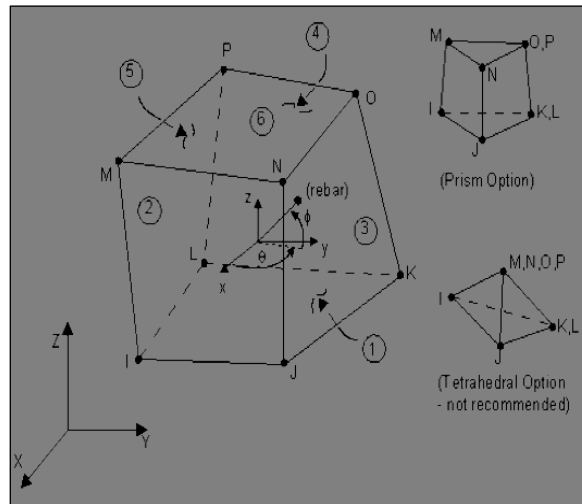


Fig. 2: Solid 65 element [25].

The steel rebar and CFRP rebar were modeled by the LINK180 element. This element is uniaxial compression-tension element with 2 nodes having 3 degrees of freedom. It also includes plasticity, stress stiffness, and deflection, Fig. 3.

The material definitions for this steel element are assumed linearly as poisson's ratio of 0.3 and elasticity modulus of 200,000 MPa. The ultimate tensile stress is taken as 520 MPa for stirrups. The material definitions for CFRP element are assumed linearly as poisson's ratio of 0.3 and elasticity modulus of 210,000 MPa. The ultimate tensile stress is taken as 3600 MPa and 3250 MPa for GFRP rebar 10 mm and 16 mm, respectively.

Load plate and supports are modeled by the SOLID 45 element. The element consists of 8 nodes having 3 degrees of freedom, Fig. 4.

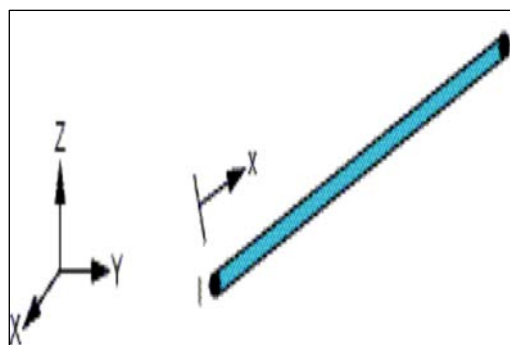


Fig. 3: Discrete element LINK180 [25].

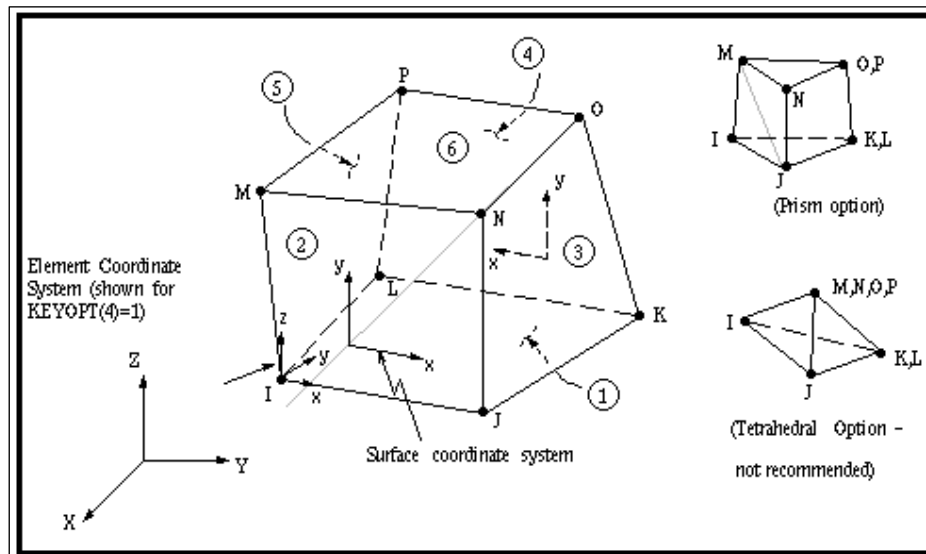


Fig. 4: SOLID 45 element [25].

The concentrated load used in this study was applied at the top of two transverse rollers. The load was divided into a series of loads at the top mesh joint in the y direction. There are two boundary conditions needed to be applied at the concrete model, where there are two supports (hinged and roller supports) as shown in Fig. 5.

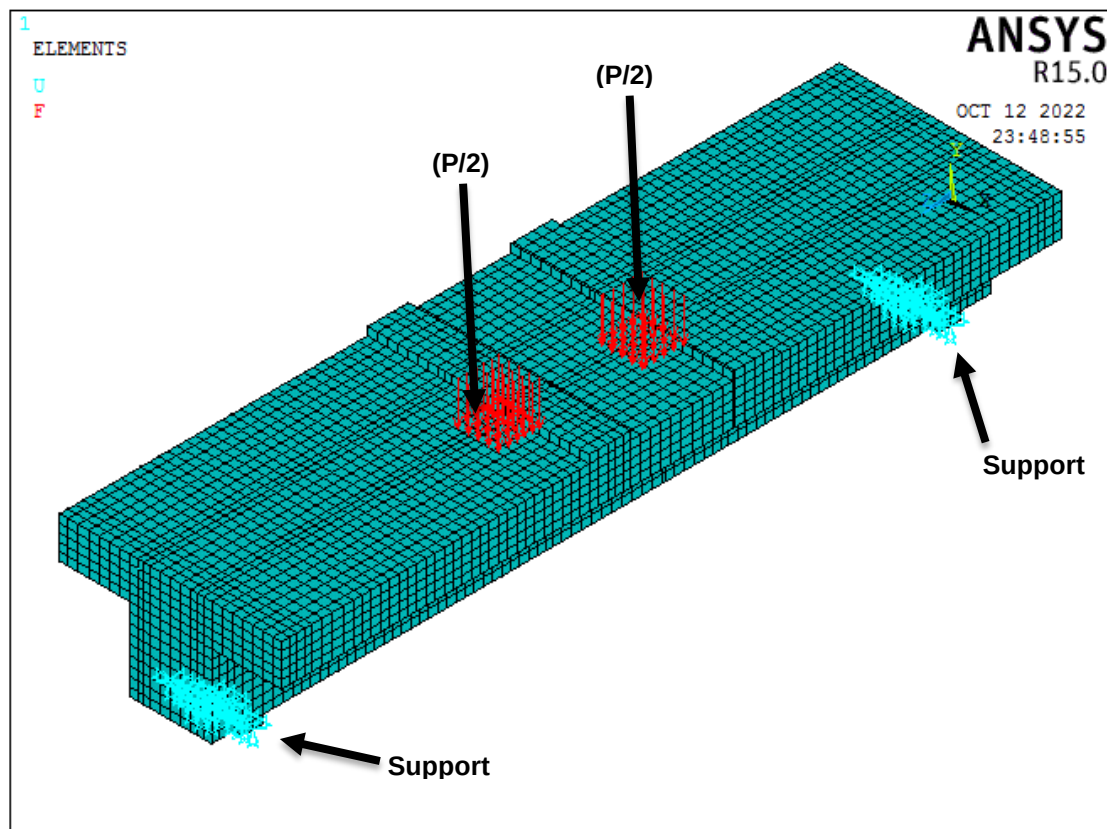


Fig. 5: Boundary conditions and loads applied to beams.

4 Validation of analytical model

The comparison consists of the tests performed by Mohamad A Hasan et al. [16] and the analytical results by ANSYS version 15. The analytical model showed valuable results regarding the behavior of the beam such as failure load, maximum central deflection, crack pattern, ductility and stiffness.

4.1 Crack patterns

Fig. 6 shows the crack pattern after failure, obtained by both the analytical and experimental results for all beams. The load was applied gradually until failure of the beam. The final failure occurred near the mid-span. The analytical results agree well with the experimental results in the crack pattern.

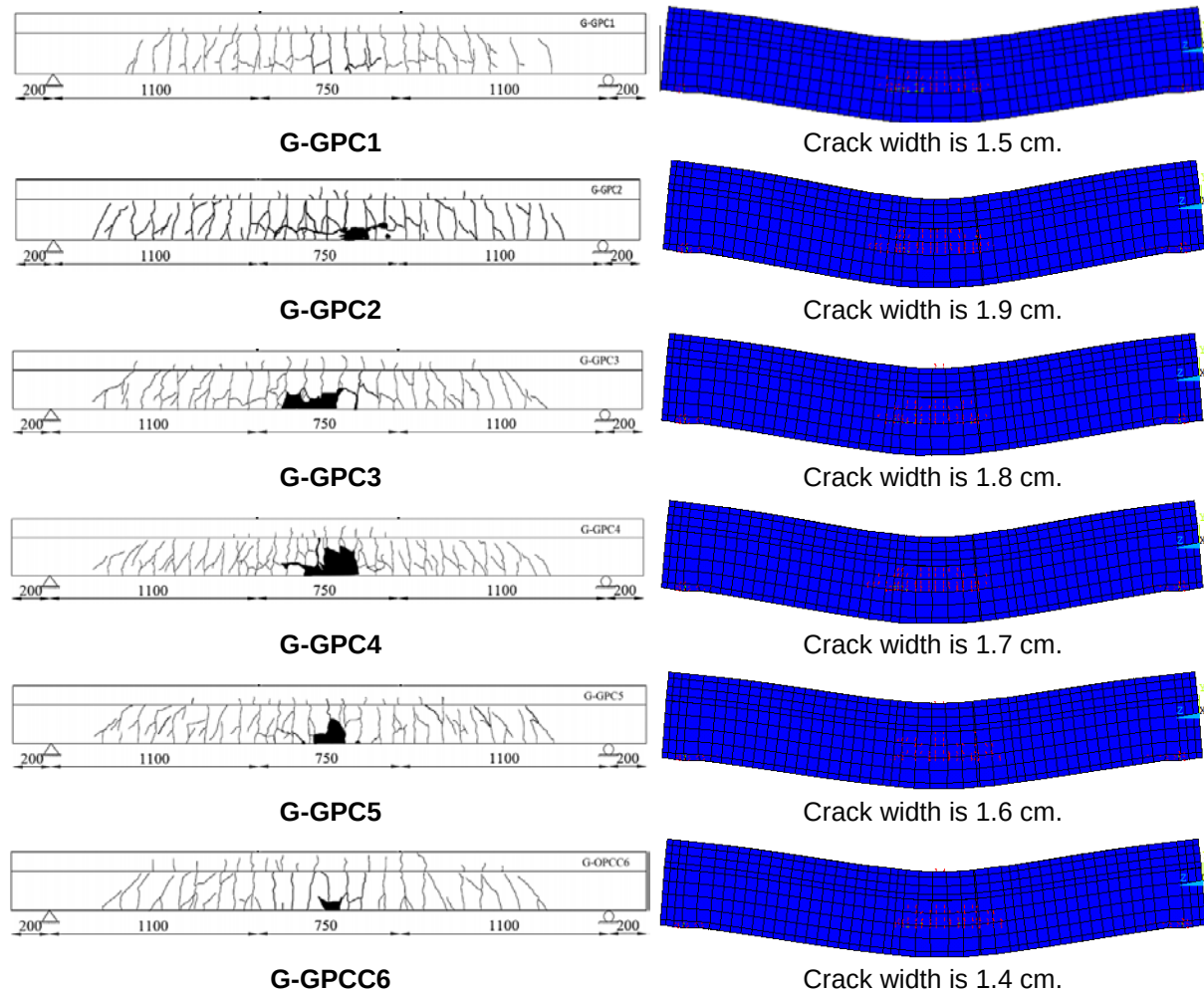


Fig. 6: Analytical and experimental crack patterns for beams.

4.2 Failure load and maximum central deflection

Tables 3 and 4 show the comparison of the failure load and maximum central deflection respectively. The results obtained by the analytical model are compared to the results obtained experimentally by Mohamad A Hasan et al. [16]. An increase in the failure load values of analytical model by approximately 8.7 % compared to the experimentally obtained one is observed. In addition, a difference in the central deflection values by 9.4 % is obtained. The deflection results for all beams are shown in Fig. 7 to 9. It can be seen that all beams had linear behavior from initial loading up to the first crack, followed by a nonlinear response after cracking.

Table 3: Comparison of the failure load results.

Specimen	Failure load [kN]		% Difference
	Proposed	Experimental	
G-GPC1	105	100.9	4.1
G-GPC2	202.5	200.9	0.8
G-GPC3	200	195.3	2.4
G-GPC4	285	269.5	5.8
G-GPC5	280	262.6	6.6
G-GPCC6	245	225.3	8.7

Table 4: Comparison of the maximum central deflection results at collapse.

Specimen	Maximum central deflection [mm]		% Difference	strains for FRP	Failure criteria
	Proposed	Experimental			
G-GPC1	74.5	82.2	-9.4	0.025	Crushing concrete
G-GPC2	81.8	88.6	-7.7	0.021	Crushing concrete
G-GPC3	85.4	91.7	-6.9	0.022	Crushing concrete
G-GPC4	88.5	95.3	-7.1	0.0195	Crushing concrete
G-GPC5	85.9	90.2	-4.8	0.02	Crushing concrete
G-GPCC6	74	77.3	-4.3	0.0225	Crushing concrete

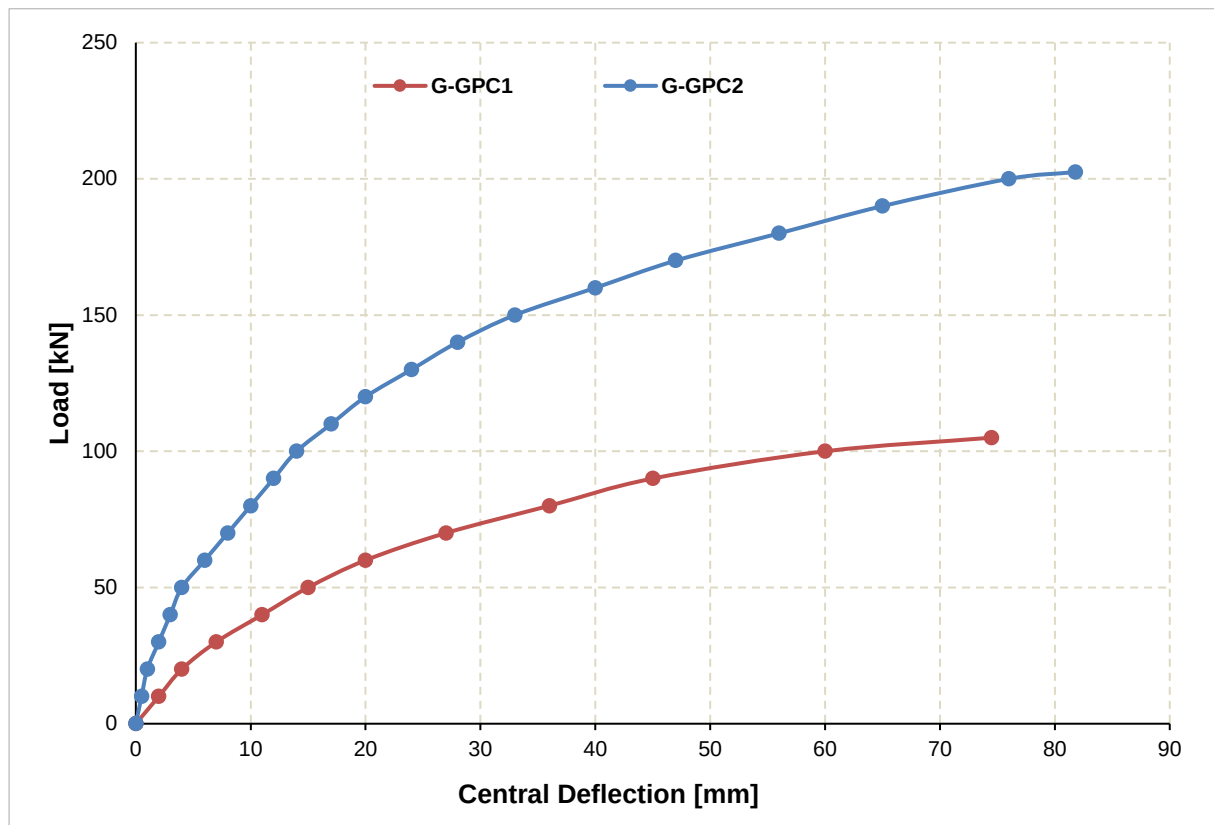


Fig. 7: Analytical load–deflection curve of specimen G-GPC1 and G-GPC2.

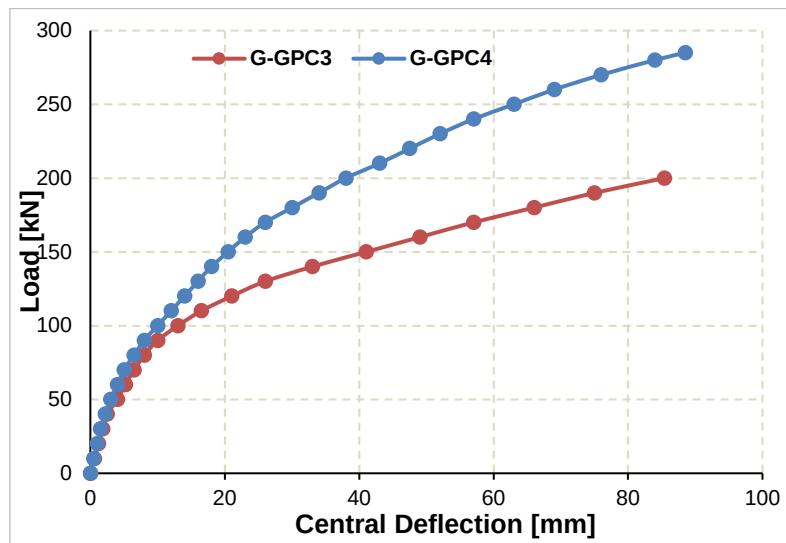


Fig. 8: Analytical load–deflection curve of specimens G-GPC3 and G-GPC4.

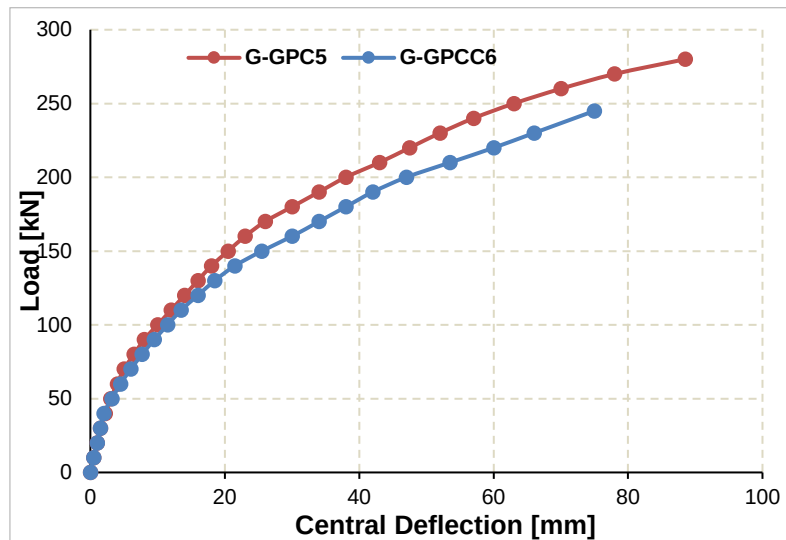


Fig. 9: Analytical load–deflection curve of specimens G-GPC5 and G-GPC6.

4.3 Ductility and stiffness

The scale of ductility is energy which equals the area under the load-deflection curve. The ductility factor is calculated as:

$$\text{ductility factor} = \frac{\text{maximum deflection}}{\text{yield displacement}} \quad (1)$$

Stiffness is a material property that means the ability of the material to resist deformation under applied load. A stiff material deforms slightly under applied loads. A rigid material is a material that never deforms slightly under applied loads. The initial stiffness is calculated as:

$$\text{Initial stiffness} = \frac{\text{load at yield displacement}}{\text{yield displacement}} \quad (2)$$

Tables 5 and 6 show the comparison of the ductility factor and initial stiffness respectively. The results obtained by the analytical model are compared to the results obtained experimentally by Mohamad A Hasan et al. [16]. A reduction in the ductility factor values of analytical model by approximately 8.6 % compared to the experimentally obtained one is observed. In addition, a difference in the initial stiffness values by 10.6 % is obtained. The analytical results are in well agreement with the experimental results.

Table 5: Comparison of the ductility factor results.

Specimen	Ductility Factor		% Difference
	Proposed	Experimental	
G-GPC1	2.80	2.83	-1.2
G-GPC2	3.55	3.74	-5.1
G-GPC3	3.65	3.86	-5.4
G-GPC4	4.05	4.21	-3.8
G-GPC5	3.70	4.05	-8.6
G-GPCC6	2.72	2.95	-7.8

Table 6: Comparison of the initial stiffness results.

Specimen	Initial Stiffness		% Difference
	Proposed	Experimental	
G-GPC1	9.21	8.33	10.6
G-GPC2	11.11	10.65	4.3
G-GPC3	10.70	10.23	4.6
G-GPC4	14.22	13.32	6.7
G-GPC5	13.51	12.97	4.2
G-GPCC6	10.41	9.5	9.6

5 Parametric Study

Due to the large number of parameters affecting the behavior of hybrid reinforced T-Beam with partial substitution recycled rubberized concrete, an extensive parametric study was performed using ANSYS version 15.

Three parameters were investigated namely: Bottom RFT, compressive strength of concrete, and the existence of opening. These specimens were divided into three groups A, B, and C where each one of these groups is assigned to study one parameter. The layout of the parameters and specimens studied are shown in Table 7.

Table 7: Layout of the parameters.

Specimens	Group	Parameter under study	Bottom RFT	Crumb rubber (C.R) [%] by volume of sand	Concrete Cube Strength [MPa]	RFT around the opening
T-1	A	Bottom RFT	2Ø10 S + 2Ø10 CFRP	0 %	46	-
T-Steel			4Ø10 S			
T-GFRP			2Ø10 S + 2Ø10 GFRP			
T-1	B	Compressive strength of concrete	2Ø10 S + 2Ø10 CFRP	0 %	46	-
T-1 (41)				5 %	41	
T-1 (35)				10 %	35	
T-1 (30)				15 %	30	
T-1 (26)				17.5 %	26	
T-1 (21)				20 %	21	
T-1 (17)				22.5 %	17	
T-1 (15)				25 %	15	
T-1	C	Solid versus opening	2Ø10 S + 2Ø10 CFRP	0 %	46	-
T -10			2Ø10 S + 2Ø10 CFRP			2Ø10 S
T -11			2Ø10 S + 2Ø10 CFRP			2Ø10 GFRF
T -12			2Ø10 S + 2Ø10 CFRP			2Ø10 CFRF

5.1 Effect of bottom RFT

To study the effect of bottom RFT on the behavior of hybrid reinforced Beam with rubber concrete, three specimens with variable bottom RFT were analyzed. The compressive strength of concrete is equal in these beams. The results of these beams are shown in Fig. 10.

Beam T-1 (reinforced by 2Ø10 Steel + 2Ø10 CFRP), Beam T-GFRP (reinforced by 2Ø10 Steel + 2Ø10 GFRP) had higher failure loads than Beam T-Steel (reinforced by 4Ø10 Steel), by 45.8 %, and 30.5 %, respectively. It can be seen that the failure load of the beam increases with bottom reinforcement by the GFRP bar or CFRP bar. Also, reinforced beams by CFRP bars had a higher failure load than reinforced beams by GFRP bars.

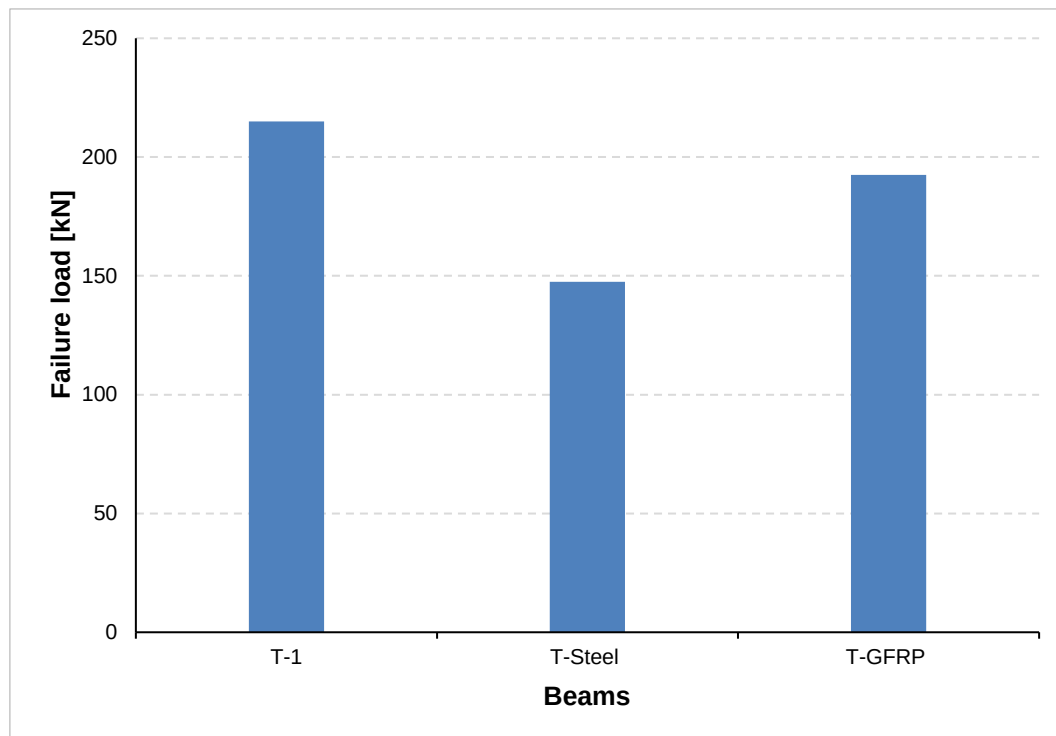


Fig. 10: Failure load for beams with different bottom RFT.

5.2 Effect compressive strength of concrete

The use of recycled rubber in the concrete mixture reduces the compressive strength f_{cu} of concrete. To study the effect of compressive strength of concrete on the behavior of hybrid reinforced Beam with rubber concrete, eight specimens with variable compressive strength of concrete were analyzed.

Beams T-1, T-1 (41), T-1 (35), T-1 (30), T-1 (26), T-1 (21), T-1 (17), and T-1 (15) reinforced by 2Ø10 Steel + 2Ø10 CFRP (bottom RFT).

Beam T-1, $f_{cu} = 46$ MPa, Beam T-1 (41), $f_{cu} = 41$ MPa, Beam T-1 (35), $f_{cu} = 35$ MPa, Beam T-1 (30), $f_{cu} = 30$ MPa, Beam T-1 (26), $f_{cu} = 26$ MPa, Beam T-1 (21), $f_{cu} = 21$ MPa, and Beam T-1 (17), $f_{cu} = 17$ MPa, had higher failure loads than Beam T-1 (15), $f_{cu} = 15$ MPa, by 88.6 %, 57 %, 40.4 %, 31.6 %, 28.1 %, 16.7 %, and 6.1 %, respectively. The results of these beams are shown in Fig. 11.

It can be seen that the failure load of the beam decreases with the increase in the use of recycled rubber in the concrete mix.

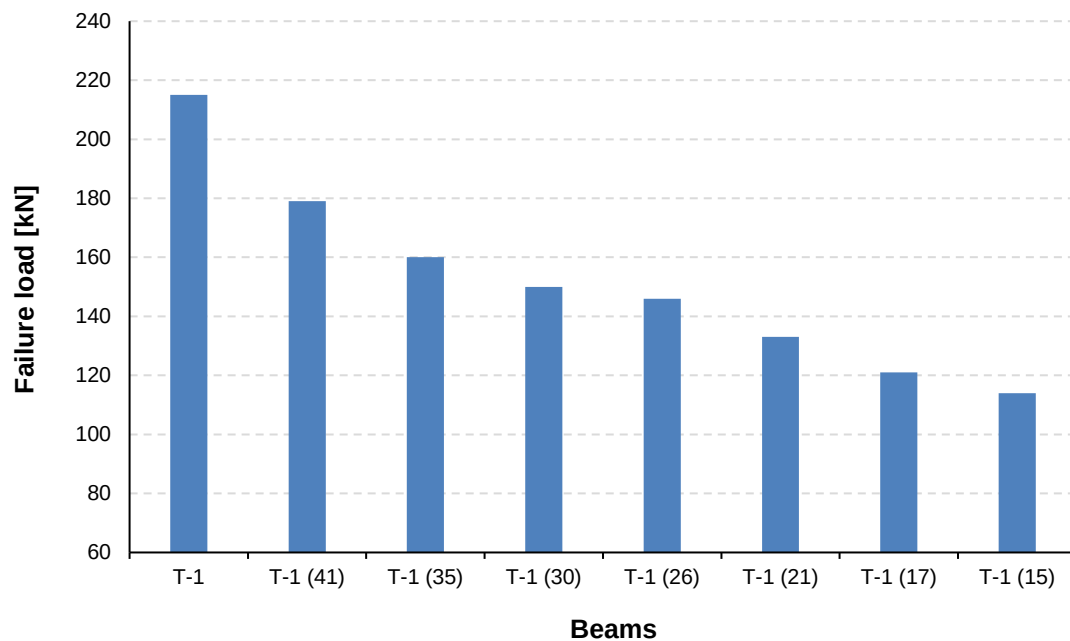


Fig. 11: Failure load for beams with different compressive strength of concrete.

5.3 Effect of the existence of opening

To study the effect of the existence of opening on the behavior of hybrid reinforced Beam with partial substitution recycled rubberized concrete, three specimens with central opening 300 x 100 mm were analyzed as shown in Fig. 12. The compressive strength of concrete and bottom RFT are equal in these beams. The results of these beams are shown in Fig. 13.

Beam T-1 (without opening), Beam T-12 (reinforced by 2Ø10 CFRP around opening), and Beam T-11 (reinforced by 2Ø10 GFRP around opening), had higher failure loads than T-10 (reinforced by 2Ø10 Steel around opening), by 50.8 %, 15.8 %, and 10.5 %, respectively.

Having an opening in hybrid reinforced T-Beam with partial substitution recycled rubberized concrete reduced the beam load capacity and maximum deflection. It can be seen that using GFRP bars, and CFRP bars in the vicinity of openings in hybrid reinforced T-Beam increased the load capacity of these beams.

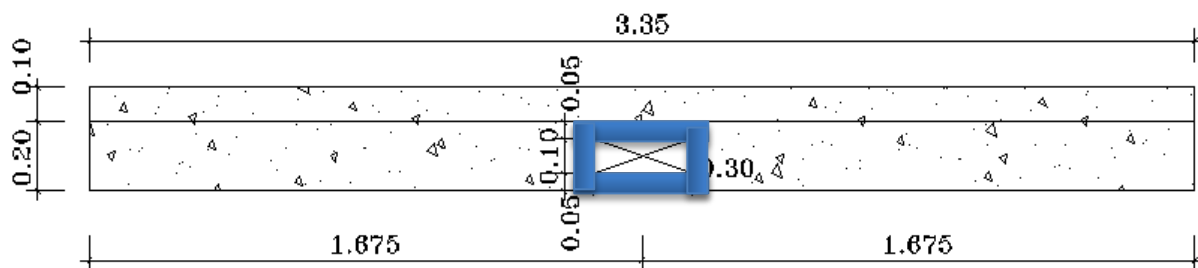


Fig. 12: Concrete dimensions of the tested specimens with opening.

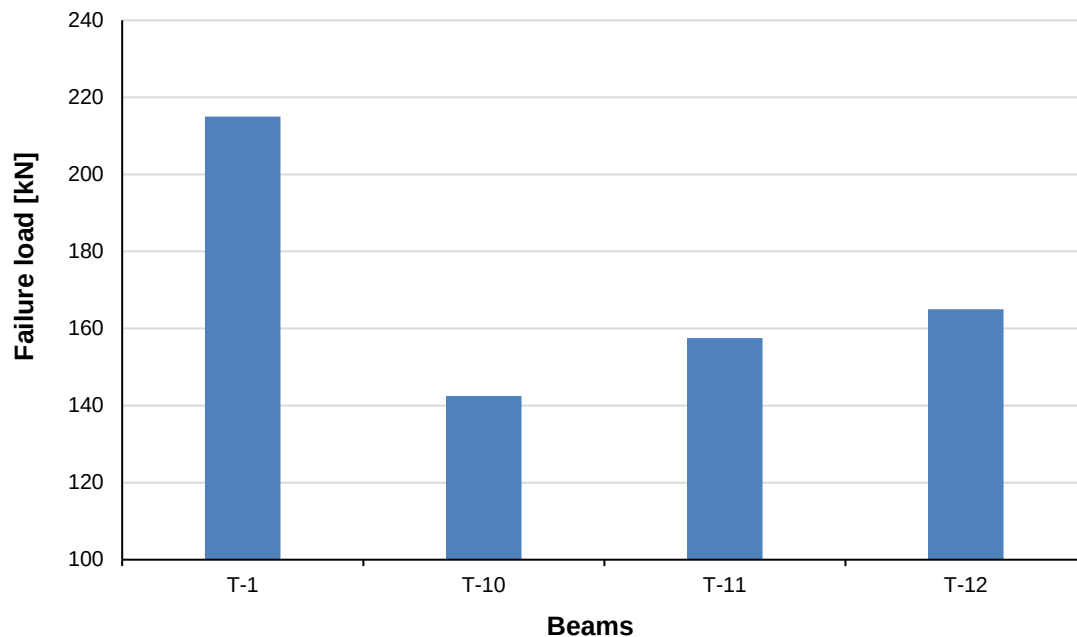


Fig. 13: Failure load for beam TCH1 (without opening) and beams with opening.

5.4 Summary

The numerical results shows that the failure load of the beam with Crumb Rubber increases with bottom reinforcement by the GFRP bar or CFRP bar and decreases with the increase in the use of recycled rubber in the concrete mix. Also, reinforced beams by CFRP bars had a higher failure load than reinforced beams by GFRP bars. Having an opening in in hybrid reinforced T-Beam with partial substitution recycled rubberized concrete reduced the beam load capacity and maximum deflection. On the other hand, using GFRP bars, and CFRP bars in the vicinity of openings in hybrid reinforced T-Beams increased the load capacity of these beams.

It can be recommended to increase the number of researches on the non-linear behavior of rubber concrete to include other parameters such as lightweight concrete and prestressed concrete.

6 Conclusion

Based on the numerical study and experimentally available result, the following conclusions were drawn:

- 1) A nonlinear analysis by ANSYS version 15 program enables a detailed understanding of hybrid reinforced T-Beam with Crumb Rubber and CFRP, leading to a good agreement when compared to available full-scale test data.
- 2) The numerical results agree well with the experimental results in the crack pattern. The pattern failure and the cracks in the tension, and compression zones of all beam were the same in both approaches.
- 3) The numerical results showed an increase in the failure load values of analytical model by approximately 8.7 % compared to the experimentally obtained one is observed. In addition, a difference in the central deflection values by 9.4 % is obtained.
- 4) The numerical results showed a reduction in the ductility factor values of analytical model by approximately 8.6 % compared to the experimentally obtained one is observed. In addition, a difference in the initial stiffness values by 10.6 % is obtained.
- 5) The failure load of the beam with Crumb Rubber increases with bottom reinforcement by the GFRP bar or CFRP bar. Also, reinforced beams by CFRP bars had a higher failure load than reinforced beams by GFRP bars.
- 6) The failure load of the beam decreases with the increase in the use of Crumb Rubber in the concrete mix.
- 7) Having an opening in hybrid reinforced T-Beam with partial substitution recycled rubberized concrete reduced the beam load capacity and maximum deflection.

8) The numerical results showed that using GFRP bars, and CFRP bars in the vicinity of openings in hybrid reinforced T-Beams increased the load capacity of these beams.

9) It is recommended to use rubberized concrete in light structural elements that are subject to low loads.

References

- [1] BATAYNEH. M. K. - IQBAL, M. – IBRAHIM, A.: Promoting the use of crumb rubber concrete in developing countries. *Waste Management*, Vol. 28, Issue 11, November 2008, pp.2171-2176.
- [2] KARA DE MAEIJER, P. - CRAEYE, B. - BLOM, J. – BERVOETS, L.: Crumb rubber in concrete – the barriers for application in the construction industry. *Innovative Solutions for Concrete Applications*, 20 August 2021, pp. 213–238.
- [3] KHALID B. - MATTHEW R.: Workability and mechanical properties of crumb-rubber concrete. *Construction Materials*, Vol. 166, Issue 1, February 2013, pp. 7-17.
- [4] PARTH, K. - TAUSIF, K.: Experimental study of crumb rubber in concrete. *GRD Journal for Engineering*, Vol. 2, May, 2017, pp. 151–155.
- [5] ABHAY, K. - SALINI, Y.: Use of crumb rubber as fine aggregate in concrete to increase the strength of concrete block. *Journal of Emerging Technologies and Innovative Research (JETIR)*, November 2017, Vol. 4, pp. 150–155.
- [6] SABIR, K. - AKANKSHA, S.: Behavior of crumb rubber concrete. *International Journal of Research in Engineering, IT and Social Sciences*, Vol. 145, February 2018, pp. 86–92.
- [7] ROMAN, C. - TOMÁŠ, T. - JOSEF, F. - PETR, B.: Mechanical properties and durability of crumb rubber concrete. *IOP Conf. Series: Materials Science and Engineering*, 236, 2017, 012093.
- [8] YANG, H. - ZHISHUAN, L. - YAQIANG, B - GUOQI, H. - DONGQIAO, L: Experimental study on the mechanical properties of crumb rubber concrete after elevated temperature. *Polymers*. 2023, 15, 3102. <https://doi.org/10.3390/polym15143102>.
- [9] OBADAT, Y. L. - HEYDEN, S. L. - DAHLBLOM, O. L. - ABU-FARSAKH, G. - ABDEL-JAWAD, Y.: Retrofitting of reinforced concrete beams using composite laminates. *Construction and Building Materials*, 25, No. 2, 2011, pp.591-597.
- [10] CHAALLAL. O. - SHAHAWY, M.: Performance of fiber-reinforced polymer-wrapped reinforced concrete column under combined axial-flexural loading. *ACI Structural Journal*, 97, No. 4, 2000, pp. 659-668.
- [11] PROTA, A. - TAN, K. Y. - NANNI, A. - PECCE, M. - MANFREDI, G.: Performance of shallow reinforced concrete beams with externally bonded steel-reinforced polymer. *ACI Structural Journal*, 103, No. 2, 2006, pp. 163-170.
- [12] HASSAN, T. - RIZKALLA, S.: Flexural strengthening of prestressed bridge slabs with FRP systems. *PCI Journal*, 47, No. 1, 2002, pp. 76-93.
- [13] HASSAN, T.: Flexural performance and bond characteristics of FRP strengthening techniques for concrete structures. PhD. thesis, University of Manitoba, Winnipeg, Canada, 2002.
- [14] YAHYA, A. - TAYEL, M. - HEIZA, K. H.: Post-tensioned reinforced concrete beams strengthened with near surface mounted technique. 2018. <https://www.researchgate.net/publication/333224510>.
- [15] ACI COMMITTEE 440: Design and construction of externally bonded FRP systems for strengthening concrete structures (ACI 440.2R-02), *ACI Manual of concrete practice*, American Concrete Institute, 2002.
- [16] HASAN, M. A. - SHEEHAN, T. - ASHOUR, A. - ELKEZZA O.: Flexural behaviour of geopolymer concrete T-beams reinforced with GFRP bars. *Structures*, Vol. 94, 2023, pp. 345–364.
- [17] MAJOR, M. - MAJOR, I. - KUČÁROVÁ, D. - KULÍNSKI, K.: Reduction of dynamic impacts in block made of concrete – rubber composites. *Civil and Environmental Engineering*, Vol. 14, Issue 1, 2018, pp. 61– 68.
- [18] SHAHJALAL, M. D. - ISLAM, K. - AHMED, T. - RAQUIB, A. A.: Mechanical characterization of fiber-reinforced rubberized recycled concrete-construction and building materials, Vol. 412, 19 January 2024, 134799.
- [19] KARUNARATHNA, S. - LINFORTH, S. - KASHANI, A. - LIU, X. – NGO, T.: Effect of recycled rubber aggregate size on fracture and other mechanical properties of structural concrete. *Journal of Cleaner Production*, Vol. 314, 10 September 2021, 128230.
- [20] SUCHARDA, O. - MATECKOVA, P. - BILEK, V.: Non-linear analysis of an RC beam without shear reinforcement with a sensitivity study of the material properties of concrete. *Slovak Journal of Civil Engineering*, Vol. 28, No. 1, 2020, pp. 33– 43.
- [21] VALAŠÍK, A. - BENKO, V. - STRAUSS, A. - TÄUBLING, B.: Reliability assessment of slender

- concrete columns at the stability failure, AIP Conference Proceedings, Vol. 1922, Art. No. 130010, 2018.
- [22] STRAUSS, A. - BENKO, V. - TÄUBLING, B. - VALAŠÍK, A. - ČUHÁK, M.: Reliability of slender columns [Zuverlässigkeit schlanker betonstützen: bewertung des stabilitätsverhaltens]. Beton- und Stahlbetonbau, Vol. 112, No. 7, 2017, pp. 392-401.
- [23] WU, L. - CHUNG C. N. - MAJOR, Z. - LAURENT, A. - LUDOVIC, N.: From sem images to elastic responses: a stochastic multiscale analysis of ud fiber reinforced composites. Composite Structures, Vol. 189, 2018.
- [24] KOZIELOVA, M. - MARCALIKOVA, Z. - MATECKOVA, P. - SUCHARDA, O.: Numerical analysis of reinforced concrete slab with subsoil. Civil and Environmental Engineering, Vol.16, No.1, 2020, pp.107-118.
- [25] SAS IP, 1999.: ANSYS theory reference release 5.6, ANSYS, INC. CANONSBURG, Pennsylvania, USA.