Periodica Polytechnica Civil Engineering, 68(2), pp. 608–624, 2024

Experimental and Numerical Investigation of the Seismic Performance of RC Moment Resisting Frames

Javad Esfandiari[1*], Mehrzad Tahmouli Roudsari[1], Soheil Esfandiari[1]

[1] Civil Engineering Department, Kermanshah Branch, Islamic Azad University, 671447342 Kermanshah, Iran
[*] Corresponding author, e-mail: j.esfandiari@iauksh.ac.ir

Received: 05 September 2023, Accepted: 12 November 2023, Published online: 15 February 2024

Abstract

The rehabilitation of concrete structures has been a subject of extensive investigation, exploring various facets. One such avenue involves the incorporation of fiber additives into concrete materials. In parallel, the construction of reinforced concrete structures inevitably encounters construction errors, necessitating constant efforts from researchers to devise solutions for mitigating their impact. In the context of this research, a series of experiments was conducted involving the construction and testing of five reinforced concrete moment-resisting frames. The initial sample served as the control, while two additional samples were integrated with polypropylene and metal fibers. The subsequent two samples deliberately introduced a manufacturing error through the application of air-entraining admixture materials at the beam-to-column connection. This deliberate error aimed to assess the influence of additive fibers on frames affected by manufacturing errors. Several critical parameters were subjected to evaluation, including ultimate strength, stiffness, ductility, energy dissipation capacity, and strength reduction factor. The results of these assessments demonstrated that the utilization of additive fibers contributes to an enhanced overall performance of the frames, as inferred from the aforementioned seismic parameters. Furthermore, it was established that the incorporation of these additive fibers substantially alleviates the impact of manufacturing errors on moment-resisting reinforced concrete frames. Although a significant reduction in energy dissipation capacity was observed in samples with manufacturing errors, the other seismic parameters remained relatively unaffected. Subsequently, numerical models were generated in ABAQUS software to validate the experimental findings, and their outcomes were compared with the results derived from the physical experiments.

Keywords

polypropylene, steel fibers, reinforced concrete, moment-resisting frame, manufacturing error, bubbles in admixture, seismic parameters

1 Introduction

Reinforced concrete structures have perennially stood as a pivotal research domain, given their fundamental significance and wide-ranging applications within the construction and infrastructure sector. Researchers have diligently explored ways to address the limitations of these structures, focusing on enhancing their seismic performance through various avenues [1, 2]. These include refining design methodologies, altering construction geometries, elevating the performance of reinforced concrete materials, and resolving recurrent issues in the execution of these structures. A persistent issue in reinforced concrete structures is their compromised performance due to construction errors, with errors in the concreting and processing of concrete materials being among the most influential factors. Accurate rebar placement and vigilant supervision during concreting of structural elements can effectively thwart significant damage to reinforced concrete structures.

One proposed solution to enhance the performance of reinforced concrete structures is the incorporation of different additive fibers and powders [3, 4] Notably, polypropylene fibers and steel fibers have been introduced in various forms to the construction industry in recent decades, and their effectiveness has been scrutinized in research endeavors. The utilization of concrete additive fibers has yielded results that include augmenting the ultimate strength, stiffness, and seismic resilience of reinforced concrete frames [5]. Furthermore, these fibers can influence crack patterns and safeguard structures against deterioration from environmental factors like corrosion, frost,

Cite this article as: Esfandiari, J., Roudsari, M. T., Esfandiari, S. "Experimental and Numerical Investigation of the Seismic Performance of RC Moment Resisting Frames", Periodica Polytechnica Civil Engineering, 68(2), pp. 608–624, 2024. https://doi.org/10.3311/PPci.23367

and fire [6]. The connections within reinforced concrete moment-resisting frames play a pivotal role in determining the overall performance of these structures. The efficacy of force transmission from slabs to beams and from beams to columns hinges on the correct functioning of these connections. Employing concrete materials with optimal characteristics, combined with measures to prevent construction errors, can mitigate damage to reinforced concrete structures during seismic events. Key instances of construction errors in reinforced concrete moment-resisting frames encompass high rebar density at joints, inadequate post-concreting monitoring, and the failure to adhere to a concrete mixing plan.

Numerous research studies have addressed these issues, striving to enhance the performance of reinforced concrete structures. Several such studies are detailed below.

The deployment of polypropylene fibers in concrete materials has been the subject of extensive investigation. Findings suggest that polypropylene-reinforced rebars can elevate load-carrying capacity, ductility, energy absorption, and stiffness in comparison to steel rebars, especially in the face of corrosion [7]. Additionally, combining basalt and polypropylene fibers can serve as a viable alternative to steel reinforcement in concrete, with polypropylene playing a prominent role in enhancing shear strength and ductility [8]. Furthermore, the addition of rubber powder to concrete materials containing polypropylene fibers can increase damping capacity but may reduce compressive strength [9]. Introducing polypropylene fibers in cases where manufacturing errors have led to inadequate rebar overlap in reinforced concrete beams can enhance energy absorption and load-carrying capacity [10]. These fibers have also exhibited positive effects on structures such as shotcrete covers in tunneling and double-sided slabs [11, 12], resulting in improved performance, reduced cracking, and better behavior during substantial deformations. Moreover, using polypropylene fibers in fire-damaged reinforced concrete structures has revealed a 20% reduction in the bearing capacity of concrete materials and bending capacity [13, 14].

Another avenue explored in the literature to enhance the performance of concrete structures is the use of steel fibers. Researchers have consistently reported the beneficial impact of steel fibers in reinforced concrete materials. These fibers alleviate and enhance crack patterns and can elevate compressive strength, modulus of elasticity, and bending strength in concrete. Optimal percentages and models of steel fibers have been suggested through various tests. These tests have demonstrated a 16% improvement in crack patterns when steel fibers are integrated [15]. Although the use of steel fibers can enhance seismic parameters in experimental samples, it cannot fully compensate for manufacturing errors, such as insufficient rebar usage [16–20]. In cases of fire-damaged reinforced concrete beams, steel fibers can increase load-carrying capacity by 65% and improve performance [21]. Additionally, research has explored the utilization of recovered steel fibers and compared them with glass polymer composite plates (GFRP) [22, 23]. These studies have demonstrated that steel fibers can inhibit corrosion in concrete materials and boost shear resistance by up to 120%, with hooked steel fibers showing a more favorable crack pattern compared to pleated steel fibers.

Using concrete additive fibers to mitigate concrete failure in freezing conditions, investigating crack patterns during repeated freeze-thaw cycles, and optimizing circular reinforced concrete column foundations in bridge construction using concrete additive fibers constitute additional noteworthy research domains [24–26]. These studies are grounded in numerical modeling, revealing crack patterns in reinforced concrete structures and the seismic performance of reinforced concrete columns when composite fibers are employed. The application of air-entraining admixture materials to combat corrosion and freezing in concrete's internal cracks has also been scrutinized [27, 28]. These investigations have highlighted the reduction of freezing in concrete as a result of using air-entraining admixture materials.

This research encompasses two primary objectives. Firstly, it evaluates the utilization of polypropylene fibers and steel fibers in concrete materials through two experimental samples, comparing the results with a reinforced concrete moment-resisting frame sample without additive fibers. Secondly, the study creates deliberate manufacturing errors in two moment-resisting frame samples using air-entraining admixture materials at the beam-column connections to investigate the impact of additional polypropylene and steel fibers. The research findings underscore the constructive role of concrete additives in mitigating the consequences of construction errors in connection on the overall performance of these structures.

2 Experimental plan

Within the scope of this research, five scaled-down models of reinforced concrete moment-resisting frames were meticulously fabricated and subsequently subjected to comprehensive testing. To ensure uniformity and adherence to rigorous standards, the rebar placement and construction procedures for these specimens were meticulously executed in strict accordance with established design regulations, following the dimensions and specifications outlined in the study conducted by TahamouliRoudsari et al. [29] in 2018.

These experimental samples featured a uniform cross-section for both the beams and columns, measuring 150 × 150 mm. The beams were each reinforced with four No. 10 rebars, while the columns were fortified with four No. 14 rebars. The stirrup rebars for both beams and columns were No. 8 in size and were spaced at 45 mm intervals. A comprehensive depiction of the moment-resisting frames constructed for the experimental specimens in this research is presented in Fig. 1.

The first experimental sample in this study comprised a reinforced concrete moment-resisting frame constructed with concrete materials devoid of additive fibers (referred to as RCMRF). Subsequently, the second (RCMRF-PP) and third (RCMRF-SF) samples incorporated polypropylene and steel fibers in their concrete materials, respectively. The fourth specimen featured a moment-resisting frame with polypropylene fibers intentionally afflicted by a construction error at the beam-to-column connection, facilitated through the use of air-entraining admixture materials (RCMRF-PP-AEA). In the fifth experimental sample, a manufacturing error was intentionally induced by introducing air-entraining admixture materials to the reinforced concrete frame with steel fibers (RCMRF-SF-AEA). It's important to note that the concrete materials remained consistent across all samples, with the differentiating factor being the use of additive fibers and air-entraining admixture materials.

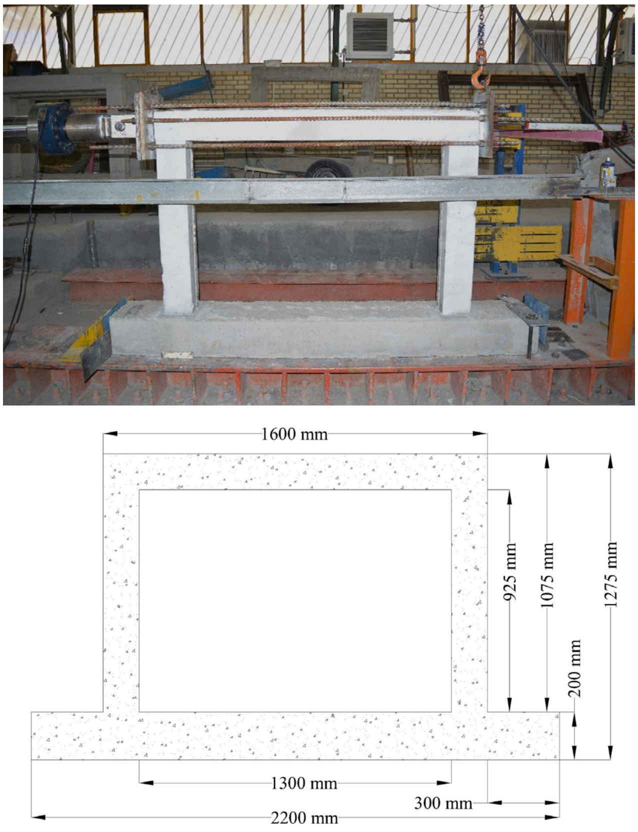


Fig. 1 Details of reinforced concrete moment-resisting frames used in experimental samples

The concrete materials employed in all experimental samples adhered to identical specifications, as previously described. This encompassed coarse aggregate characterized by a specific weight of 2.72 t/m³ and fine aggregate with a specific weight of 2.68 t/m³. The preparation of concrete entailed the utilization of potable water with a pH level of 7. Furthermore, a super-lubricant, comprising 1–1.6% of the total weight, was added to enhance concrete workability. The determination of the appropriate super-lubricant percentage was based on a slump test conducted in accordance with the BS 1881-102:1983 [30]. The concrete mixing plan was implemented following the guidelines outlined in Table 1, which delineated the weight ratios of the constituent ingredients.

The additives employed in this research, according to the specific objectives, encompassed polypropylene fibers, steel fibers, and air-entraining admixture materials. For clarity, a representative image of these materials is provided in Fig. 2. The steel fibers utilized were of the stainless steel variety, featuring an end hook, a length of 35 mm, and a diameter of 0.80 mm, resulting in an aspect ratio of 43. This particular type of steel fiber boasted a standard tensile strength of 1400 MPa, a modulus of elasticity measuring 200 GPa, and a density of 7.85 g/cm³. A comprehensive breakdown of its specifications can be found in Table 2. Furthermore, micro polypropylene fibers, adhering to the specifications delineated in Table 2, were also incorporated into the concrete mix.

The proportions of polypropylene and steel fibers used in this research were determined based on the findings of Esfandiari and Heydari [31] in 2021. According to their research, the recommended usage ratio for polypropylene fibers is 0.15% by weight of cement, while for steel

Table 1 Specifications of concrete materials used in experimental samples

Sand	Coarse aggregate	Fine aggregates	Water	Cement	Material
1011	407	332	216	407	Weight (Kg)

(a) (b)

Fig. 2 Steel and propylene fibers used in experimental samples (a) steel fibers and (b) polypropylene fibers

Table 2 Characteristics of polypropylene additive fibers and steel fibers in experimental samples

Properties	Specific mass (g/cm^3)	Fiber length (mm)	Fiber diameter (μm)	Elongation (%)	Tensile strength (MPa)	Young modulus (MPa)
Polypropylene fiber (*P*)	0.91	14	35	35	293	3400
Steel fiber (*S*)	7.85	35	800	20	1400	200000

fibers, the optimal ratio is 1.5% by weight of cement. Consequently, these ratios were adopted for the incorporation of fibers in the experimental samples.

In the case of the RCMRF-PP-AEA and RCMRF-SF-AEA samples, air-entraining materials were additionally introduced within the beam-to-column connection range, as per the research objectives.

In the laboratory, all the samples underwent quasi-static loading through a displacement-controlled loading system. Loading on the samples was administered in a cyclic manner, adhering to the loading protocol as outlined in ACI 374.1-05 [32]. This loading protocol stipulated that the displacement applied to the specimen, determined in relation to yield displacement, was imposed on the structure in a sequence of triple cycles and half cycles with a single repetition. The loading protocol diagram that illustrates these specifications is provided in Fig. 3 for reference.

During the tests, a hydraulic actuator with a capacity of 1000 kN and a load cell capable of handling 1000 kN loads were employed. The load cell's accuracy was within ±200 N. Displacement values were measured using a Linear Potentiometer Transducer (LPT) with a precision level of ±0.5 mm.

To secure the samples during testing, they were firmly anchored to the robust laboratory floor using 12 sturdy bolts, each with a diameter of 27 mm. Additionally, a lateral anchoring system was implemented to prevent any lateral movement of the samples. At the foundation level of the samples, two steel heels were strategically used to

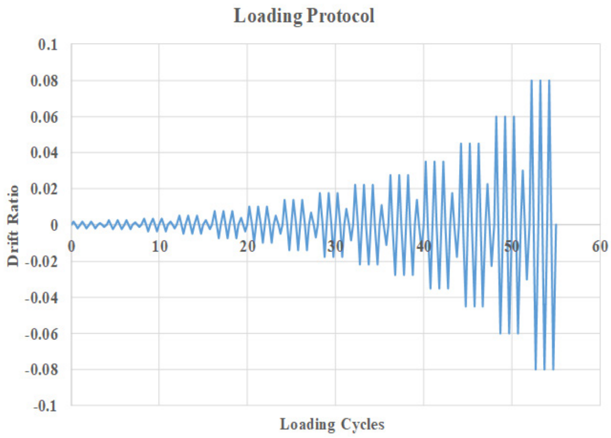


Fig. 3 Loading protocol

restrict the samples from slipping and to align them with the movement of the actuator. For visual reference, the laboratory test setup for the samples is illustrated in Fig. 4.

The RCMRF specimen was designated as the control sample for the testing. Initially, during the loading process, minimal cracks emerged in the vicinity of the beam-to-column connection. Up to a displacement equal to 1% of the drift, there was no notable change in the rate of force increase relative to displacement. However, as loading progressed on the RCMRF sample, the cracks in the beam-to-column connection area began to enlarge, resulting in a decline in the rate of force increase. Once the displacement reached 6% of the drift, the experiment reached its conclusion, with the ultimate force recorded at 39.69 kN. Visual records of the test conducted on the RCMRF sample are depicted in Fig. 5 for reference.

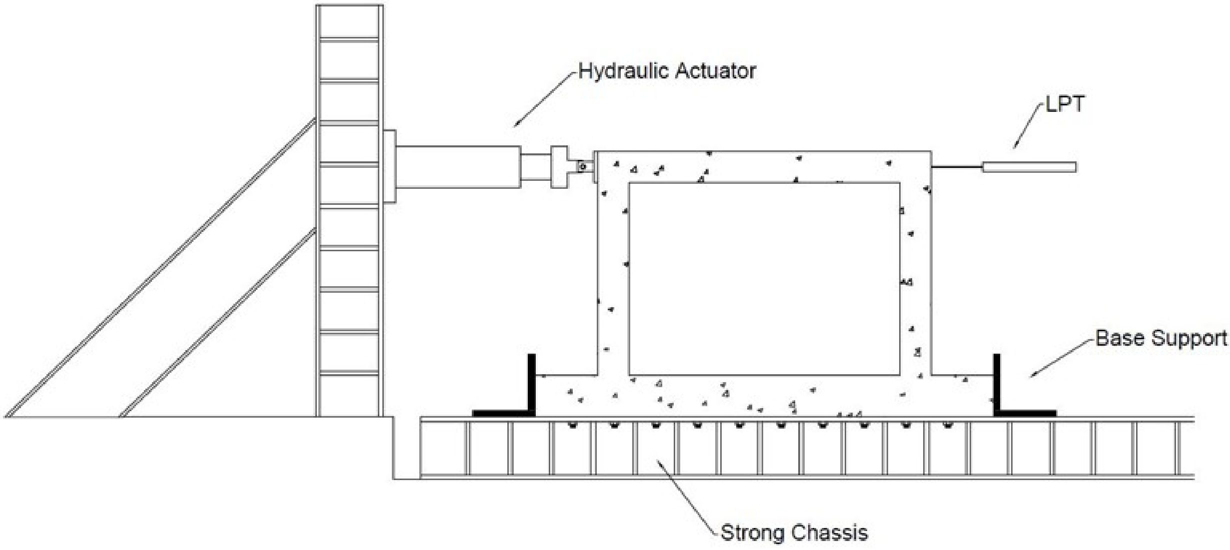


Fig. 4 Test setup

(a)

(b)

(c)

(d)

Fig. 5 Test images related to the RCMRF experimental sample (a) the beginning of test (b) column at 4% drift (c) deep cracks in the connection of the beam to the column at the end of test (d) the end of the test

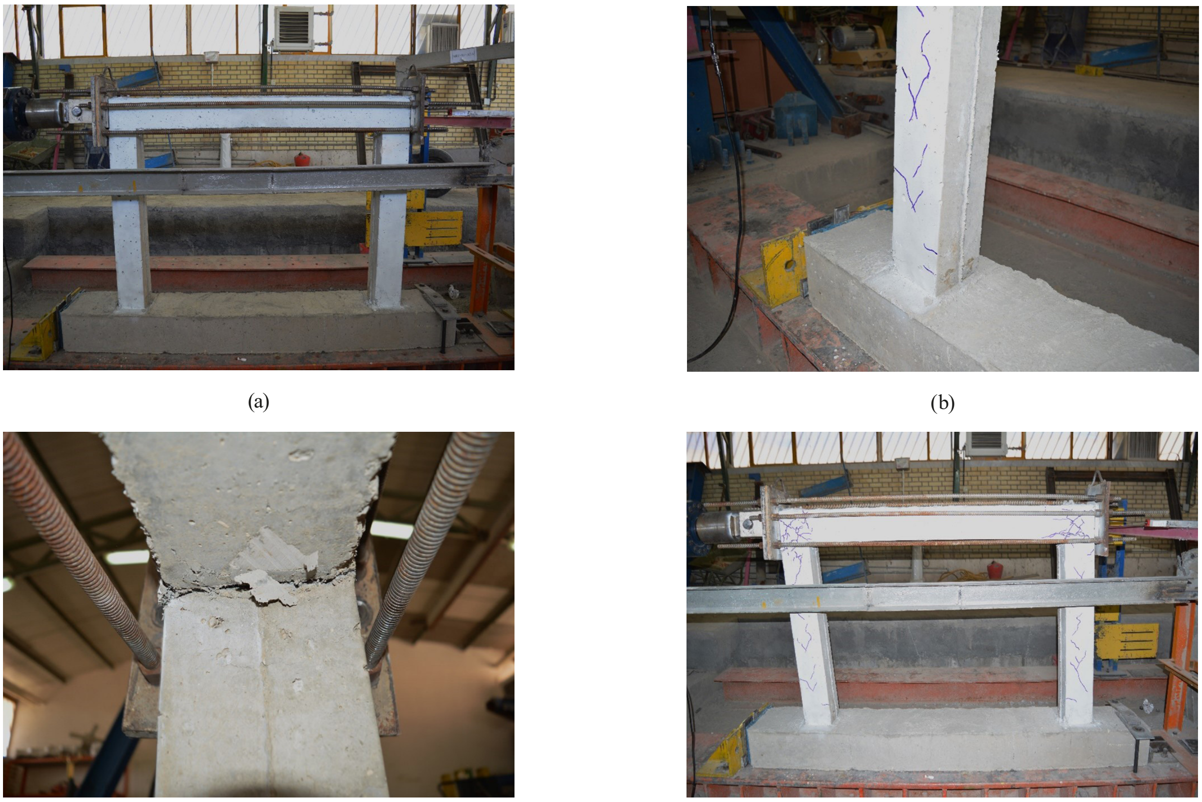
During the test conducted on the RCMRF-PP sample, where polypropylene fibers were introduced, a linear increase in force was observed, akin to the control sample, until reaching a 1% drift, indicating the elastic behavior of the sample. However, in contrast to the control sample, this sample exhibited significantly higher force values. The maximum force recorded for the RCMRF-PP sample was 46.05 kN at a 4.5% drift. As the cracks in the connection between the beam and the column, as well as in the area of the column foot, increased, the sample experienced a relatively minor decrease in strength. This outcome aligns with the anticipated effects of polypropylene fibers, as the sample displayed fewer and shallower cracks. Visual documentation of this experiment is available in Fig. 6 for reference.

In the third experimental sample featuring steel fibers (RCMRF-SF), a noticeable increase in strength was observed, accompanied by a significant reduction in cracks when compared to the control sample. Similar to the RCMRF-PP sample, the force increase rate was linear up to a 1% drift, and the final force was recorded at 44.42 kN when the drift reached 4.5%. The connection in this sample exhibited fewer cracks, indicative of the favorable impact of utilizing hooked metal fibers at the optimal weight ratio. Fig. 7 provides visual documentation of the RCMRF-SF experimental sample for reference.

The fourth sample, RCMRF-PP-AEA, where air-entraining admixture materials were employed in its connections, exhibited a distinctive behavior during testing. Notably, this sample displayed a greater number of cracks at the joint area from the outset of the test. Interestingly, the force rate was nearly identical to that of the control sample, which could be attributed to the presence of polypropylene fibers in the experimental mix. In this sample, the final force was recorded at 40.58 kN when the drift reached 3.5%, after which there was a noticeable decline in force values. This premature failure in the sample can be attributed to a manufacturing error in the connection area. Visual records of this experiment can be found in Fig. 8 for reference.

The second sample, RCMRF-SF-AEA, featuring a manufacturing error at the beam-to-column connection, demonstrated a performance similar to that of the RCMRF-PP-AEA sample. The sample displayed a linear response until it reached a 1% drift, at which point deep cracks began to emerge at the beam-to-column junction, continuing until a 3.5% drift was achieved. The final resistance force for this sample, at a 3.5% drift, was recorded at 40.17 kN. The presence of air-entraining admixtures in this sample contributed to significant damage in the beam-to-column connection. Fig. 9 provides visual documentation of this experiment for reference.

The laboratory results are depicted in the form of hysteresis diagrams in Fig. 10. An overall examination of these graphs reveals that, in general, the samples with additional fibers, and without manufacturing errors,



(a) (b) (c) (d)

Fig. 6 Test images of RCMRF-PP sample (a) beginning of test (b) column in 4% drift (c) connection of the beam to the column on the actuator side (d) end of the test

(a) (b) (c) (d)

Fig. 7 Images related to the RCMRF-SF sample test (a) the beginning of test (b) the column foot in 4% drift (c) the connection of the beam to the column at the end of test (d) the end of the test

(a) (b) (c) (d)

Fig. 8 Images of RCMRF-PP-AEA sample (a) at the beginning of the test (b) beam to column connection at 4% drift (c) beam to column connection at the end of the test (d) end of the test

(a) (b) (c) (d)

Fig. 9 Images related to the test of RCMRF-SF-AEA sample (a) at the beginning of the test (b) column foot connection at 4% drift (c) beam to column connection at the end of test (d) end of the test

exhibited superior performance compared to the control sample. The higher final strength and stable hysteresis cycles can be attributed to the improved performance of samples containing additive fibers.

Conversely, in the samples with manufacturing errors, the loss of strength compared to the samples with additional fibers underscores the importance of precision in connection implementation. Furthermore, the premature failure due to increased cracking in the experimental samples highlights the significance of well-executed connections.

Nonetheless, the presence of additional polypropylene fibers and steel fibers proved effective in preventing strength loss when compared to the control sample. A comprehensive review and evaluation are provided in Section 3.

3 Result assessment

To accurately evaluate the experimental results, it is necessary to obtain the seismic parameters using the laboratory output information. To reach this purpose, the backbone diagram should be obtained from the hysteresis diagram, and then using the instructions provided in FEMA 440 (2005) [33] regulations, the equivalent bilinear diagram should be drawn for each of the experimental samples. Seismic parameters investigated in this research included ultimate strength, stiffness, ductility, and energy dissipation capacity. The ultimate strength is the highest force number recorded in the tests for each sample. Also, the energy dissipation capacity is obtained from the calculation of the area under the diagram in all cycles of the hysteresis diagram. To calculate the stiffness and ductility, it is necessary to define the yield point for each backbone diagram using a bilinear diagram.

In order to obtain a backbone curve from a hysteresis diagram, the maximum displacement points recorded for each loading drift in the cycles in which that drift was repeated should be compared with each other; and the point with the lowest force recorded for that loading drift chosen to consider the low cycle fatigue effect in the backbone diagram. Using FEMA 440 instructions, it is possible to draw an equivalent bilinear diagram on the backbone diagrams and obtain the yield point of the backbone diagram. This diagram is drawn based on the energy

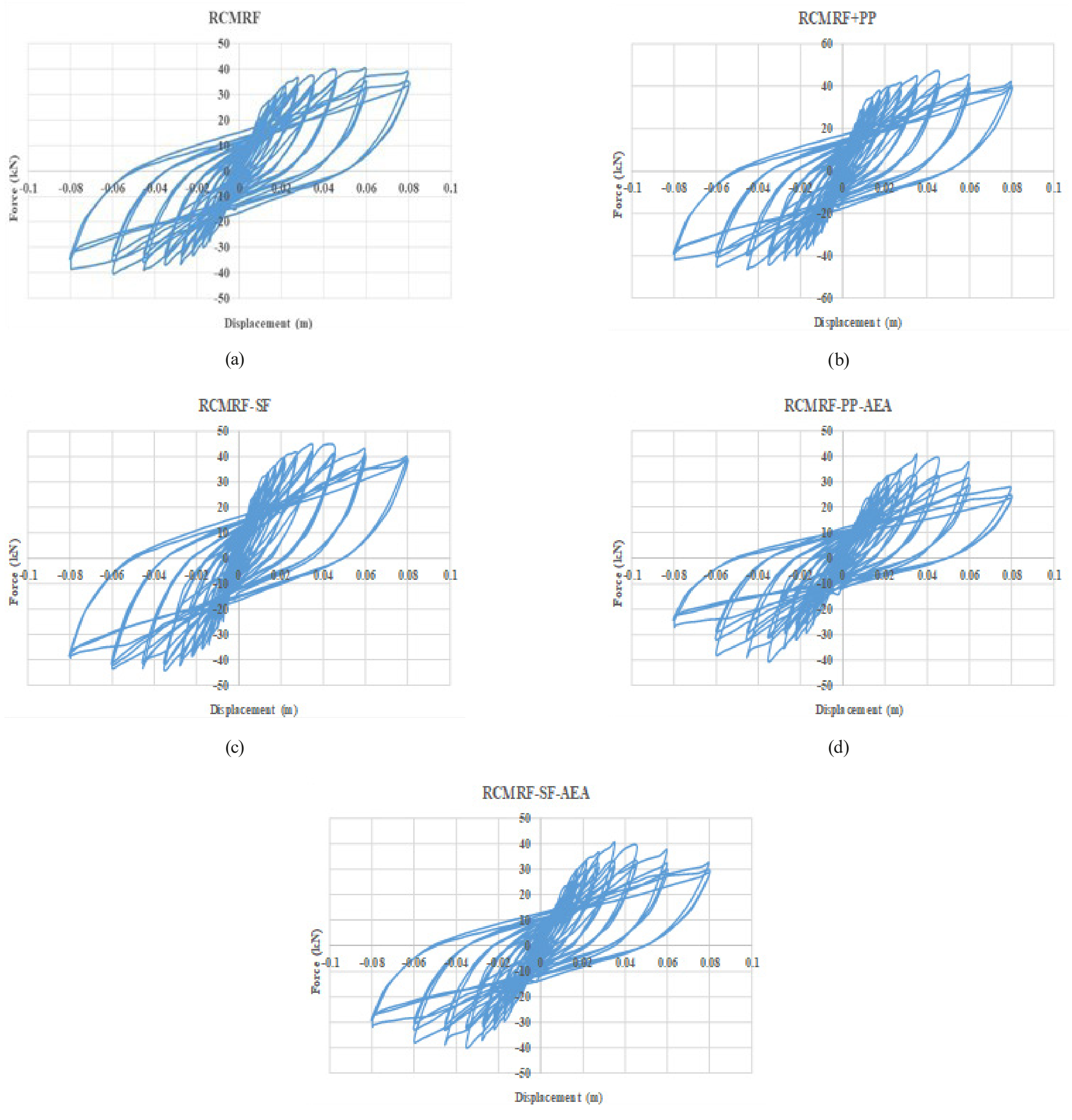


Fig. 10 Hysteresis diagrams related to experimental samples (a) RCMRF (b) RCMRF-PP (c) RCMRF-SF (d) RRCMRF-PP-AEA (e) RCMRF-SF-AEA

equivalence method, in which the area under the backbone and the equivalent bilinear diagrams must be the same. Also, the two conditions of the yield point force being less than the maximum force of the backbone diagram and the crossing of the two diagrams within 0.6 of the yield point from each other are also included in this instruction. Fig. 11 showcases the backbone diagrams and equivalent bilinear diagrams for the experimental samples.

The seismic parameters investigated in this study are detailed and presented in Table 3. The results, in general, suggest the effective performance of polypropylene fibers and steel fibers in the experimental samples. Notably, in the experimental samples with manufacturing errors, the presence of polypropylene and steel fibers is observed to prevent a significant decline in seismic parameters when compared to the control sample.

However, it's worth noting that the energy dissipation capacity has decreased in samples with manufacturing errors due to the early reduction in force during the hysteresis cycles.

The ultimate strength of the tested samples exhibits a noticeable increase as a result of the presence of polypropylene fibers and steel fibers. Specifically, polypropylene fibers and steel fibers have enhanced the final strength

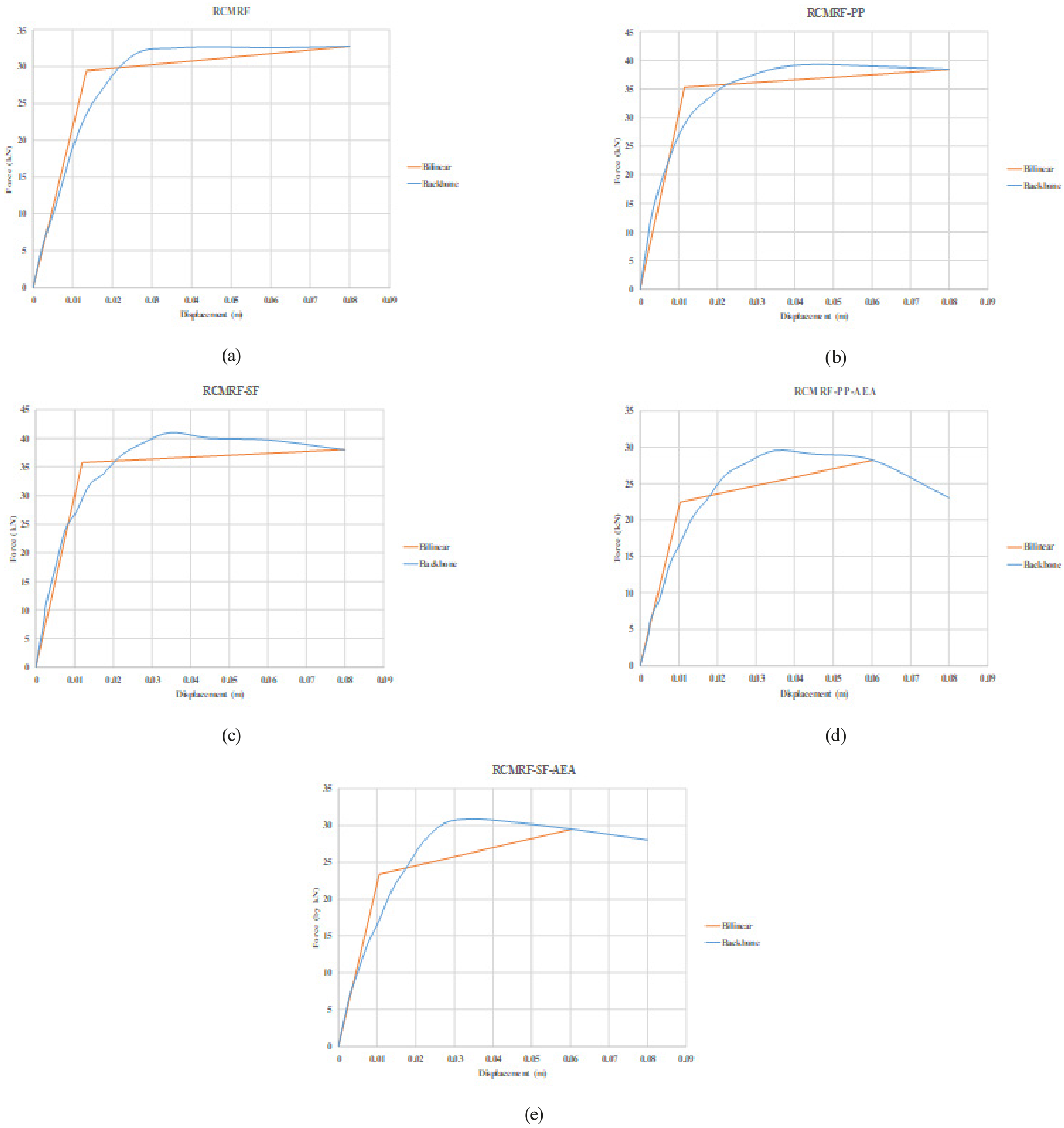


Fig. 11 Backbone and equivalent bilinear diagram for experimental samples (a) RCMRF (b) RCMRF-PP (c) RCMRF-SF (d) RCMRF-PP-AEA (e) RCMRF-SF-AEA

Table 3 Seismic parameters calculated for experimental samples

	Seismic parameters based on reverse calculations				
Specimen	*Fu* (kN)	*K* (kN/m)	Duct.	EDC (kN m)	*R*
RCMRF	39.69	2183.74	5.93	32.66	5.63
RCMRF-PP	46.05	3067.82	6.95	37.77	6.11
RCMRF-SF	44.42	3008.40	6.72	37.35	5.96
RCMRF-PP-AEA	40.58	2177.78	5.83	19.16	5.75
RCMRF-SF-AEA	40.17	2219.37	5.72	19.67	5.69

by 16% and 12%, respectively, when compared to the control sample. Importantly, in the presence of air-entraining admixture, acting as an artificial manufacturing error, the final strength values did not decrease in comparison to the control sample. This outcome can be attributed to the effective performance of the additive fibers in these samples. Fig. 12 visually represents the bar chart of ultimate strength for the experimental samples.

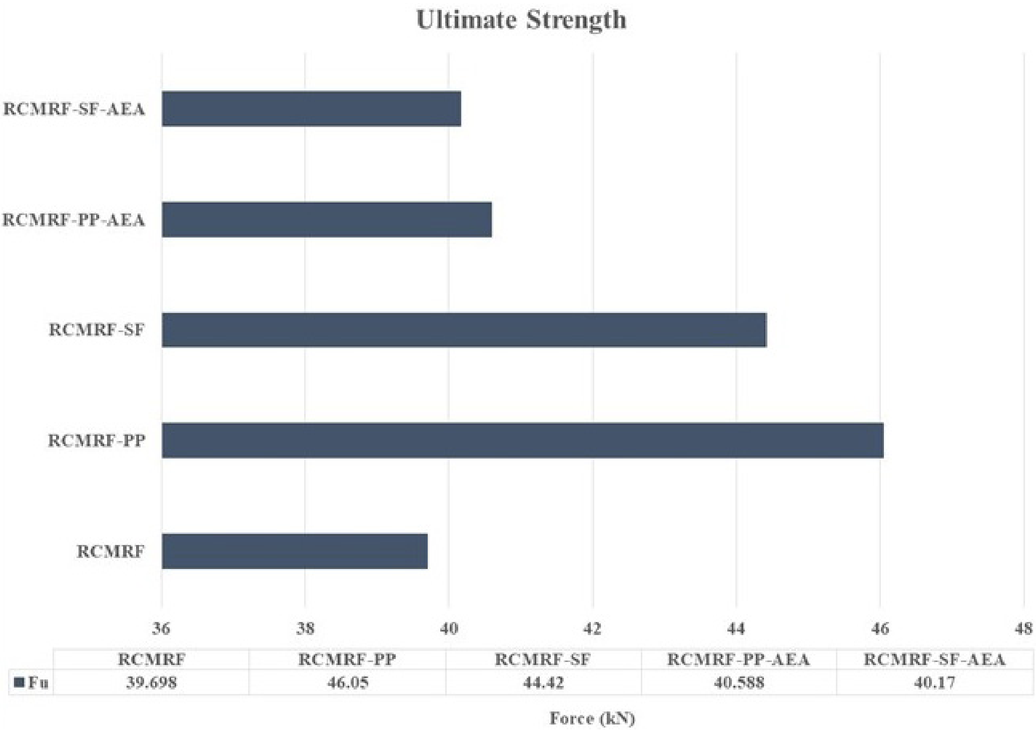


Fig. 12 Bar graph of ultimate strength for experimental samples

Stiffness in the experimental samples has experienced substantial changes. The stiffness of RCMRF-PP and RCMRF-SF samples increased by 40% and 37%, respectively. The use of polypropylene fibers and steel fibers has effectively reduced the crack pattern and enhanced the integrity of the moment-resisting frame, which is a likely reason for the increased stiffness in these samples.

Even in the samples with manufacturing errors, stiffness remains comparable to the control sample. This indicates that the utilization of these fibers can effectively mitigate the impact of manufacturing errors in critical areas of the frame, such as the connection of the beam to the column, preventing any deterioration in the frame's performance. Fig. 13 illustrates the bar graph of stiffness for the experimental samples.

Ductility is a critical seismic parameter for assessing the performance of a reinforced concrete moment-resisting frame. In the tested samples, it's evident that the inclusion of polypropylene fibers and steel fibers has led to increased ductility values compared to the sample with concrete materials without fibers. The increase of approximately 15% in samples with polypropylene and steel fibers demonstrates the positive impact of these fibers on the performance and flexibility of reinforced concrete frames.

In the samples with manufacturing errors, the ductility values have decreased by 2% and 4% for the RCMRF-PP-AEA and RCMRF-SF-AEA samples, respectively, in comparison to the control sample. However, given the relatively minor nature of this decrease, it can be concluded that the use of additive fibers can effectively prevent the loss of ductility when manufacturing errors are present. Fig. 14 provides a bar chart representing the ductility values in the experimental samples.

In the RCMRF-PP and RCMRF-SF samples, the energy dissipation capacity increased by 15%, indicating optimal performance in the use of fibers. However, in samples with manufacturing errors, the premature drop in force values at lower drifts resulted in a 40% reduction in energy dissipation capacity.

By comparing these values, it can be concluded that while the presence of polypropylene fibers and steel fibers can increase or maintain parameters such as ultimate strength, stiffness, or ductility, the capacity for energy dissipation experiences a significant drop in the presence of manufacturing defects in the beam-to-column connections of the experimental samples. Fig. 15 provides a bar chart illustrating the energy dissipation capacity in the experimental samples.

The strength reduction factor is determined by dividing the elastic force demand of the design by 0.6 of the yield point force. In this research, the results indicate that the presence of polypropylene fibers and steel fibers did not have a significant effect on this seismic parameter. The increase of less than 10% in RCMRF-PP and

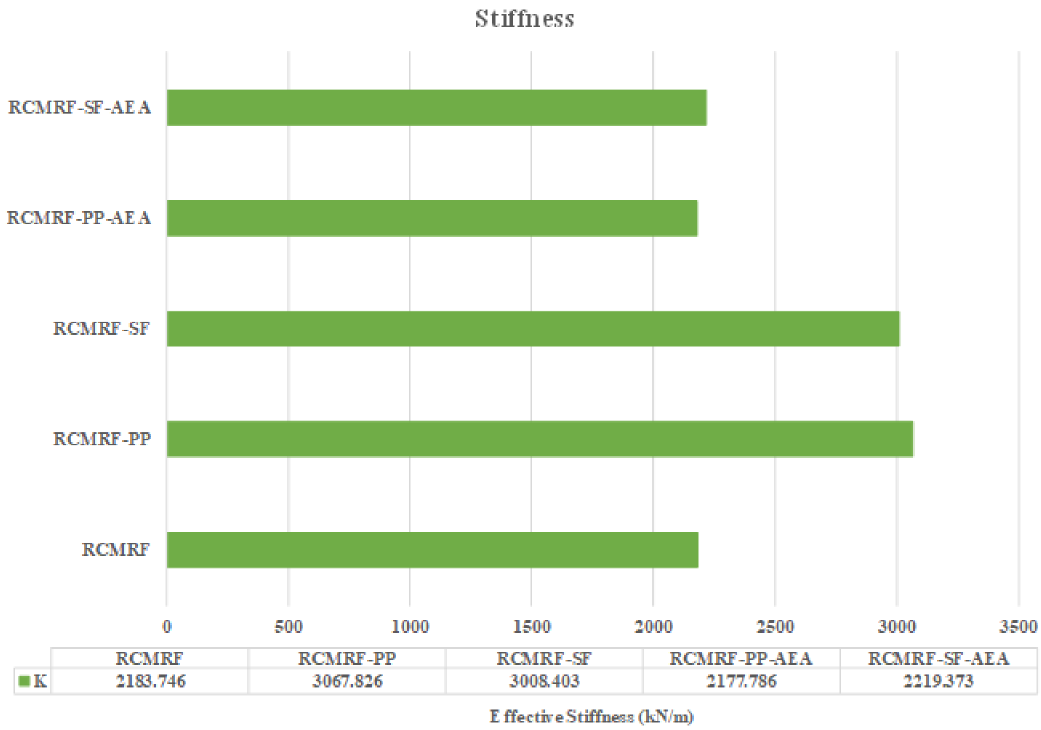


Fig. 13 Stiffness bar chart for experimental samples

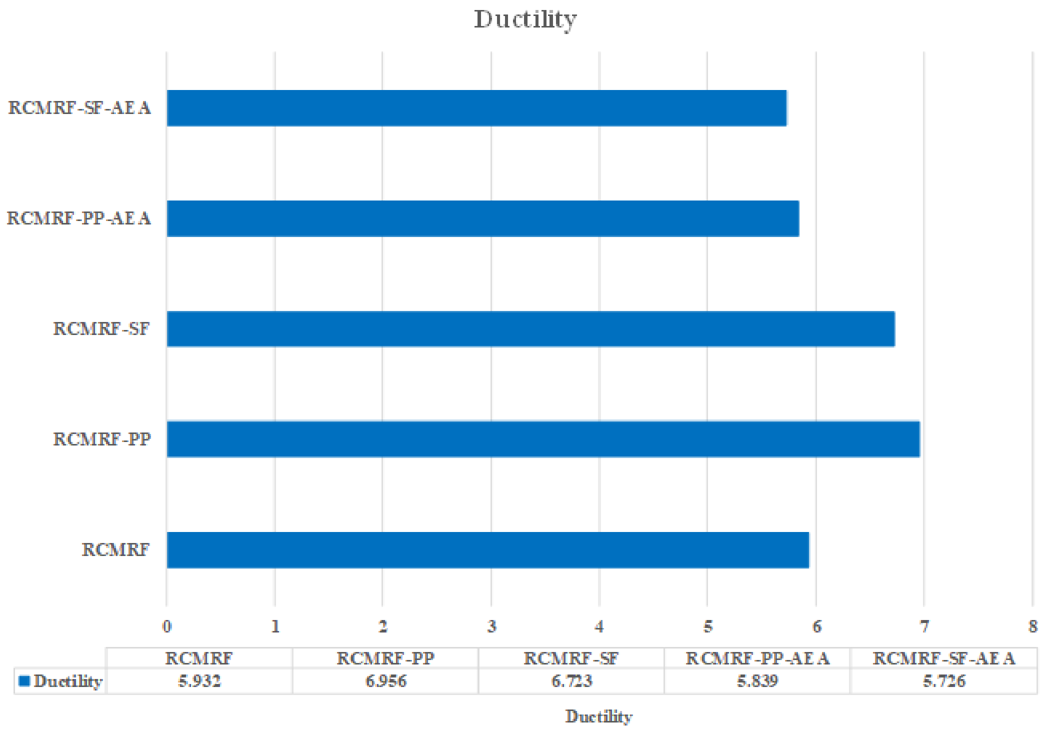


Fig. 14 Bar chart of ductility for experimental samples

RCMRF-SF samples cannot be considered a significant improvement. Moreover, the effect of manufacturing errors on the strength reduction factor in the presence of additive fibers in these samples was also very insignificant. Fig. 16 provides a bar chart illustrating the strength reduction factor in the experimental samples.

4 Numerical modeling

Conducting a substantial number of experiments to assess the factors influencing column behavior is not only expensive but also time intensive. Therefore, utilizing simulation through the finite element method offers a practical solution to create accurate models for real-scale

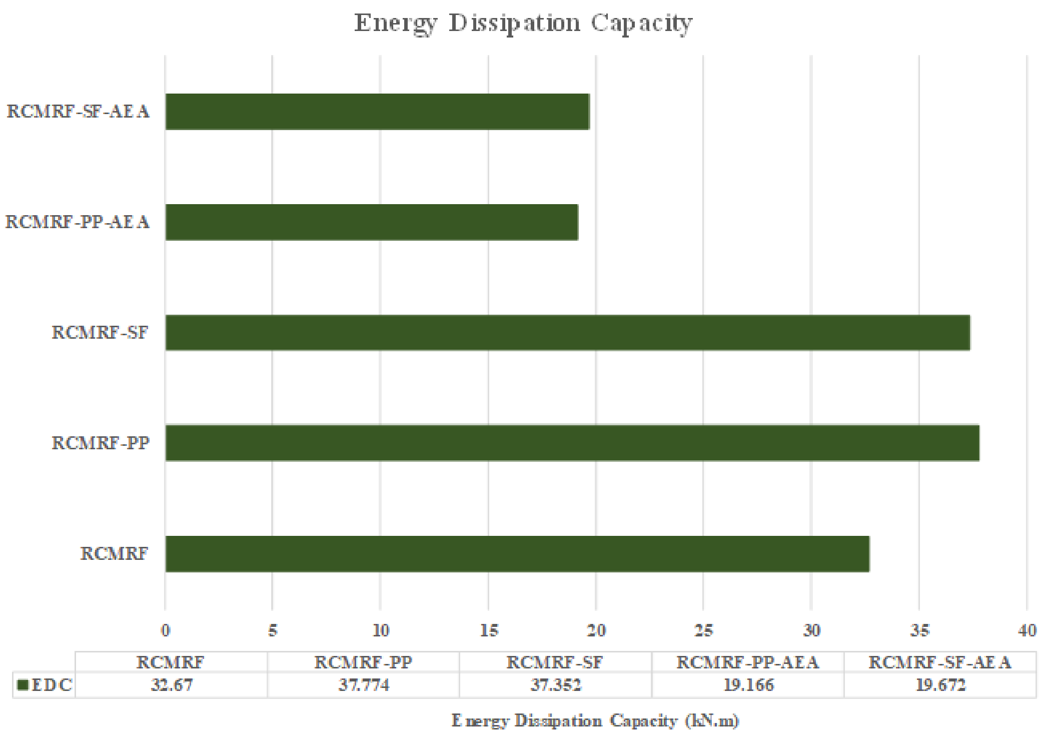


Fig. 15 Bar chart of energy dissipation capacity for experimental samples

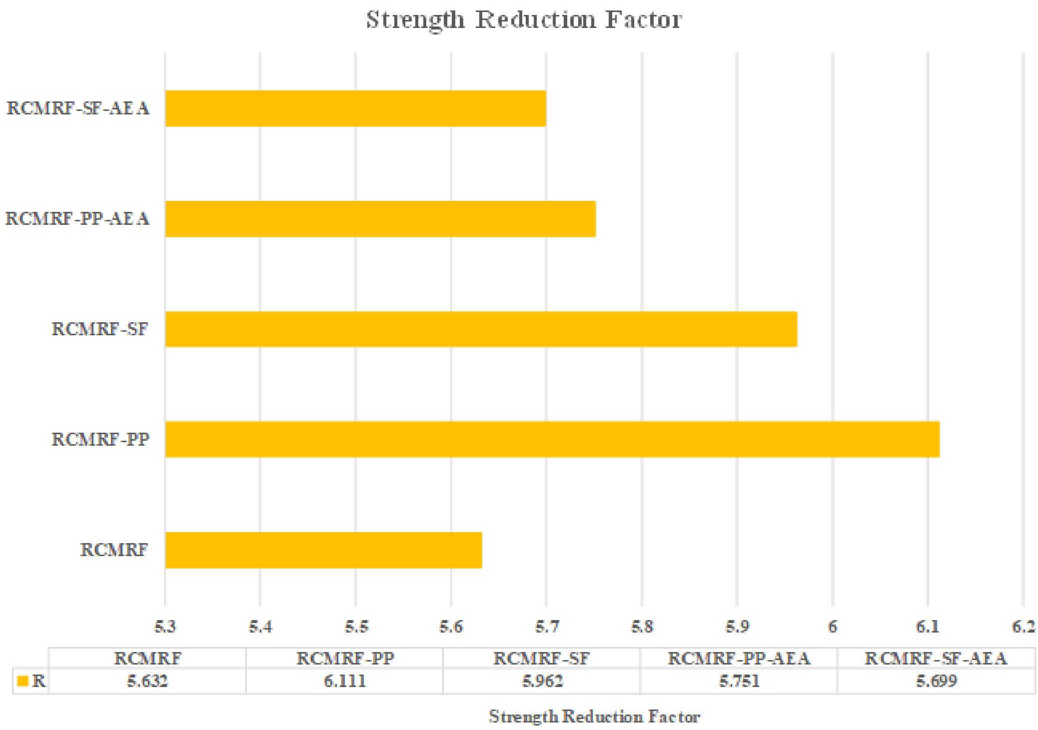


Fig. 16 Bar chart of strength reduction factor for experimental samples

experiments. Simulations are advantageous because they are relatively free from many of the constraints associated with experimental work, and they are renowned for producing valuable and reliable results [16, 34, 35]. To assess the laboratory results through numerical models, three experimental samples – RCMRF, RCMRF-PP, and RCMRF-SF – were meticulously replicated within the ABAQUS finite element software.

In the modeling part of this research, in Abaqus finite element software, solid elements were used to model the concrete frame, and wire elements were used to model the rebars. The specifications of the materials were taken based on the results of the compression tests on the cubic and cylindrical prisms that were made from the materials used in the experimental samples and assigned to the modeled frame. Quad elements were used for meshing, and based on mesh sensitivity analysis, the dimensions of the mesh were considered to be 5 cm for the solid element of the frame and 3 cm for the rebars, based on this, 630 cubic meshes were created in the reinforced concrete frame.

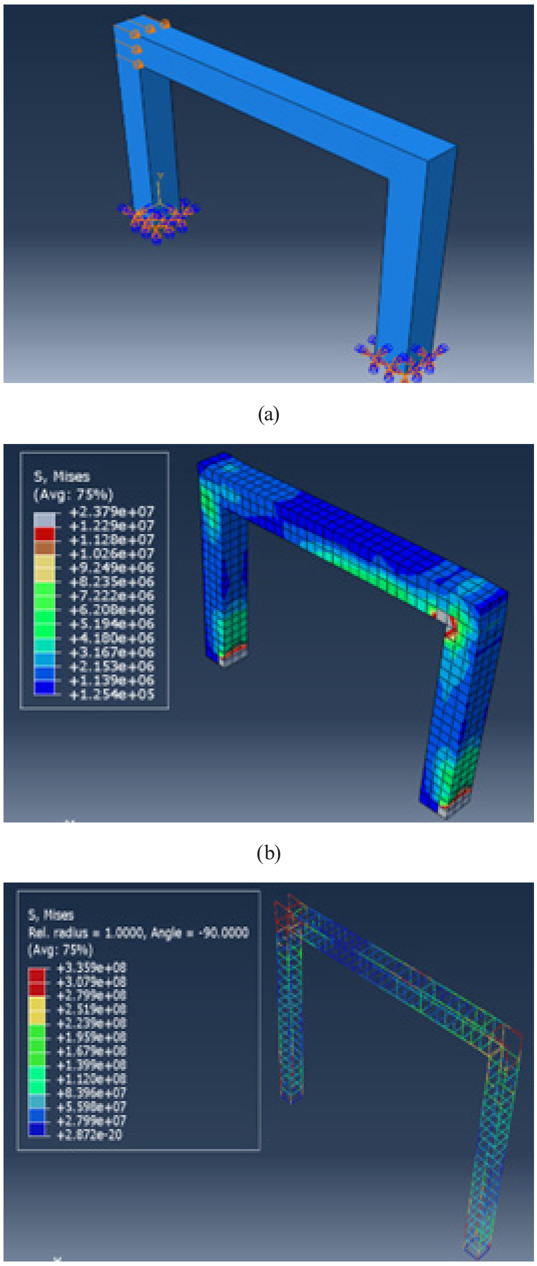
These models were constructed using solid elements and subjected to a quasi-static, monotonic loading regime with an 80 mm displacement, equivalent to an 8% drift. Quad mesh elements were employed in these models, and the force-displacement profiles derived from these numerical simulations exhibit a satisfactory alignment with the experimental data.

The boundary conditions in the numerical models were judiciously established to mirror the actual test setup, including the constraint of out-of-plane movement. Fig. 17 provides a visual representation of the numerical modeling procedures applied to the experimental samples.

Furthermore, it's essential to highlight the significance of this numerical modeling approach. By employing finite element software like ABAQUS, engineers, and researchers can gain valuable insights into the behavior of reinforced concrete structures, enabling them to optimize designs, assess the impact of different materials, and explore structural performance under various loading conditions [36]. Such modeling can also serve as a cost-effective and efficient means to complement experimental studies, facilitating the exploration of a broader range of scenarios, including those that may be impractical or too costly to reproduce in a physical laboratory. In this way, the synergy of experimental and numerical methods enhances our understanding of structural mechanics and contributes to the ongoing advancement of construction and engineering practices.

The accuracy and reliability of the numerical models were ensured by obtaining material specifications from compression tests conducted on cubic and prismatic samples fabricated from the materials used in the experimental samples. These material properties encompass elastic, plastic, and concrete damage plasticity characteristics, both in the compressive and tensile domains. These crucial data were meticulously integrated into the numerical models [37, 38].

As a result, the outcomes obtained from these numerical models closely align with the experimental findings, demonstrating a commendable equivalence between the two. Fig. 18 visually depicts the numerical modeling and experimental results for the three samples.



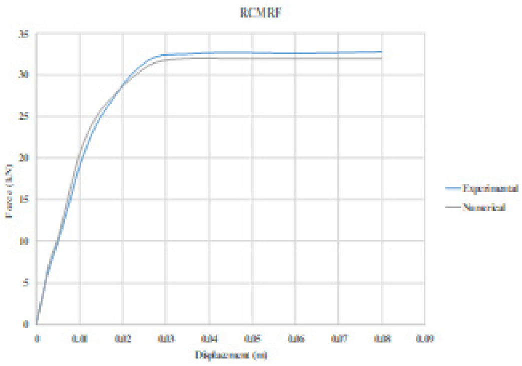
(a)

(b)

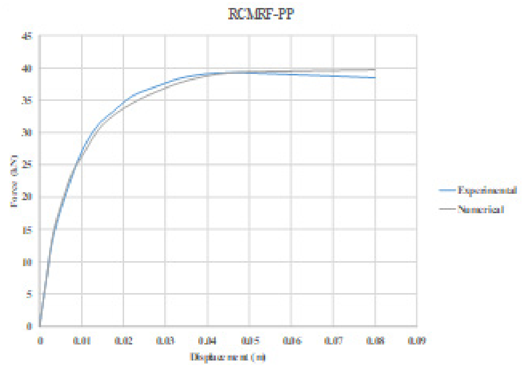
(c)

Fig. 17 (a) Boundary conditions in the modeling of frames (b) Mises's stress in the RCMRF frame numerical model (c) Mises's stress in the RCMRF rebars numerical model

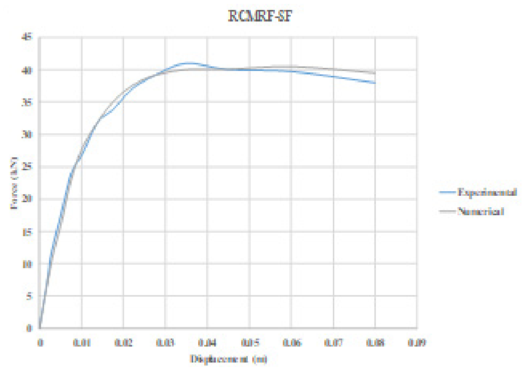
This harmonious relationship between numerical and experimental data is not merely coincidental but rather the product of a systematic and well-calibrated approach to numerical modeling. The precision and credibility of such models in replicating real-world behaviors contribute significantly to our understanding of structural mechanics, thereby informing the design, assessment, and refinement of reinforced concrete structures. This approach is invaluable in improving safety, efficiency, and resilience in the construction and infrastructure industry.



(a)



(b)



(c)

Fig. 18 Experimental and numerical comparison charts for samples (a) RCMRF (b) RCMRF-PP (c) RCMRF-SF

5 Conclusions

Reinforced concrete moment-resisting frames are complex structural elements, where connections play a pivotal role in ensuring structural integrity and safety. Research efforts aimed at enhancing the performance of these structures have led to the exploration of various additives for concrete, with a particular focus on steel fibers and polypropylene fibers. In the pursuit of advancing our understanding of these materials and their impact on structural behavior, this research involved the construction and testing of five one-third-scale experimental samples of reinforced concrete moment-resisting frames.

The experimental samples were rigorously tested under quasi-static and cyclic loading conditions, each designed to serve a distinct purpose in evaluating the impact of concrete additives and manufacturing errors. The control sample employed plain concrete, devoid of additives, while the subsequent experimental samples incorporated polypropylene fibers and steel fibers to assess their influence on the frames' bending behavior. Additionally, two samples were intentionally subjected to manufacturing errors within the beam-to-column connection region, with the inclusion of specified fibers.

The results of these comprehensive experimental tests, coupled with the calculation of critical seismic parameters, provided invaluable insights into the performance of these structural frames. It was observed that both polypropylene fibers and steel fibers significantly augmented the ultimate strength, stiffness, and load-carrying capacity of the samples. Ductility, a vital seismic parameter, exhibited substantial growth with the incorporation of these additive fibers. Moreover, the energy dissipation capacity of the samples with fibers surpassed that of the control sample, aligning with ultimate strength and stiffness. These findings underscore the potential for polypropylene and steel fibers to markedly improve the seismic performance of bending frames.

To further investigate the resilience of these additive-enhanced frames, two additional experimental samples were crafted with intentional manufacturing errors, involving the application of air-entraining admixture material in the beam-to-column connection region. Remarkably, stiffness and ductility exhibited only marginal decreases in comparison to the control sample. This suggests that the use of fibers at optimal weight ratios can effectively mitigate premature failures in frames with manufacturing errors. Notably, the coefficient of behavior parameter was calculated for all samples, revealing that the impact of polypropylene fibers and steel fibers on this parameter was relatively negligible.

In parallel to the experimental tests, numerical models of three experimental samples were meticulously constructed using ABAQUS finite element software. The material characteristics integrated into these models were derived from the strength tests conducted on cubic and prismatic samples composed of the same materials used in the experimental samples. The remarkable correlation between the numerical models and experimental results further underscores the reliability and precision of the numerical simulations.

In summary, this research contributes significantly to the understanding of how additive fibers, such as polypropylene fibers and steel fibers, can enhance the performance of reinforced concrete moment-resisting frames. Moreover, it highlights the potential for these fibers to mitigate the effects of manufacturing errors, fostering structural resilience and safety. The close alignment between experimental and numerical results underscores the efficacy of numerical modeling as a tool for predicting and understanding structural behaviors, ultimately advancing the construction and infrastructure industry's knowledge and practices.

Author contributions

Javad Esfandiari: Conceptualization, Methodology, Investigation, Visualization, Writing – Original Draft Preparation, Resources; Mehrzad Tahmouli Rodsari: Supervision, Visualization, Writing – Review & Editing Soheil Esfandiari: Methodology, Investigation, Supervision, Writing – Review, Software.

Declaration statement

The authors collectively confirm that they do not possess any affiliations or involvement with any organization or entity that holds a financial interest or non-financial interest in the subject matter or materials under discussion within this manuscript.

References

[1] Esfandiari, J., Khezeli, Y. "Seismic behavior evaluation of zipper braced steel frames based on push-over and incremental dynamic analyses", World Journal of Engineering, 16(3), pp. 401–411, 2019. https://doi.org/10.1108/WJE-11-2018-0389

[2] Esfandiari, J., Zangeneh, E., Esfandiari, S. "Experimental and numerical investigation on RC moment-Resisting frames retrofitted with NSD yielding dampers", Advances in Concrete Construction, 13(4), pp. 339–347, 2022. https://doi.org/10.12989/acc.2022.13.4.339

[3] Khaleel Ibrahim, S., Movahedi Rad, M. "Limited Optimal Plastic Behavior of RC Beams Strengthened by Carbon Fiber Polymers Using Reliability-Based Design", Polymers, 15(3), 569, 2023. https://doi.org/10.3390/polym15030569

[4] Magbool, H. M., Zeyad, A. M. "The effect of various steel fibers and volcanic pumice powder on fracture characteristics of Self-Compacting concrete", Construction and Building Materials, 312, 125444, 2021. https://doi.org/10.1016/j.conbuildmat.2021.125444

[5] Abdullah, G. M. S., Alshaikh, I. M. H., Zeyad, A. M., Magbool, H. M., Bakar, B. H. A. "The effect of openings on the performance of self-compacting concrete with volcanic pumice powder and different steel fibers", Case Studies in Construction Materials, 17, e01148, 2022. https://doi.org/10.1016/j.cscm.2022.e01148

[6] Amin, M., Hakeem, I. Y., Zeyad, A. M., Tayeh, B. A., Maglad, A. M., Agwa, I. S. "Influence of recycled aggregates and carbon nanofibres on properties of ultra-high-performance concrete under elevated temperatures", Case Studies in Construction Materials, 16, e01063, 2022. https://doi.org/10.1016/j.cscm.2022.e01063

[7] Vijay, T. J., Raj, A. V. S., Sarath Babu, M. "Experimental investigation of concrete beams reinforced with polypropylene bars", Materials Today: Proceedings, 37, pp. 1654–1658, 2021. https://doi.org/10.1016/j.matpr.2020.07.181

[8] Murad, Y., Abdel-Jabbar, H. "Shear behavior of RC beams prepared with basalt and polypropylene fibers", Case Studies in Construction Materials, 16, e00835, 2022. https://doi.org/10.1016/j.cscm.2021.e00835

[9] Mo, J., Zeng, L., Liu, Y., Ma, L., Liu, C., Xiang, S., Cheng, G. "Mechanical properties and damping capacity of polypropylene fiber reinforced concrete modified by rubber powder", Construction and Building Materials, 242, 118111, 2020. https://doi.org/10.1016/j.conbuildmat.2020.118111

[10] Akın, S. K., Kartal, S., Müsevitoğlu, A., Sancıoğlu, S., Zia, A. J., İlgün, A. "Macro and micro polypropylene fiber effect on reinforced concrete beams with insufficient lap splice length", Case Studies in Construction Materials, 16, e01005, 2022. https://doi.org/10.1016/j.cscm.2022.e01005

[11] Xin, C. L., Wang, Z. Z., Zhou, J. M., Gao, B. "Shaking table tests on seismic behavior of polypropylene fiber reinforced concrete tunnel lining", Tunnelling and Underground Space Technology, 88, pp. 1–15, 2019. https://doi.org/10.1016/j.tust.2019.02.019

[12] Ding, Y., Wang, Q., Pacheco-Torgal, F., Zhang, Y. "Hybrid effect of basalt fiber textile and macro polypropylene fiber on flexural load-bearing capacity and toughness of two-way concrete slabs", Construction and Building Materials, 261, 119881, 2020. https://doi.org/10.1016/j.conbuildmat.2020.119881

[13] Abdul Rasoul, Z. M. R., Radhi, M. S., Alsaad, A. J., Muhannad, H. "Elevated temperature performance of reinforced concrete beams containing waste polypropylene fibers", Case Studies in Thermal Engineering, 21, 100705, 2020. https://doi.org/10.1016/j.csite.2020.100705

[14] Chung, C. H., Lee, J., Kim, H. J. "Evaluation of fire performance of polypropylene fiber RC slabs", KSCE Journal of Civil Engineering, 17, pp. 1040–1050, 2013. https://doi.org/10.1007/s12205-013-0101-y

[15] Esfandiari, J., Heidari, O., Esfandiari, S. "Experimental behavior of buckling restrained braces by adding diferent admixtures concrete and using the steel core under cyclic loads", Case Studies in Construction Materials, 18, e01876, 2023.
https://doi.org/10.1016/j.cscm.2023.e01876

[16] Köksal, F., Rao, K. S., Babayev, Z., Kaya, M. "Effect of steel fibres on flexural toughness of concrete and RC beams", Arabian Journal for Science and Engineering, 47(4), pp. 4375–4384, 2022.
https://doi.org/10.1007/s13369-021-06113-5

[17] Sakthivel, P. B., Vijay Aravind, S. "Flexural strength and toughness of steel fiber reinforced concrete beams", Asian Journal of Civil Engineering, 21(8), pp. 1309–1330, 2020.
https://doi.org/10.1007/s42107-020-00279-3

[18] Ramkumar, K. B., Kannan Rajkumar, P. R., Gunasekaran, K. "Performance of hybrid steel fiber-reinforced self-compacting concrete RC beam under flexure", Engineering Science and Technology, an International Journal, 42, 101432, 2023.
https://doi.org/10.1016/j.jestch.2023.101432

[19] Chen, X., Diong, Y., Azevedo, C. "Combined effect of steel fibers and steel rebars on impact resistance of high-performance concrete", Journal of Central South University, 18(5), pp. 1677–1684, 2011.
https://doi.org/10.1007/s11771-011-0888-y

[20] Yoo, D.-Y., Moon, D.-Y. "Effect of steel fibers on the flexural behavior of RC beams with very low reinforcement ratios", Construction and Building Materials, 188, pp. 237–254, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.08.099

[21] Khalighi, A., Izadifard, R. A., Zarifian, A. "Role of macro fibers (steel and hybrid-synthetic) in the residual response of RC beams exposed to high temperatures", SN Applied Sciences, 2, 1981, 2020.
https://doi.org/10.1007/s42452-020-03790-z

[22] Roshan, N., Ghalehnovi, M. "The effect of recycled-tire steel fiber and engineered steel fiber on rebar corrosion and shear behavior of corroded RC beam", Case Studies in Construction Materials, 19, e02251, 2023.
https://doi.org/10.1016/j.cscm.2023.e02251

[23] Soltani, H., Khaloo, A., Sadraie, H. "Dynamic performance enhancement of RC slabs by steel fibers vs. externally bonded GFRP sheets under impact loading", Engineering Structures, 213, 110539, 2020.
https://doi.org/10.1016/j.engstruct.2020.110539

[24] Gong, F., Ren, M., Maekawa, K. "Simulation of spatially non-uniform frost damage in RC beams under various exposure and confining conditions", Engineering Structures, 176, pp. 859–870, 2018.
https://doi.org/10.1016/j.engstruct.2018.09.044

[25] Wang, Z., Hayashida, H., Zhang, D., Gong, F., Ueda, T. "Structural behaviors evaluation of RC beam under frost damage – A methodology with meso-macro material/bond simulation and integrating into structural analysis", Engineering Structures, 206, 110162, 2020.
https://doi.org/10.1016/j.engstruct.2019.110162

[26] Chung, Y. S., Lee, D. H., Park, C. K., Park, J. Y. "Seismic enhancement of circular RC bridge piers with fiber composites", KSCE Journal of Civil Engineering, 6, pp. 485–493, 2002.
https://doi.org/10.1007/BF02842002

[27] Nowak-Michta, A. "Impact analysis of air-entraining and superplasticizing admixtures on concrete compressive strength", Procedia Structural Integrity, 23, pp. 77–82, 2019.
https://doi.org/10.1016/j.prostr.2020.01.066

[28] Eskandari, H., Nic, A. M., Ghanei, A. "Effect of air entraining admixture on corrosion of reinforced concrete", Procedia Engineering, 150, pp. 2178–2184, 2016.
https://doi.org/10.1016/j.proeng.2016.07.261

[29] TahamouliRoudsari, M., Eslamimanesh, M. B., Entezari, A. R., Noori, O., Torkaman, M. "Experimental assessment of retrofitting RC moment resisting frames with ADAS and TADAS yielding dampers", Structures, 14, pp. 75–87, 2018.
https://doi.org/10.1016/j.istruc.2018.02.005

[30] BSI "BS 1881-102:1983 Testing Concrete - Method for Determination of Slump", British Standard Institution, London, UK, 1983.

[31] Esfandiari, J., Heidari, O. "Investigation on the behavior of concrete with optimum percentage of steel fiber, microsilica, fly ash and hybrid fiber under different loading pattern", Journal of Structural and Construction Engineering, 8(6), pp. 130–150, 2021.
https://doi.org/10.22065/JSCE.2020.182908.1840

[32] ACI Committee 374 "ACI 374.1-05 Acceptance Criteria for Moment Frames Based on Structural Testing and Commentary: An ACI Standard", American Concrete Institute, Farmington Hills, MI, USA, 2005.

[33] FEMA "FEMA-440 Improvement of nonlinear static seismic procedures", Federal Emergency Management Agency, Washington, DC, USA, 2005.

[34] Esfandiari, S., Esfandiari, J. "Simulation of the behaviour of RC columns strengthen with CFRP under rapid loading", Advances in Concrete Construction, 4(4), pp. 319–332, 2016.
https://doi.org/10.12989/ACC.2016.4.4.319

[35] Esfandiari, S. "Numerical investigations of the fatigue behavior of the concrete with the Microplane-Model MS1", Master Thesis, RWTH Aachen University, 2023.
https://doi.org/10.13140/RG.2.2.12337.35688/1

[36] Szép, J., Habashneh, M., Lógó, J., Movahedi Rad, M. "Reliability Assessment of Reinforced Concrete Beams under Elevated Temperatures: A Probabilistic Approach Using Finite Element and Physical Models", Sustainability, 15(7), 6077, 2023.
https://doi.org/10.3390/su15076077

[37] Rad, M. M., Papp, F., Ibrahim, S. K., Szép, J., Gosztola, D., Harrach, D. "Elasto-plastic analysis and optimal design of composite integral abutment bridge extended with limited residual plastic deformation", Scientific Reports, 13, 5461, 2023.
https://doi.org/10.1038/s41598-023-32787-y

[38] Movahedi Rad, M., Ibrahim, S. K., Lógó, J. "Limit design of reinforced concrete haunched beams by the control of the residual plastic deformation", Structures, 39, pp. 987–996, 2022.
https://doi.org/10.1016/j.istruc.2022.03.080