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A STUDY ON STRENGTHENING RC STRUCTURAL ELEMENTS WITH FIBERS-BASED POLYMERS

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ABSTRACT

The structural damage and destruction after the devastating earthquakes bring the importance of the seismic performance of existing structures and the precautions to be taken regarding such structures to the agenda. The different levels of damage and destruction that occurred in reinforced-concrete (RC) structures after the earthquakes reveal that the earthquake performances of these structures are not at a sufficient level. Different reinforcement techniques and materials can be used to increase the seismic performance of existing structures compared to the predicted seismic performance. Insufficient transverse reinforcement used to resist the shear force in RC columns and beams and low concrete strength play a critical role in the damage in these elements. New technologies and advanced materials can be used to increase the earthquake performances of such structural elements. Within the scope of this study, firstly, element-based shear force capacities were obtained for an RC beam and column using steel and aramid fiber materials. In addition, in a selected sample RC structure, steel and aramid fiber was applied only to the columns and the results were compared. The results obtained reveal that these fibers significantly increase the shear force capacity.

Keywords: Aramid, Reinforced-concrete, Shear capacity, Steel, Strengthening.

1 INTRODUCTION

Large-scale structural destruction and damage following devastating earthquakes that occurred in regions with high seismic risk such as Türkiye bring to the agenda the measures that can be taken by determining the seismic performance of existing structures. The decisions to be made for existing RC structures, which are the dominant building stock of urban settlements, will play a critical role in the loss of life and property that may occur in a possible earthquake. After detailed earthquake performance analyses are carried out for existing structures, decisions such as demolition, reinforcement, and reconstruction can be made to increase the earthquake safety of existing structures. The destruction and damage following the Kahramanmaraş earthquakes that occurred on February 6, 2023, are sufficient to reveal the importance of this issue. In RC structures, the incomplete or complete lack of application of earthquake-resistant structural design principles, especially during the implementation phase, directly affected the level of damage [1]-[5].

The structural destruction and damages that occur after devastating earthquakes cause the focus to be on the studies carried out to bring the seismic performances of existing structures to the expected level. The weaknesses that occur as a result of not applying earthquake-resistant structural design principles in the load-bearing elements of RC structures, which constitute a large part of the urban building stock, can cause these elements to be damaged more easily and quickly. The effects of earthquakes on structures can directly determine the level of structural damage, such as the components of ground motion, acceleration, velocity, displacement, frequency content, magnitude and duration. Earthquakes of the same magnitude can lead to different damage results depending on factors such as local soil conditions, quality and structural characteristics building stock and regional engineering practices. The characteristics of the structural elements in RC structures can also affect the damage, following earthquakes. The vulnerability of columns and beams, which are important structural elements of RC structures, during an earthquake, depends on the dimensions and properties of the concrete and reinforcement [6]-[15].

Post-earthquake studies contribute to the formation of societies that are more conscious, prepared, and resilient against earthquakes. Studies that take into account the effects of earthquakes on buildings are of great importance in terms of both individual safety and the economic and social sustainability of societies. These studies not only reduce immediate damages but also enable the management of long-term effects and the construction of a safer future. One of the studies to be carried out on the existing building stock after earthquakes is the repair and reinforcement of structures. Different engineering methods and materials are used to strengthen structures. These studies are of critical importance in terms of strengthening old buildings, constructing new buildings in accordance with earthquake regulations, and ensuring general structural safety [16]-[23].

One of the reasons for damage in columns and beams is the exceeding of the shear force capacities of these elements. The shear force capacities of columns and beams forming RC structures are an important factor that directly affects the structural capacity of the structure. The shear force effect, which is calculated differently for each load-bearing element, plays a critical role both in the design and under-construction stages. Although the structural elements were designed following the earthquake-resistant structure design principles in the project phase, incomplete and faulty applications in the implementation phase caused the structural elements to be damaged by exceeding their load-bearing capacity. Damages based on elements negatively affect the total seismic performance of the structure and may cause destruction or structural damage at different levels. To prevent these structural damages and demolitions that occur after an earthquake and to keep structural losses at low levels in a possible earthquake, strengthening existing structures based on elements and/or systems is one of the precautions that can be taken before a disaster.

Reinforcement in RC structures can be done on an element or system basis. With the reinforcement of vertical load-bearing elements in RC structures, the stability problems of the structures can be reduced to the minimum possible levels. The load-carrying capacity of the vertical load-bearing elements in RC structures directly affects the overall load-carrying capacity of the structure and therefore its earthquake performance. The seismic capacity of buildings can be increased by adding vertical load-bearing elements and/or increasing the dimensions of the vertical load-bearing elements and/or also using different reinforcement methods. This study is about the reinforcement of columns in RC structures with steel and aramid fiber fabrics.

Today, with the developing construction technologies and materials, more effective reinforcement methods have begun to be used in structures. Traditional reinforcement methods have begun to give way to modern reinforcement techniques and materials [24]-[29]. One of these materials, steel, and aramid fibers, are the main subject of this study. Using steel and aramid fibers, the shear force capacity was obtained and compared separately for both the element and the entire structure.

The aim of the experimental and theoretical strengthening studies carried out using different types of materials in RC columns is to increase the bending, shear, and axial force capacities of the columns. Studies on increasing the bearing capacity of columns by using materials such as Carbon Fiber fiber-reinforced polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), Basalt Fiber Reinforced Polymer (BFRP), and Aramid Fiber Reinforced Polymer (AFRP) reveal the usability of such materials for reinforcement [30]-[41]. Steel fiber fabrics are one of the high-strength materials that are being used today as reinforcement materials in reinforced concrete structures. Such reinforcement materials are more widely preferred in the reinforcement of RC structures.

In recent years, steel fiber reinforced concretes and steel fiber polymers have emerged as a remarkable alternative in this area. Research on the potential of steel fibers to improve the mechanical properties of concrete and thus increase the resistance of structures against shear forces is increasing. Steel fibers are components that can be homogeneously distributed in concrete and are generally composed of short, thin wires. Steel fiber fabrics are composite materials obtained by combining these fibers in a woven or knitted form. Such fabrics can be applied to concrete to make columns and other structural elements more resistant to shear forces. RC columns can be weak against shear forces, which can endanger the safety of structures. Steel fiber reinforcement stands out in the literature as an effective method to eliminate this weakness. It investigated the effect of steel fibers in increasing the shear capacity of reinforced concrete columns and found that the shear resistance of columns was significantly improved with the increase in the fiber ratio. In addition, it has been noted that the fibers provide a more uniform resistance to shear force by controlling the cracking behavior of concrete [42]-[45].

Having high strength properties and lightweight, aramid fibers are widely preferred in the reinforcement of concrete and RC elements. In addition to these properties, low elongation capacity and good impact absorption properties reveal the applicability of this material in reinforcement. In addition, the resistance of these materials to corrosion allows them to be used in elements to be made in areas exposed to corrosion. Like every building material, aramid fibers have some weaknesses. In particular, its high cost and sensitivity to ultraviolet rays can be considered as disadvantages for this material [46]-[51]. Theoretical and experimental studies evaluating the reinforcement using aramid fibers are available in the literature. Melchiors et al. [52] investigated the properties of beams using microfiber materials both experimentally and numerically. Rebouh et al. [53] tried to determine the strength of concrete reinforced with aramid fibers by machine learning. Yin [54] examined the stress distribution of aramid fibers in concrete in his study. Gnanamoorthy et al. [55] evaluated the mechanical properties of concrete obtained by using aramid and carbon fiber. Çakır et al. [56] examined the effect of different hybrid reinforcement materials on the mechanical properties of concrete. These and similar studies reveal the usability of this material in reinforcement processes.

Steel and aramid fiber polymers are seen as promising materials for increasing column shear force capacity. Studies have shown that steel and aramid fibers are particularly effective in increasing the shear strength of columns. However, further research is required to fully evaluate the performance of steel and aramid fiber fabrics. Within the scope of this study, Φ8/300mm was selected as the insufficient transverse reinforcement spacing for an RC structure model selected as an example. In structural analyses performed using pushover analysis, steel, and aramid fiber fabric were applied to columns whose shear force capacity was exceeded, and the analyses were re-performed. The obtained shear force capacities were compared and the results were interpreted. In the study, sample images of damages caused by insufficient transverse reinforcement in the February 06, 2023 earthquake were added, and the need for reinforcement in columns was demonstrated. In addition, within the scope of this study, the reinforcement process was theoretically carried out using element-based steel and aramid fiber for an RC column and a beam. The shear force capacities of the elements before and after reinforcement were compared for both the beam and column elements. The study differs from other studies in that it numerically investigates the effect of reinforcement with aramid and steel fiber polymer on the shear force capacity both on an element basis and in the entire structure.

2 MATERIAL AND METHOD

In RC structures damaged on February 06, 2023, Kahramanmaraş and similar earthquakes, it is seen that insufficient transverse reinforcement spacing in load-bearing elements is one of the main reasons for damage. Insufficient transverse reinforcement in columns and beams can cause structural damage at different levels. Determining the seismic behavior of structures under the effect of shear force has an important place in the design of RC structures. Insufficient transverse reinforcement can lead to serious structural problems, especially in structural elements exposed to high loads such as columns. Investigating such damages and taking the necessary precautions is of great importance in terms of structural safety and durability [57]-[67].

Insufficient transverse reinforcement spacing, low material properties, and insufficient concrete cover thickness cause RC structural elements to exhibit less earthquake resistance against shear forces. One or more of these negativities together can easily cause the elements to crack, crush, and break, especially when exposed to high shear forces. In this case, elements may begin to crack over time under the effect of loads, and fractures and deteriorations occur on the surface of the concrete. Cracking can be observed more rapidly in columns, especially under dynamic loads such as earthquakes. Lack of transverse reinforcement can weaken the buckling capacity of columns. This poses a serious risk, especially for long columns.

Insufficient reinforcement spacing can disrupt the stability of the column and make it more prone to buckling or deformation. Columns are one of the most critical load-bearing elements of structures. Insufficient transverse reinforcement spacing negatively affects the carrying capacity of these elements and can cause the column to deform prematurely at weak points. This can lead to structural instability and increase the risk of collapse, especially under heavy loads. For these reasons, examples of damage to reinforced concrete columns following the Kahramanmaraş earthquakes are shown in the Figure 1.

Figure 1. Damage to the RC columns due to various reasons.

Following the Kahramanmaraş earthquakes, different levels of damage occurred in RC beams due to reasons similar to those in RC columns. In particular, inadequate transverse reinforcement and low strength concrete were the main causes of damage in beams. Examples of damage to RC beams due to these reasons are shown in Figure 2.

Figure 2. Damage to the RC beams due to various reasons.

In this study, firstly, shear force capacities were compared as a result of element-based reinforcement. Seismosoft-FRP Designer [68] software was used for reinforcement with aramid fiber in the RC column and beam considered. In this study, two variables were taken into consideration, namely insufficient transverse reinforcement and low strength concrete, which are the main causes of damage in columns and beams. While the low-strength concrete C8/10 class was considered as the concrete class, Φ8/350 mm was selected as transverse reinforcement in both column and beam. The column and beam cross-sections that are the basis for reinforcement are given in Figure 1.

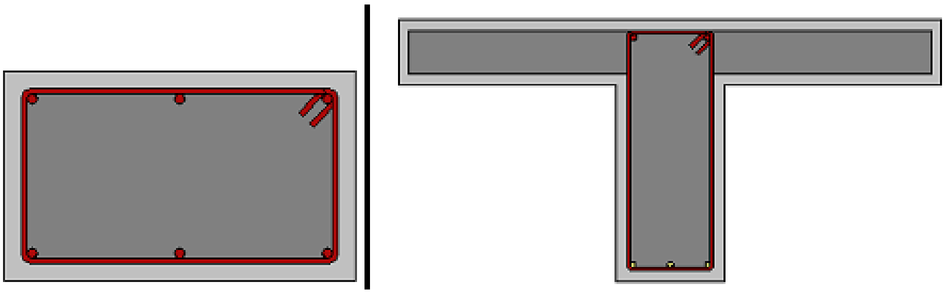

Figure 3. Cross sections of columns and beams considered in the study.

This model, which was obtained without any reinforcement, was accepted as the reference model. Steel and aramid fibers were used to increase the shear force capacity in both the column and the beam. In element-based reinforcement, the width of steel aramid fibers was considered as 300 mm and the spacing as 500 mm. These values were kept constant in both RC beams and columns. A single layer was considered in the reinforcement works in both carrier elements. The fibers used to increase the shear force capacities of the columns and beams considered in the study are shown on the elements in Figure 4.

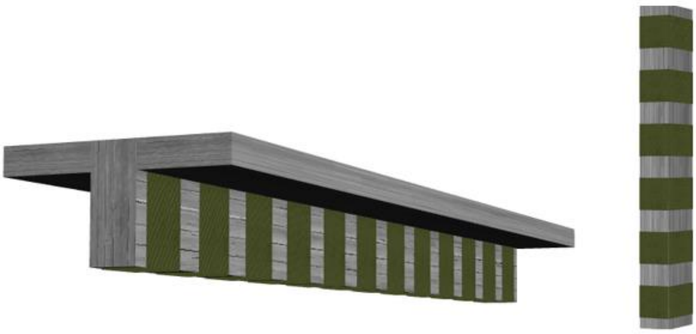

Figure 4. Models created for steel and aramid fiber reinforced RC beam and column.

In the same order of element-based reinforcement, a 6-storey RC building example was considered within the scope of this study. The structure is symmetrical and consists of three openings, each 5 m in both X and Y directions. In the building model where C25-B420C was selected as the material, each story height was considered as 3 m. Structural analyses were made using the pushover analysis in the Seismostruct-2025 [69] software. The formwork plan and 2- and 3-dimensional models obtained for the structural model considered are shown in Figure 5. The structural model considered does not contain any irregularities and represents mid-rise reinforced concrete structures.

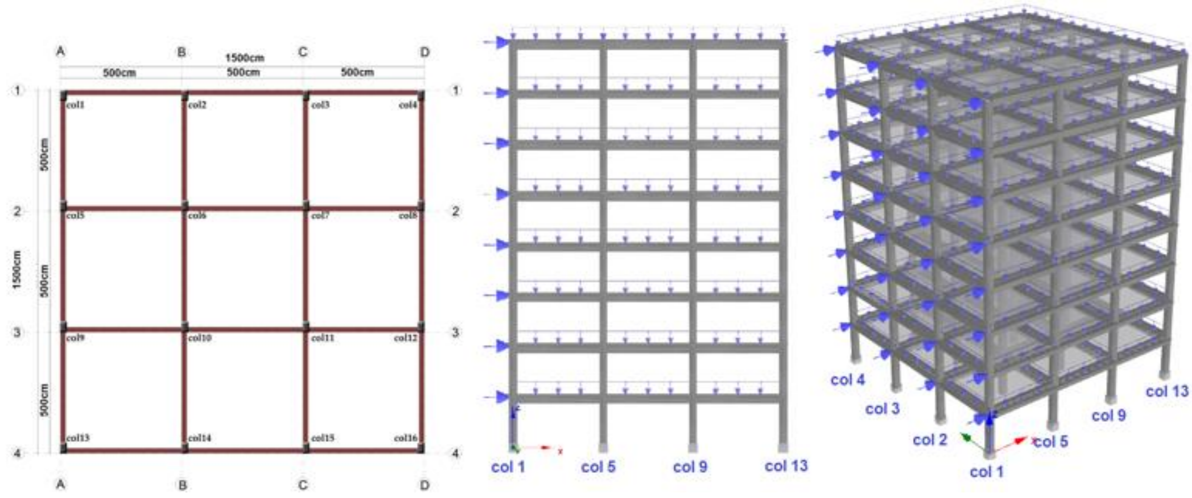

Figure 5. The blueprint, 2D and 3D models for the sample RC structure.

Only columns were taken into consideration in the reinforcement of the entire structure. The column cross-sections obtained before and after reinforcement for the effect of steel and aramid fiber polymers on the shear force capacity of columns are shown in Figure 6. It has been assumed that these fibers will be used throughout the column in both reinforcements to be applied as a single layer.

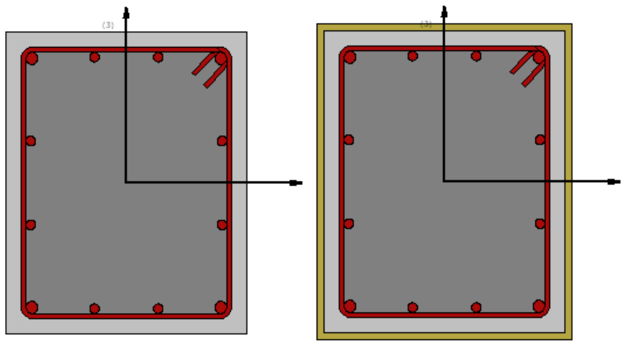

Figure 6. Column cross-sections before and after reinforcement.

Properties of steel and aramid fibers used for reinforcement in columns are shown in Table 1.

Table 1. Properties of fiber polymers.

Parameter	Aramid	Steel
Fiber thickness	0.200 mm	0.2660 mm
Tensile strength	2231 MPa	2580 MPa
Tensile Modulus	92308 MPa	200000 MPa
Elongation	2.50 %	1.29 %
Weight	290 gr/m^2	2000 gr/m^2

The structural characteristics considered in the RC structural model selected as an example are given in Table 2.

Table 2. Structural properties of sample RC model.

Parameter		Value
Concrete		C25
Reinforcement		B420C
Beam (mm)		250*600
Height of floor (mm)		120
Story height (m)		3
Thickness of concrete (mm)		25
Columns (mm)		400*500
Longitudinal reinforcement (Columns)	Corner	4Φ20
	Top-bottom	4Φ16
	Left-right	4Φ16
Transverse reinforcement (beam)		Φ8/200
Damping ratio		5%
Importance class		II

The structure considered without using any fibrous polymer was accepted as the reference building model. In the structural analyses performed for the reference building model, aramid and steel fibers were used separately to strengthen the columns where the shear force was exceeded. Reinforcement was carried out only for RC columns whose shear force capacity was exceeded for both different fiber materials. Reinforced RC column elements and 2, 3-dimensional models obtained for this are shown in Figure 7. In the columns shown in green, both steel and aramid reinforcement were done separately.

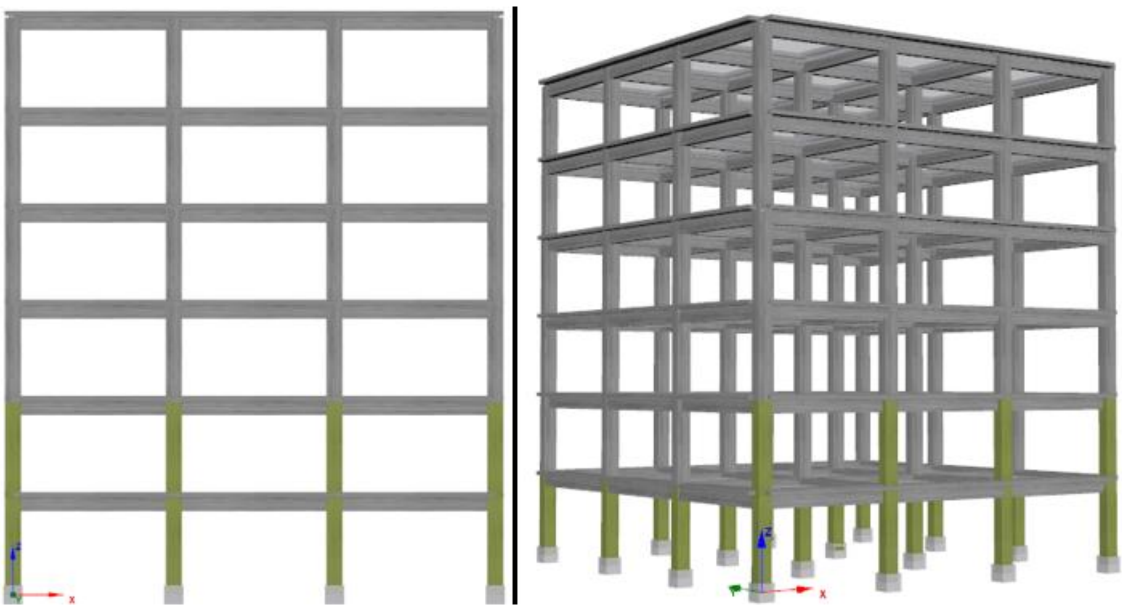

Figure 7. Reinforced columns and their 2, 3D models.

3 RESULTS AND DISCUSSION

In the results section, firstly the effects of element based reinforcement on shear force capacity were tried to be revealed. Then, the analysis results were compared considering the whole structure.

3.1 Comparison of Element-Based Reinforcement Results

Shear force capacities for all element models considered within the scope of the study were obtained according to EC8-fib90 [70]. The comparison of shear force capacities before and after reinforcement in the columns and beams considered in this study is given in Table 3. The model without any reinforcement was accepted as the reference model.

Table 3. Comparison of shear force capacities obtained for RC column and beam.

Model	Aramid		Steel	
	Shear force capacity (kN)	Change (%)	Shear force capacity (kN)	Change (%)
Reference (Column) (X)	22.18	0	22.18	0
Reference(Column) (Y)	47.45	0	47.45	0
Reinforced column (X)	43.83	98	52.47	137
Reinforced column (Y)	95.80	102	118.03	149
Reference (Beam)	38.46	0	38.46	0
Reinforced beam	62.57	63	76.81	100

Shear force capacities increased significantly in element-based reinforcement using steel and aramid fibers. The increase rate was more than 50% in both columns and beams. This increase would be much greater if the fibrous polymers were applied continuously. In the element-based reinforcement considered in the study, fibers were applied intermittently.

3.2 Comparison of Whole Structural Model-Based Reinforcement Results

In the study, firstly, numerical analyses for the reference building model were carried out using pushover analysis. For the reference building model, the transverse reinforcement spacing was selected as Φ8/350mm for all RC columns in the structural model. The columns where the shear force capacities were exceeded after the pushover analysis for the reference building model are shown in Figure 8. Red color indicates columns where shear force capacity is exceeded.

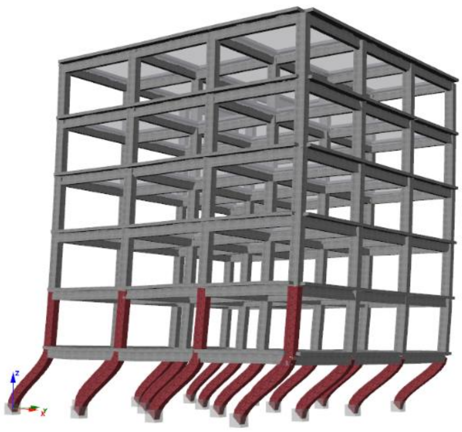

Figure 8. Shear deformation condition for the reference building model.

As can be seen from Figure 8, the shear force capacity of all columns on the first story was exceeded, while the shear force capacity of only four columns on the second story was exceeded. There was no exceedance on the other stories, and the shear force capacity of a total of twenty columns was exceeded in the structural model.

One of the main goals of strengthening buildings is to improve the seismic safety of structures that do not perform well during earthquakes and to correct deficiencies that may lead to earthquake-related damage. In addition, improving the seismic behavior of existing structural elements is another effective strengthening approach. In columns, the application of fiber-reinforced polymers by wrapping improves the ductility, shear strength, and compressive strength of RC columns, especially when the longitudinal reinforcement floor length is insufficient. 2D and 3D images of the deformation states obtained for the shear force capacity obtained after reinforcement are shown in Figure 9. Since the deformation caused by shear force is the same in both strengthening methods, a single figure was used to illustrate. Different colors indicate reinforced columns with fibers. In case of any exceedance, as in the reference building, the column colors become red. There is no red column because there is no exceedance.

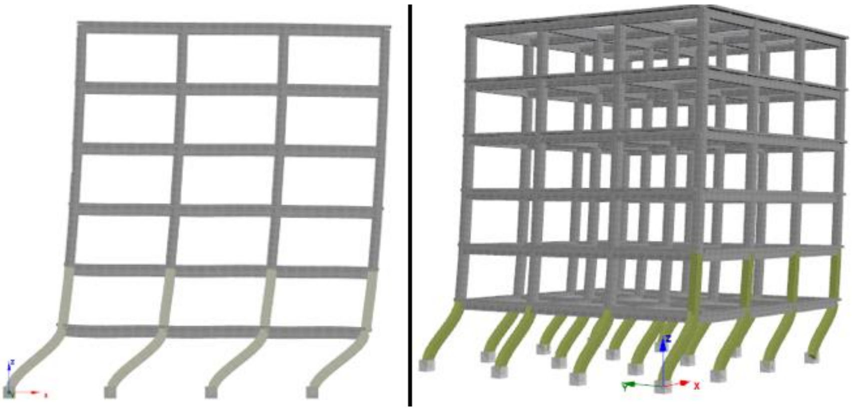

Figure 9. Deformation condition for the shear force capacity obtained after the proposed reinforcement.

As can be seen from Figure 9, there is no column whose shear force is exceeded after the reinforcement using steel and aramid fibers.

4 CONCLUSION AND SUGGESTIONS

06 February 2023 Kahramanmaraş centered and similar earthquake damages in RC structures reveal the necessity of precautions that can be taken regarding existing structures. Different reinforcement techniques and materials can be used in structures to bring the earthquake performances of existing structures to the expected level. Within the scope of this study, reinforcement was made by using steel and aramid fiber polymers in columns with insufficient transverse reinforcement. The analysis results obtained revealed that steel and aramid fiber polymers significantly increase the shear force capacities of columns.

The structural damage and destruction that occur after earthquakes reveal that the earthquake safety of existing structures is not at the expected level. One of the precautions that can be taken before a disaster within the scope of modern disaster management is to strengthen existing structures and make them meet the expected seismic performance levels. The basic stages of strengthening applications are collecting as much detailed information as possible about the existing structure before strengthening, proposing a strengthening method, and checking whether the proposed strengthening method provides the expected performance level of the structure. The last stage is to fully implement the envisaged strengthening project and check it. In this context, structural damage can be minimized in a possible earthquake by obtaining the earthquake performances of reinforced concrete structures that constitute a large part of the locality units' building stock as specified in the earthquake regulation and deciding on the strengthening method and implementing it. In this context, the earthquake safety levels of structures can be increased to higher levels by using different strengthening techniques and materials.

Within the scope of this study, it was tried to reveal the effect of shear force capacities on both element and entire structure models using steel and aramid fibers, one of the current materials. Shear force capacities of elements increased significantly with reinforcement made with steel and aramid fibers both in column and beam models created based on element and for the entire structure. Shear force is an important factor affecting the carrying capacity of both RC columns and beams. If columns and beams are designed correctly and sufficient reinforcement is added against shear force, the safety of the structure can be ensured. Correct calculation of shear force and appropriate design will ensure the long life and safety of the structure. It reveals that such materials are ideal materials for reinforcement. One of the points to be considered here is that in reinforcement applications to be made with these materials, it is important to apply them as recommended by the manufacturers and to perform these applications by experts in the field. However, the applicability of fibrous polymers requires a design process shaped by factors such as cost, structural integration, and long-term performance. Steel, aramid fiber, and similar materials are some of the strong and effective material options in the reinforcement of reinforced concrete structures. Their high strength, lightweight, and corrosion resistance make them a preferred choice for structural reinforcements. However, choosing the right design and appropriate methods during application maximizes the effectiveness of the reinforcement application. Accurately knowing the reasons for the low seismic performance of existing structures will allow the reinforcement method to be applied and recommended to be more realistic.

Structural reinforcement techniques with aramid and steel fibers offer different advantages and limitations in terms of cost effectiveness, durability and constructability. Steel fibers are widely preferred due to their relatively low initial costs and high resistance to fire, but they can increase maintenance costs in the long term due to their sensitivity to corrosion. On the other hand, aramid fibers stand out with their superior mechanical and environmental properties such as high tensile strength, lightness and chemical resistance, but their high material and application costs and limited fire resistance limit their areas of use. In this context, choosing the appropriate fiber type by considering the structural needs, environmental conditions and economic constraints of the reinforcement project is of critical importance for the success of the project.

Evaluating the effect of reinforcement techniques on the ductility and collapse behaviour of structures is important for a comprehensive analysis. It is known that reinforcements made with aramid and steel fibers not only increase the bearing capacity but also significantly affect the ductility and energy absorption capacity of structures. Therefore, the application of different fiber types can directly affect the ultimate collapse mechanism of the structure and plays a critical role especially in seismic performance evaluations. In future studies, it will be useful to examine the different ductility levels that occur depending on the fiber type in more detail with experimental and numerical analyses in order to optimize the reinforcement strategies.

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Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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