COMPARISON OF REINFORCEMENT METHODS WITH ADVANCED MATERIALS FOR R/C COLUMNS

UDC:624.012.45:699.841
Original scientific paper https://doi.org/10.46793/adeletters.2025.4.1.1

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Abstract:
Earthquake damage in regions with high seismic risk highlights the need for measures to improve the earthquake performance of existing structures. One such measure is strengthening these structures to bring them up to the desired performance levels. In this study, the damage to reinforced concrete (RC) buildings was examined in light of the February 6, 2023, Kahramanmaraş (Türkiye) earthquakes to identify the reinforcement needs of RC structures. Numerical analyses were conducted, considering two main factors affecting the shear force capacity in RC columns: low-strength concrete and inadequate transverse reinforcement. The columns were strengthened using four different types of fibre-reinforced polymer (FRP) wrapping, applied to all columns where the shear force was exceeded. The results for the reference building and the four different wrapping methods were compared, and suggestions were made. It was found that all four wrapping methods significantly increased the shear strength capacities of the columns without causing any failure.

ARTICLE HISTORY
Received: 16 December 2024
Revised: 9 February 2025
Accepted: 23 February 2025
Published: 31 March 2025

KEYWORDS
Column, CFRP, GFRP, AFRP, BRFP, Reinforcement, Shear force capacity, Advanced materials, Sustainable structure

1. INTRODUCTION

The large-scale structural damage and varying levels of damage caused by earthquakes highlight the importance of improving building performance. Most recently, the destruction or damage to hundreds of thousands of buildings during the February 6, 2023, Kahramanmaraş earthquakes clearly revealed that the earthquake performance of existing building stocks was below the anticipated level. Different structural systems can experience varying degrees of structural damage in regions with high seismic risk. Given the damage caused by earthquakes, especially to reinforced concrete structures – the dominant type in urban building stocks – it is evident that the earthquake performance of such existing buildings needs to be improved, demolished, or rebuilt [1-7].

The studies conducted after the earthquakes contribute to the creation of more conscious, prepared, and resilient societies against earthquakes. Research that considers the effects of earthquakes on buildings is of great importance for both individual safety and the economic and social sustainability of societies. These studies not only reduce immediate damage but also allow for managing long-term effects and constructing a safer future. In this context, determining the earthquake performance of existing buildings and upgrading buildings with insufficient earthquake performance to the anticipated level is one of the measures to be taken. This is one of the most important factors in reducing the potential loss of

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life and property in an earthquake. Engineering studies related to earthquakes have developed new methods and materials to strengthen buildings, and these developments continue. These studies are critical in terms of strengthening old buildings, constructing new buildings in compliance with earthquake regulations, and ensuring overall structural safety [8-15].

Reinforcing existing RC load-bearing systems with different element- or system-based techniques is commonly preferred. Vertical load-bearing elements are of particular importance in this context. The load-bearing capacity of vertical load-bearing members in reinforced concrete buildings directly impacts the overall load-bearing capacity of the structure and, thus, its earthquake performance. The seismic capacity of buildings can be increased by adding vertical load-bearing elements and/or increasing the size of vertical load-bearing elements, as well as by using different reinforcement methods. This study focuses on the reinforcement of columns in reinforced concrete structures with different reinforcement materials. In this study, analyses were carried out and results were compared using materials such as Carbon Fibre Reinforced Polymer (CFRP), Glass Fibre Reinforced Polymer (GFRP), Basalt Fibre Reinforced Polymer (BFRP), and Aramid Fibre Reinforced Polymer (AFRP).

CFRP has recently become a frequently used material for strengthening structures due to its high strength and lightweight. Columns, one of the most critical load-bearing elements in buildings and other structures, may weaken over time due to earthquakes, overload, or aging. Strengthening columns with carbon fibre ensures that these weak structural elements become safer and more durable. The use of carbon fibre for column strengthening is an effective and innovative method in modern civil engineering. Columns can be strengthened with carbon fibre to increase the load-bearing capacity of the structure, ensure safety, and support longevity. This method increases durability while making the structure lighter and more aesthetically acceptable [16-25].

Glass fibre is the dominant reinforcement fibre in all FRPs. GFRP is a lightweight, durable, and high-strength composite material used in civil engineering. GFRP typically consists of resin (usually epoxy or polyester) reinforced with glass fibre, and this material is often preferred for reinforcing structural elements like columns. Columns are among the most important load-bearing elements in buildings, and over time, they may experience a loss of strength due to aging, overload, or natural disasters. Strengthening columns with glass fibre-reinforced polymer can help prevent such weaknesses and improve the durability of the structure [26-30].

AFRP is a composite material with high durability and strength properties. Aramid fibre, used primarily in ballistic and military applications, is also used in the construction sector to strengthen load-bearing elements such as columns. AFRP is a composite material formed by combining aramid fibres with a polymer resin (usually epoxy or polyester). AFRP applications in column strengthening can increase the load-bearing capacity of structural elements, making the structure more durable and safe [31-34].

Basalt fibre is produced by processing natural basalt rocks at high temperatures. These fibres can be combined with polymer matrices to create composite materials. BFRP is a system used to reinforce concrete structures. Strengthening columns with basalt fibre-reinforced polymer (BFRP) is an effective method in structural engineering. This material is particularly preferred for reinforcing concrete structures due to its high strength, lightweight, corrosion resistance, and good thermal properties [35-38].

Studies show that such reinforcement applications significantly increase the shear force capacities of columns, providing higher deformation resistance under shear loads. In this study, numerical analyses were performed utilizing these four various reinforcement materials. For this purpose, analyses were first performed on a reference building model made of lowest-strength concrete (C8/10) in software [39]. The lowest-strength reinforcement material grade was selected as S220 in software [39], and the reinforced concrete structure design rules were used in Türkiye [40]. Using Seismostruct software, analyses of the reference building were conducted, and shear force capacities were exceeded in all columns. Four different fibre-reinforced polymer applications were implemented on these columns. The results obtained from these analyses were compared, and suggestions were made. Additionally, the earthquake performance of reinforced-concrete buildings was examined in light of the February 6, 2023 Kahramanmaraş earthquakes, and the strengthening needs of existing buildings were explored.

2. DAMAGES IN R/C STRUCTURES IN THE FEBRUARY 6, 2023 KAHRAMANMARAŞ EARTHQUAKES

Earthquakes can weaken, damage, or even cause the complete collapse of structures by generating forces from ground movements. The severity of the earthquake, local soil conditions, and the characteristics of the buildings directly affect the extent of the damage that occurs in a structure. The engineering properties of the existing building stock in areas affected by earthquakes, along with the adherence of structures to earthquake-resistant design principles, are the most important factors determining their durability and response to earthquakes. Therefore, proper design and construction practices ensure that buildings sustain less damage during an earthquake. The earthquakes that occurred on February 6, 2023, in Kahramanmaraş, were a major disaster affecting south-eastern Turkey. The earthquake pair, with epicentres in the Pazarcık and Elbistan districts of Kahramanmaraş, caused massive destruction and loss of life in 11 different provinces. With magnitudes of M_w=7.7 and M_w=7.6, the earthquakes occurred on the same day and in the same region, and aftershocks significantly amplified the destruction, making interventions in damaged buildings more difficult. The earthquakes caused severe destruction, particularly in provinces such as Kahramanmaraş, Hatay, Adıyaman, and Gaziantep, resulting in extensive damage to many buildings. Reinforced concrete structures, which dominate the urban building stock, were one of the main types of buildings affected by these large earthquakes. Examples of totally collapsed RC buildings are shown in Fig. 1.

Fig. 1. Totally collapsed R/C buildings.

One of the major causes of damage in RC buildings is soft/weak story damage caused by differences in stiffness and strength between stories. Such stories generally cause the structure to be unbalanced in terms of story mass and story rigidity [41-44]. In this case, total or partial collapses may occur in the stories with differences. Examples of such failure are illustrated in Fig. 2.

Fig. 2. Examples of damages caused by soft/weak story

In RC buildings, different levels of damage have been observed as a consequence of irregularities and negativities that affect earthquake performance. Examples of such damage are shown in Fig. 3.

Fig. 3. Structural damages caused by different structural negativities a) pounding effect, b) strong beam-weak column, c) short column, d) irregularity in plan, e) heavy overhang, f) lack of RC frame

The usage of low-strength concrete and insufficient transverse reinforcement in reinforced-concrete (RC) load-bearing elements, the lack or incorrect interlocking between the reinforcements, insufficient concrete cover thickness, corrosion of the reinforcements, inappropriate aggregate gradation, and the installation of different utility elements in load-bearing components have particularly caused significant damage to RC columns. For these reasons, examples of damage that occurred in RC columns are shown in Fig. 4. The presence of one or more of these negativities together has reduced the bearing capacity of R/C columns, causing the damage levels to rise to a higher level.

Fig. 4. Examples of damage to RC columns due to different reasons

In many studies where the earthquake performance of RC structures was investigated through both observational and numerical analyses after the Kahramanmaraş earthquakes, it was stated that the main reason for the damage in a large portion of the buildings in the earthquake zone was the incomplete or non-application of earthquake-resistant design rules. Additionally, irregularities and deficiencies in the buildings directly affected the level of damage. Buildings that were constructed according to earthquake-resistant design principles without irregularities or deficiencies met the required safety performance levels. The situation is no different for columns, which play a critical role in RC structures. It has been noted that the main cause of damage in RC columns is the use of low-strength concrete and insufficient transverse reinforcement. Furthermore, it was indicated that the reinforcements corroded due to insufficient concrete cover thickness, leading to a reduction in the load-bearing capacities. Installing utility elements within the load-bearing components reduced the concrete cross-sectional area, which negatively impacted the load-bearing capacity. In addition to all these studies, research conducted after other earthquakes in Türkiye has indicated that many of the country's existing structure stock does not meet sufficient earthquake performance levels. Therefore, one of the measures that can be taken to reduce structural damage and associated loss of life in the event of a future earthquake is to carry out necessary structural assessments and detailed analyses to make fast and practical decisions regarding the existing structures. Element-based and system-based strengthening can be performed to upgrade the insufficient earthquake performance of existing buildings to the anticipated performance levels [45-65]. In this study, element strengthening was carried out using different types of fibre-reinforced polymers in columns.

3. MATERIALS AND METHODS

An 8-story example reinforced concrete (RC) building model was created to compare different column wrapping methods. In the analyses conducted without any wrapping, the building was considered as the reference model. Factors such as incorrect selection of material mixing ratios used in concrete, not using the appropriate size and quality aggregate, weather conditions, unforeseen chemical interactions, poor workmanship, and insufficient curing cause the strength of concrete to decrease. To clearly observe the effects of the wrapping, the reference building model was assumed to have C8/10 concrete and S220 plain reinforcement. In the experimental studies conducted after the Kahramanmaraş earthquakes, C8/10 was obtained as the lowest concrete grade [66-69]. For the transverse reinforcement in the columns, ϕ8/300mm was selected throughout the entire column. In this model, all other structural characteristics were kept constant, and it was used as the reference building model for evaluation.

The numerical model created was assessed using pushover analysis in the Seismostruct software. Pushover analysis is a technique performed to determine the earthquake behaviour of buildings, especially under lateral loads. Such structural analyses play a significant role in evaluating the seismic performance of structures. The results of static pushover analysis provide critical information about the safety and performance of the structure. Additionally, these analyses are also used to assess the potential performance of existing structures during an earthquake. Pushover analysis was utilized as part of these numerical simulations. Earthquake-induced structural nonlinear behaviour can be evaluated using either nonlinear time history analysis or static pushover analysis. The pushover analysis technique assesses the nonlinear responses of a structure through a series of linear steps, facilitating the creation of a structural capacity curve. This method effectively monitors the damage states of a structure, showing the progression of deterioration from minor damage to complete failure. Pushover analysis offers a comprehensive view of the sequential failure process in structures, which has contributed to its widespread use among structural engineers [70-75].

Structural analyses were performed in RC structures by altering key factors that influence the insufficient shear capacity in columns, such as concrete strength and the spacing of transverse reinforcement. The numerical analyses were carried out using Seismostruct [39] software. In modelling all structural samples, force-based plastic hinge frame members (infrmFBPH) were used for the columns and beams. These elements simulate the distribution of inelastic behaviour based on force, restricting plasticity to a finite length. The number of fibres in the cross-section should be sufficient to depict the stress-strain distribution accurately [60]. For the selected sections, a total of 100 fibre elements were defined, which is adequate for this type of modelling. The plastic hinge length (L_p/L) was set to 16.67%. The selected RC structure model has three spans in each direction, with each span chosen to be 5.50 meters. In this study, columns were strengthened using four different wrapping methods. The cross-sections of the columns considered before and after strengthening are shown in Fig. 5.

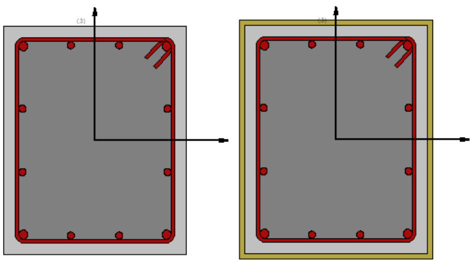

Fig. 5. Column cross-sections before and after reinforcement

The blueprint of the RC structural model and the representation of the columns are illustrated in Fig. 6.

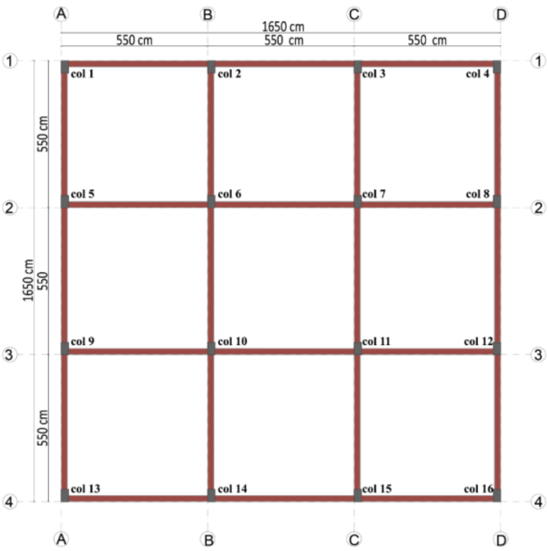

Fig. 6. The blueprint and columns of the model

The 2D and 3D visuals of the sample R/C building model are shown in Fig. 7.

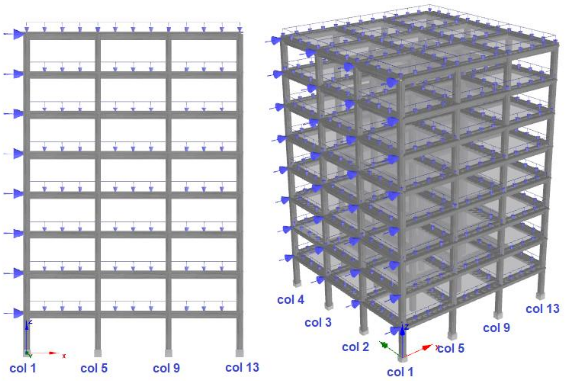

Fig. 7. 2D and 3D models of the RC structural model

The structural characteristics that remain constant in the models used for numerical analyses are shown in Table 1.

Table 1. Characteristics of the RC structural models

Parameter		Value
Concrete grade		C8/10
Reinforcement grade		S220
Beams (mm)		250x600
Height of slab (mm)		120
Each story height (m)		3
Concrete cover (mm)		25
Columns(mm)		400x500
Longitudinal bar (columns)	Corner	4Φ20
	Top and bottom	4Φ16
	Left and right	4Φ16
Stirrup (beam)		Φ8/200
Local ground type		ZA
Damping ratio		5%
Importance class		II
Target displacement (m)		0.48

The deformation status obtained for the shear force capacities after the pushover analysis of the reference building model is shown in Fig. 8.

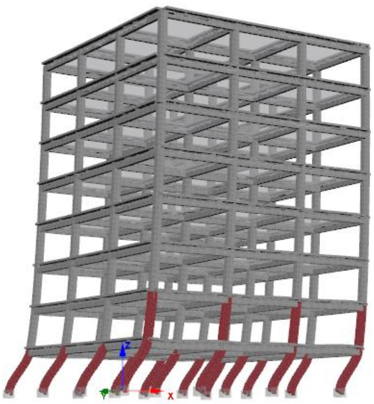

Fig. 8. Deformation status for shear force capacity

As can be seen from Figure 8, the shear force capacities of all columns on the ground story of the reference building model have been exceeded. Additionally, the shear force capacities of four columns on the second story of the example building model have also been exceeded. The comparison of the target and limit shear forces for the columns where shear forces have been exceeded are shown in Table 2. Performance ratio (PR) values have also been obtained for these columns.

Table 2. Comparison of demand and limit values in columns where shear force (kN) is exceeded

Story	Column	Reference		
		Demand	Limit	PR
1	Col 1	120.60	75.77	1.59
	Col 2	137.33	94.24	1.46
	Col 3	137.13	93.96	1.46
	Col 4	120.52	75.68	1.59
	Col 5	171.36	102.08	1.68
	Col 6	174.28	96.35	1.81
	Col 7	174.35	96.38	1.81
	Col 8	171.39	102.07	1.68
	Col 9	170.22	106.67	1.60
	Col 10	173.72	100.09	1.74
	Col 11	173.78	100.09	1.74
	Col 12	170.24	106.67	1.60
	Col 13	176.71	96.67	1.83
	Col 14	175.27	94.51	1.85
	Col 15	175.27	94.50	1.85
	Col 16	176.70	96.66	1.83
2	Col 1	68.26	67.92	1.01
	Col 5	171.28	111.44	1.54
	Col 9	172.46	111.47	1.55
	Col 13	149.93	99.44	1.51

For the reference building model, PR values were obtained above 1 in all columns where the shear force was exceeded. This clearly shows that the seismic performance of these columns is not at a sufficient level. In order to prevent this situation, it was envisaged that the elements be strengthened by using the wrapping method in the columns where the shear force was exceeded.

3.1. Strengthening Columns with Different Fibrous Reinforcement Polymer (FRP)

One of the primary goals of strengthening buildings is to improve the seismic safety of structures that do not perform well during earthquakes and to correct deficiencies that could lead to earthquake-related damage. Additionally, enhancing the seismic behaviour of existing structural elements is another effective strengthening approach. In columns, applying fibre-reinforced polymers through wrapping improves the ductility, shear strength, and compressive strength of reinforced concrete columns, particularly when the longitudinal reinforcement lap length is insufficient [76].

Strengthening RC columns with carbon fibre is an effective method to enhance the load-bearing capacity and durability of the structure. The different fibrous polymers considered in this study are shown in Fig. 9.

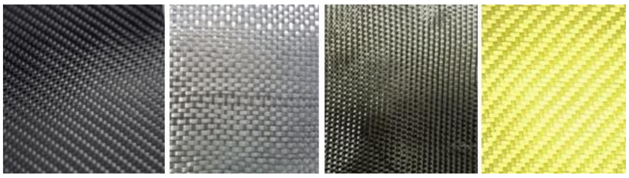

Fig. 9. Different fibrous polymers: CFRP, GFRP, BFRP and AFRP

Typical properties of different fibrous polymer types considered in this study are given in Table 3.

Table 3. Typical properties of the different FRP's

Parameter	CFRP	GFRP	BFRP	AFRP
Fibre thickness (mm)	0.331	1.016	0.215	0.200
Tensile strength (MPa)	3800	2276	4840	2231
Tensile Modulus (MPa)	242000	72413	89000	92308
Elongation (%)	1.55	2.33	3.15	2.50
Weight (g/m^2)	600	913	600	290

In the reference building model, columns with exceeded shear force capacity were strengthened using fibrous polymers. All columns on the first floor and four columns on the second floor were reinforced with fibrous polymer. While applying the fibrous polymer, continuous fibre application was considered without leaving any gaps along the column height. The pre-reinforcement and post-reinforcement views of the columns considered in the study and an application example are shown in Fig. 10. The numerical analyses were performed for each fibrous polymer, respectively. Fibrous polymers were consistently included in the analyses as a single layer. The diameter of the rounded corners of the fibres was taken into account as 40 mm. No anchoring is considered at the corners. These properties have not changed for different FRPs. No changes were made to the concrete and reinforcement conditions while applying FRP reinforcement to the existing structural model.

Fig. 10. Before/after reinforcement and application example

Afterward, structural analyses were performed separately for different types of fibrous polymers. The 2D and 3D structural models created for the strengthened column elements are shown in Fig. 11.

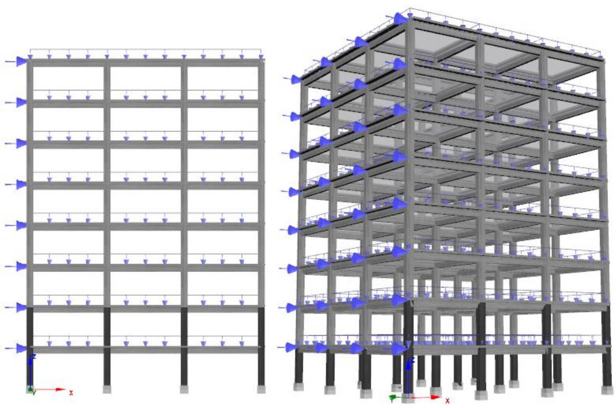

Fig. 11. 2D and 3D structural models after reinforcement

4. RESULTS AND DISCUSSION

Pushover analyses were performed separately for each selected fibrous polymer. The demand and limit shear values for each material were obtained from the code-based section of the software. The comparison of demand and limit shear forces for the structural models strengthened with different FRPs are presented in Table 4. In these analyses, the reference reinforced concrete structure model properties were kept constant.

Table 4. Comparison of demand and limit shear forces (kN) in FRP strengthened structural models

Story	Column	CFRP		GFRP	
		Demand	Limit	Demand	Limit
1	Col 1	123.88	341.81	101.29	210.68
	Col 2	119.90	345.53	94.23	208.66
	Col 3	120.44	345.76	94.27	208.66
	Col 4	123.78	342.83	101.25	210.68
	Col 5	106.69	336.59	79.64	204.35
	Col 6	98.17	336.59	67.02	198.79
	Col 7	98.56	336.59	67.28	198.79
	Col 8	107.55	336.59	79.42	204.35
	Col 9	96.10	336.59	71.56	202.83
	Col 10	86.58	334.32	47.52	198.79
	Col 11	86.52	334.32	47.41	198.79
	Col 12	97.16	336.59	71.96	201.57
	Col 13	78.17	334.32	50.42	198.79
	Col 14	67.58	328.76	40.03	195.44
	Col 15	69.13	328.76	39.99	195.44
	Col 16	79.40	334.32	50.26	198.79
2	Col 1	17.25	337.09	27.88	194.99
	Col 5	9.53	320.88	16.92	189.04
	Col 9	122.29	444.61	89.61	274.38
	Col 13	122.17	431.91	97.33	252.48
Story	Column	BFRP		AFRP	
		Demand	Limit	Demand	Limit
1	Col 1	103.58	297.30	99.29	178.68
	Col 2	95.98	296.21	92.54	174.63
	Col 3	96.03	296.73	98.05	175.52
	Col 4	103.99	297.30	109.40	180.48
	Col 5	83.02	290.97	75.44	170.75
	Col 6	70.21	285.41	60.90	166.79
	Col 7	70.81	285.41	66.26	167.39
	Col 8	83.35	290.97	88.19	170.75
	Col 9	71.18	288.19	59.70	167.99
	Col 10	49.25	285.41	45.72	164.78
	Col 11	49.27	285.41	49.74	164.53
	Col 12	72.14	288.79	71.63	167.50
	Col 13	52.88	285.41	44.01	164.53
	Col 14	41.83	282.06	35.03	162.35
	Col 15	42.03	282.06	38.06	162.35
	Col 16	53.45	285.41	54.02	165.04
2	Col 1	28.22	285.52	24.34	162.82
	Col 5	17.30	279.63	15.42	156.65
	Col 9	92.55	388.59	88.46	229.57
	Col 13	98.91	369.69	92.39	209.55

The performance ratio (PR) for different types of FRPs is given in Table 5.

Table 5. Comparison of PR for FRP's

CFRP	GFRP	BFRP	AFRP
0.362	0.481	0.348	0.556
0.347	0.452	0.324	0.530
0.348	0.452	0.324	0.559
0.361	0.481	0.350	0.606
0.317	0.390	0.285	0.442
0.292	0.337	0.246	0.365
0.293	0.338	0.248	0.396
0.320	0.389	0.286	0.516
0.286	0.353	0.247	0.355
0.259	0.239	0.173	0.277
0.259	0.238	0.173	0.302
0.289	0.357	0.250	0.428
0.234	0.254	0.185	0.267
0.206	0.205	0.148	0.216
0.210	0.205	0.149	0.234
0.237	0.253	0.187	0.327
0.051	0.143	0.099	0.149
0.030	0.090	0.062	0.098
0.275	0.327	0.238	0.385
0.283	0.385	0.268	0.441

The results clearly show that wrapping columns using different types of fibrous polymers significantly increases their shear force capacity. The PR values obtained for the shear forces of the columns in the four different wrapping methods used remained below 1. The shear force capacity was not exceeded for any column in all the wrapping methods applied. This shows that these strengthening methods can be used, especially in columns with insufficient shear force capacity. The material properties of the fibres directly affect their shear force capacity. The thickness and tensile modulus of FRPs applied continuously along the height of the columns are critical factors in the shear force capacity.

Strengthening columns with CFRP has emerged as an effective and innovative method in modern construction engineering. Columns can be reinforced with carbon fibre to enhance the load-bearing capacity of the structure, ensure its safety, and support its longevity. This method not only increases durability but also makes the structure lighter and more aesthetically pleasing. However, its applicability and effectiveness should be evaluated based on engineering analyses for each specific project.

GFRP stands out as an effective and modern method for strengthening columns. This method offers many advantages over traditional strengthening techniques, such as lightness and durability. It enhances the load-bearing capacity of columns, making structures safer and more resilient. However, certain conditions and costs should be considered during the application process. With proper engineering analyses, GFRP column reinforcement provides a safe and sustainable structural solution in the long term.

AFRP is another effective and modern method for column strengthening. AFRP, with its advantages such as high strength, lightness, chemical resistance, and flexibility, can improve column performance under seismic and other dynamic loads, making the structure safer and more durable. However, ensuring proper application conditions and considering the cost is essential. AFRP column reinforcement offers an effective solution that increases the durability and safety of structures over the long term.

Strengthening columns with BFRP is a modern and effective solution that enhances the durability of concrete structures. This method increases the load-bearing capacity of columns, provides resistance to corrosion, and reduces maintenance costs in the long term. It is particularly suitable for urban transformation projects and older buildings.

5. CONCLUSION

Earthquakes in regions with high seismic risk clearly highlight the importance of evaluating and deciding on the existing building stock. In this study, numerical analyses were conducted based on the damage observed in reinforced concrete (RC) structures after the Kahramanmaraş earthquakes on February 6, 2023, focusing on low-strength concrete and inadequate reinforcement choices, which are the primary causes of damage in columns. Based on these observations, a structural model was created, and column strengthening was performed using a wrapping method where the shear capacity was exceeded. Structural analyses were then repeated, considering four commonly used wrapping methods. It was found that all four wrapping methods significantly increased the shear strength of the columns.

The applicability and effectiveness of these strengthening methods, or their combination, in a project should be evaluated based on engineering analyses. Factors such as economic considerations, limitations of use, and application requirements must also be taken into account.

Among the four different fibre-reinforced polymer strengthening methods considered in this study, the highest shear forces were achieved with CFRP, which had the highest modulus of elasticity. Additionally, the effects of the thickness of the fibre-reinforced polymers and other material properties should not be overlooked.

Acknowledgements

The results presented in this scientific paper have been partially obtained through the research activities within the project 2023-1-HR01-KA220-HED-000165929 Intelligent Methods for Structures, Elements, and Materials (https://im4stem.eu/en/home/ accessed on June 4, 2024) co-funded by the European Union under the program Erasmus+ KA220-HED-Cooperation partnerships in higher education.

Conflicts of Interest

The authors declare no conflict of interest.

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