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Research Article

Effects of Steel Springs on the Flexural Strength of Normal Concrete Beams: A Numerical and Experimental Study

Ilham Ibrahim Mohammed [1,*]

[1] Civil Engineering Department, Faculty of Engineering, Tishk International University, Sulaymaniyah 46001, Iraq

*Corresponding Author: Ilham Ibrahim Mohammed, E-mail: ilham.ibrahim@tiu.edu.iq

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Abstract

In this research study, the possibility of deployment of steel spring utilization to reinforce a concrete beam is investigated and compared with steel bars; this is done to enhance the flexural strength of the structural concrete beam. For this purpose, three specimens are prepared: a plain concrete beam, a reinforced concrete beam, and a spring-reinforced concrete beam. A point bending test is dedicated to calculating the failure strength of each specimen. ABAQUS program is being used to simulate the three test specimens with the same properties as the experimental test samples to verify the results. The results of the numerical simulations for the flexural stress and the plastic strain of each model are collected and compared with the experimental tests. The results manifested a particularly good verification for the experimental tests, and the spring-reinforced concrete beam displayed an excellent flexural strength that exceeded the flexural strength of the reinforced concrete beam. This indicates that the spring-reinforced concrete beam, according to the properties of the spring, is a promising endeavor for use in the construction industry.

1. Introduction

The Flexural strength of concrete beams, also known better as bending strength, is a critical property of concrete beams used to determine their ability to withstand bending loads without cracking or failing. It is an indirect measure of concrete's tensile strength, which is relatively low compared to its compressive strength. The flexural strength of normal-weight concrete can be altered and affected by the steel reinforcement percentage, positioning of steel reinforcement, and their greater tensile strength, flexibility, and high stiffness, the steel spring positioning if used as the reinforcement material in concrete beams. The specific behavior of steel springs in concrete has not been extensively studied due to its impact on concrete structures' overall performance and durability. To produce concrete beams reinforced with steel springs with greater flexural capacity than steel reinforcement and provide a good response in the plastic region, understanding the behavior of steel spring positioning is crucial for engineers and researchers to design and construct safe and reliable concrete structures.

The shear strength of concrete is an essential parameter in the design of structural elements such as beams, slabs, and columns. The shear strength and flexural capacity are related together in several ways.

Modifying the flexural capacity will, directly and indirectly, impact the shear performance of reinforced concrete members.

Potentially, steel springs can be used as reinforcement in concrete structures due to their high tensile strength depending on the spring type by providing additional support to counteract tensile stresses that occur in structural members subjected to bending or shear forces. Properly positioning steel springs within a concrete element is crucial for achieving optimal load-carrying capacity and ensuring structural integrity.

Numerous studies have investigated the positioning of reinforced steel effects on conventional concrete's shear and flexural strengths. This research focused on various aspects, including how steel spacing, orientation, diameter, length, and anchorage factors affected reinforced concrete element performance.

The effect of steel spring on the flexure and shear behavior of reinforced concrete beams has been studied [1]. Different beam samples have been evaluated with varying spring spacing ratios, and they have noticed that closer spacing will result in higher flexure and shear resistance due to the increased restriction provided by adjacent springs [2].

The influence of spring positioning on the flexural strength of reinforced concrete slabs was explored by Zhang, et al. [3]. They made a comparison between the effectiveness of slabs with vertical and horizontal spring positioning and saw that the vertical orientation resulted in much higher flexural strength, and this is due to the enhanced load distribution along the slab length. In addition to the positioning and spacing, the steel spring diameter and length have also been shown to have played a significant role in determining their effectiveness in reinforcing concrete structures.

Also, Yousefi and Khatibi [4] have investigated the effect of spring diameter on the shear strength of reinforced concrete columns. The researchers observed that increasing the diameter of steel springs led to increased shear resistance due to enhanced confinement provided by larger springs. Similarly, a study by Alrshoudi [5] focused on the influence of spring length on the flexural strength of reinforced concrete beams. The team evaluated beams with different spring lengths and discovered that longer springs resulted in greater flexural strength due to improved reinforcing efficacy across a broader span. Aside from these considerations, appropriate anchoring of steel springs within a concrete element is critical for optimal performance. Several studies have evaluated various anchoring mechanisms, such as hooking, bending, and mechanical connections. Zhong, et al. [6] investigated several anchoring options for steel springs in reinforced concrete slabs and determined that mechanical connections offered greater load transfer performance.

This study attempts to deploy a steel spring to reinforce a concrete beam instead of steel bars to enhance the flexural strength of the structural beam. Three specimens were prepared: a plain concrete beam, a reinforced concrete beam, and a spring-reinforced concrete beam. Four four-point bending tests are dedicated to calculating the failure strength of each specimen. ABAQUS program is being used to simulate the three tests to verify the experimental tests. The results of the numerical simulations for the flexural stress and the plastic strain of each model are collected and compared with the experimental tests. The results manifested an outstanding verification for the experimental tests, and the spring-reinforced concrete beam displayed an excellent flexural strength of 5 times that of the reinforced concrete beam. This indicates that the spring-reinforced concrete beam is a promising endeavor for use in the construction industry.

2. Literature Review

Numerical simulations play a key role in understanding the extraordinarily complex behavior of reinforced concrete structures. Several research studies have employed finite element analysis (FEA) to investigate the impact of steel reinforcement and spring effect on concrete beam flexural behavior. In a study by Xingyu, et al. [7], Finite element analysis was used to explore the impact of steel springs on the load-deflection response of reinforced concrete beams. The results showed that steel springs significantly increased load-carrying capacity and beam stiffness.

Another numerical investigation by Xiao, et al. [8] focused on analyzing the stress distribution within concrete beams with embedded steel springs. The findings revealed that steel springs effectively redistributed stress, reducing crack propagation and enhancing beam performance. Experimental studies provide valuable insights into real-world behavior and validate numerical models. Numerous researchers have conducted laboratory experiments to evaluate the impact of steel spring effect on concrete beam flexure.

In an experimental study by Pachideh, et al. [9], reinforced concrete beams with embedded steel springs were evaluated under four-point bending loads. The results demonstrated that incorporating steel springs improved beam ductility, delayed crack initiation, and reduced crack width.

Another researcher, Maranan, et al. [10], conducted an experimental investigation comparing plain concrete beams with those containing embedded steel springs subjected to three-point bending tests. The study revealed that incorporating steel springs enhanced the beams' load-carrying and energy absorption capacity. Similar studies have been conducted to investigate the flexural behavior of BFRC-concrete composite beams. The study aimed to determine the effect of BFRC (Basalt Fiber Reinforced Concrete) height on the flexural capacity of the composite beams. The study included three specimens of composite beams, which were assessed under a four-point bending test. The height of the BFRC layer was modified in each specimen to investigate its effect on flexural behavior. The study's findings indicated that the flexural capacity of BFRC-concrete composite beams was greater than that of standard concrete beams. The composite beams' flexural capacity increased as the BFRC layer's height increased. This implies that the BFRC reinforcement positively impacts the composite beams' flexural behavior [3].

It is important to note that these findings are based on experimentation and the study's unique settings. More research and experimentation may be required to generalize the findings and discover the best design parameters for BFRC-concrete composite beams in various conditions. Nonetheless, the work sheds light on the flexural behavior of BFRC-concrete composite beams and underlines the potential advantages of integrating BFRC reinforcement [3]. Several studies have combined numerical simulations with experimental tests to provide an in-depth understanding of the effect of steel springs on concrete beam flexural capacity.

The adoption of steel springs within concrete beams can have promising results in enhancing their flexural capacity depending on the type and orientation of the material. Both numerical and experimental studies have consistently shown that incorporating steel springs increases load-carrying capacity, ductility, beam stiffness, and energy absorption capacity. However, further studies are required to explore this technique's long-term durability and cost-effectiveness for practical applications in construction projects.

3. Methodology

3.1. Experimental Models

As shown in Figure 1, three prism specimens with the dimensions of 10x15x60 cm were prepared and assessed for flexure, and cube specimens (15*15*15)cm were prepared to test the compressive strength. The samples had different reinforcement configurations as follows:

- Sample 1: Plain concrete beam without any reinforcement
- Sample 2: Concrete beam with normal reinforcement (three 10 mm diameter steel bars at the bottom and two10 mm diameter steel bars at the top)
- Sample 3: Concrete beam with steel spring reinforcement (The steel spring had a length of 55 cm and a diameter of 0.5 cm, and a steel plate with a dimension of (7x7) cm and 0.4 cm thickness was used as reinforcement inside the concrete beam.

Figure 1. Three different specimens from the study

The longitudinal steel reinforcement cover used was 2 cm from each side**,** and the rebar mechanical properties used in this test setup w**ere** tested in the lab its yield strength was found to be 240 Mpa, Elongation 8%**,** and its strain value was 0.4%.

The shear reinforcement (stirrups) was placed at 15 cm interval**s**. The concrete mix used for all samples had a water-cement ratio of 0.35 and a design compressive strength of 35 MPa.

Before testing, the samples were left to stay in water for 28 days in a curing tank. For each sample, three cube specimens with dimensions of 15x15x15 cm were also prepared and assessed for compressive strength according to ASTM C39/C39M-18. The average compressive strength of the cubes was used to represent the compressive strength of the corresponding beam sample.

The flexural test was conducted using a four-point bending setup, as shown in Figure 2. The span length was 50 cm, and the loading points were located 12.5 cm from each support. The load was applied at a constant rate of 0.5 kN/s until failure. The load-deflection curves were recorded using a data acquisition system. The flexural strength was calculated as follows:

$$f_r = \frac{3PL}{2bd^2}$$

Where P is the maximum load, L is the span length, b is the width of the beam, and d is the depth of the beam.

Figure 2. Four-point bending test setup

3.2. Finite Element Models

The finite element models consist of three models: a plain concrete beam, a reinforced concrete beam, and a spring-reinforced concrete beam. The length of the concrete beam is 60 cm, and the cross-section dimensions are (15x10) cm. For the reinforced concrete beam, there are five longitudinal steel bars (two in the compression zone and three in the tension zone) with a diameter of 1 cm each and five stirrups with a diameter of 0.3 cm for each distributed regularly along the length of the beam. The steel spring has a length of 55 cm and a diameter of 0.5 cm, and a steel plate with a dimension of (7x7) cm and 0.4 cm thickness (See Figure 3). The concrete damage plasticity model would be deployed to analyze all models.

The loading is four point bending test where the loading parts are positioned 12.5 cm from the ends for each, and the distance between both loading parts is 16 cm. The supports are positioned 6cm from the ends where they have a 2 cm diameter as they are for the loading parts. A dynamic step is applied in the three cases with different duration times. The maximum failure time for the plain concrete was 51 seconds, for the reinforced concrete was 61 seconds, and for the spring reinforced concrete was 69 seconds. The concrete element is C3D8R, the steel bar element is B31, and the steel spring element is C3D4.

The material properties of the concrete and steel, which are needed for the numerical simulation using the ABAQUS program, are displayed in Table 1 as follows:

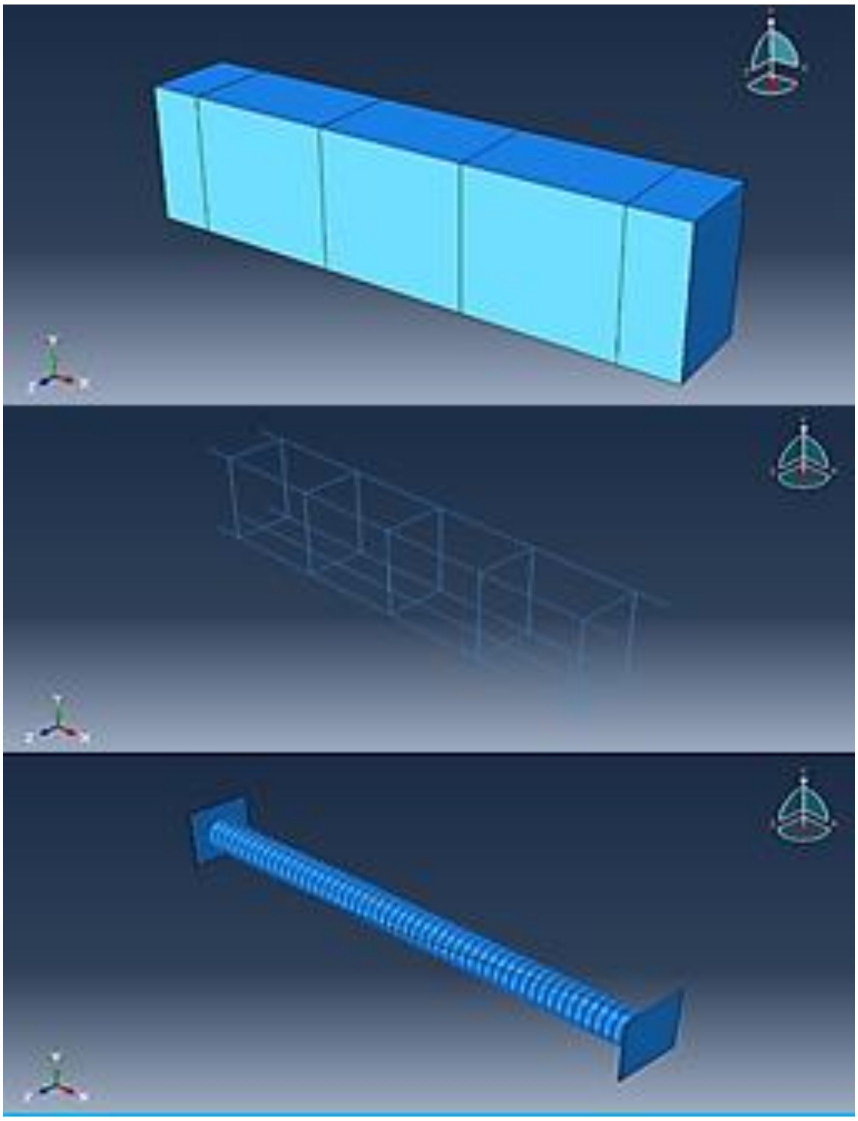

Figure 3. Finite Element Models

Table 1. Material Properties

Model	Density (kg/m^3)	Young's Modulus (Pa)	Poisson's Ratio
Concrete	2300	14000000000	0.21
Steel	7800	200000000000	0.30

4. Result and Discussion

4.1. Flexural Stress

The loading on the plain concrete beam took 51 seconds until the failure of the structural member. The flexural stress generated in the middle of the tension zone has reached 9.7 e+6 Pa, which is clearly shown by a wide orange color as an indication of the crack generation in that region compared to the other parts which are seen at the support explaining the fact of the beginning of shear crack generation spread to the loading in the compression zones in both sides (see Figure 4).

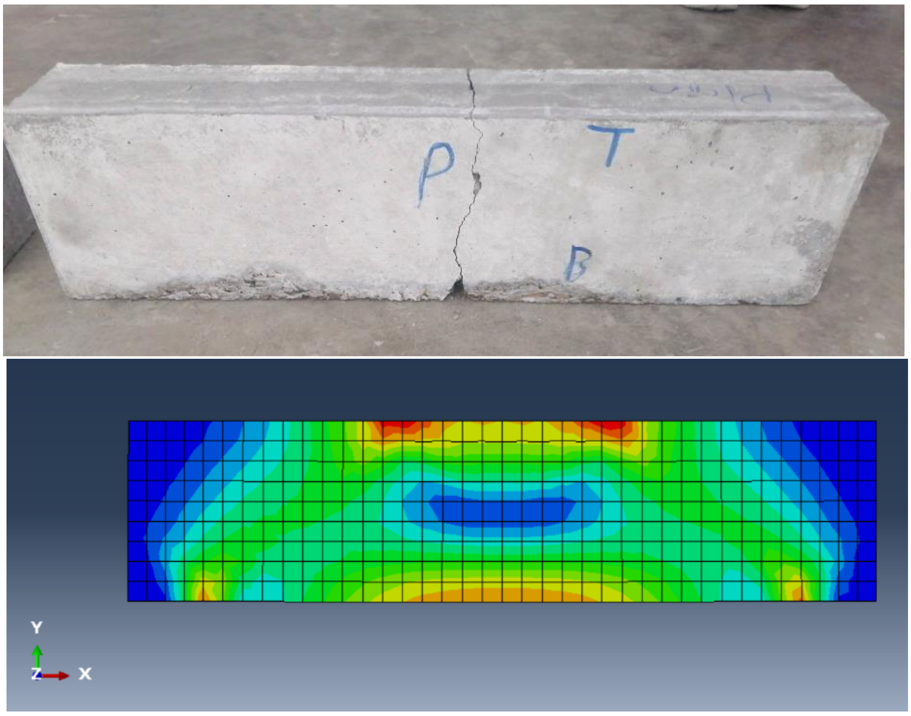

Figure 4. Plain Concrete Beam - Under the Flexural Stresses

The loading on the reinforced concrete beam took 61 seconds until the failure of the structural member. The flexural stress generated in a small part in the middle of the tension zone has reached 2.4 e+6 Pa, which can be seen as a grey color, indicating the start of the crack. Meanwhile, shear crack generation starts at the supports, which is not continued to the compression zones (see Figure 5). This stress is less than the plain concrete's case due to the consideration of steel reinforcement, which strengthened the beam four times.

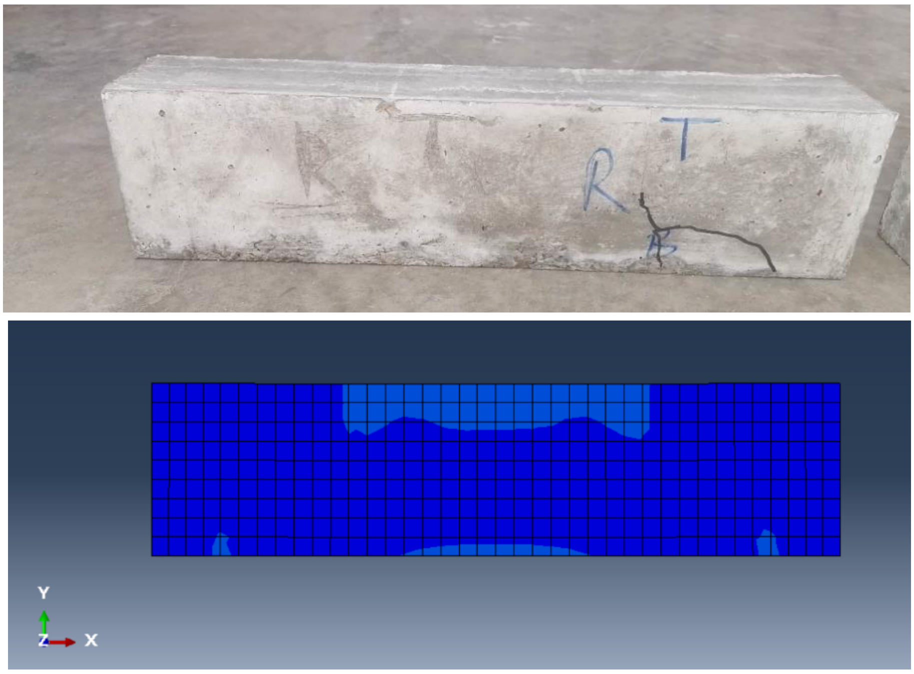

Figure 5. Reinforced Concrete Beam - Under the Flexural Stresses

Considering the spring-reinforced concrete beam, where the loading took 69 seconds till the failure of the structural member. The flexural stress has not propagated in the middle of the tension zone, reaching only 4.2 e+5 Pa but in small parts at the supports. The flexural stress can be seen as grey, indicating the start of the shear crack only (see Figure 6). This stress is less than the case of the plain concrete by 23 times and the reinforced concrete beam case by five times, which is a great indication that positioning the steel spring instead of the steel bars has strengthened the beam for flexure better than the reinforced concrete beam.

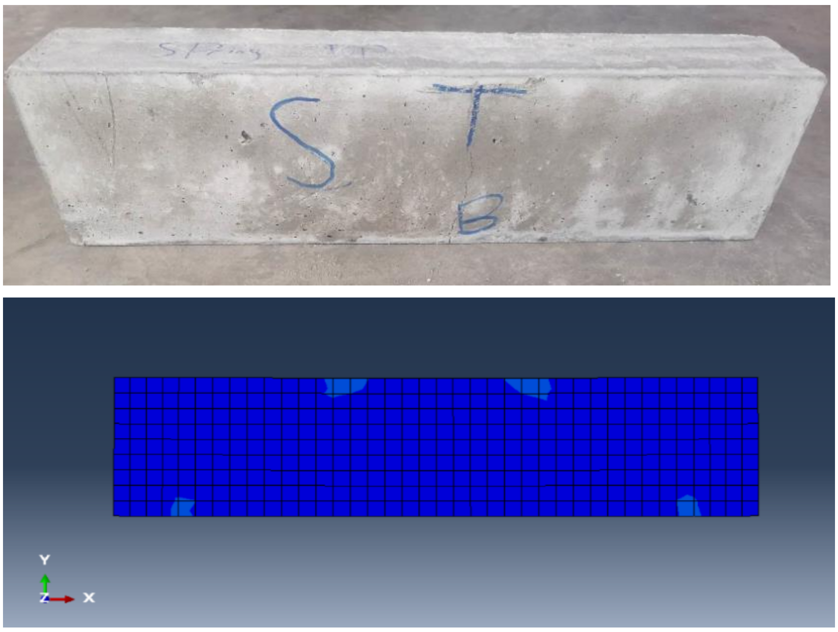

Figure 6. Spring Reinforced Concrete Beam - Flexural Stress

We realize the relation between the results for the plain concrete beam, reinforced concrete beam, and the spring reinforced concrete beam is non-linear (see Figure 7). This proves that many sensitivity parameters greatly determine the flexural stress values under loading. As a result, adopting steel springs as a reinforcement solution is a successful process that can develop the flexural strength of plain concrete compared to reinforced concrete beams.

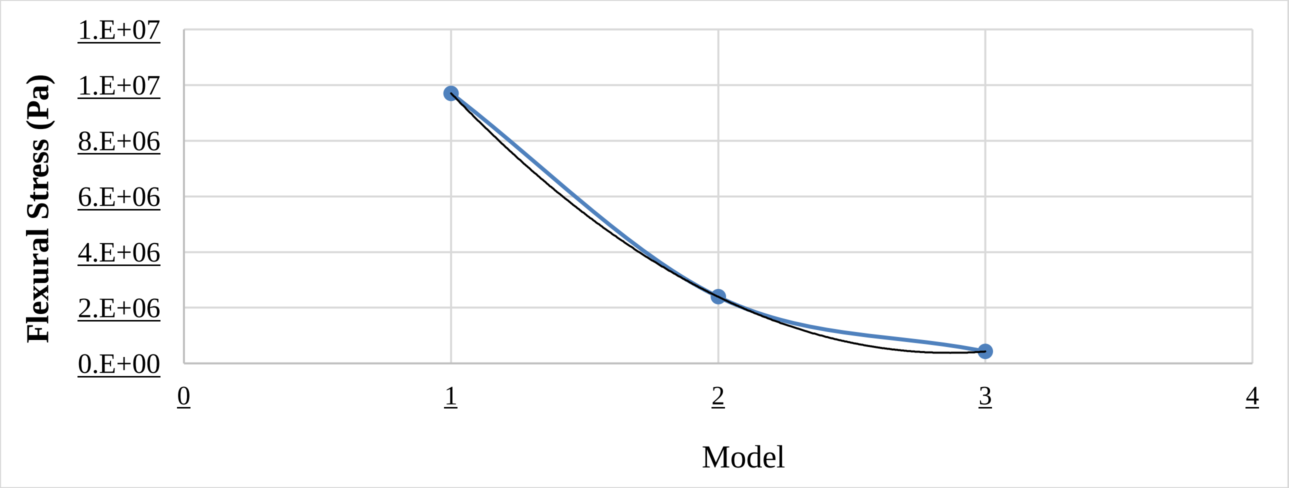

Figure 5. Relation between Models - Flexural Stress

4.2. Plastic Strain

The plastic strain value for the plain concrete beam model has reached 0.0005659, which can be seen in (Figure 8) as a green color in the bottom region of the beam in the middle part. In addition to the flexural stress, we can see the shear stress generation at the supports propagating towards the compression zone in red and blue colors. The controlling failure is a flexural failure, which can be distinguished clearly by comparing the stress values.

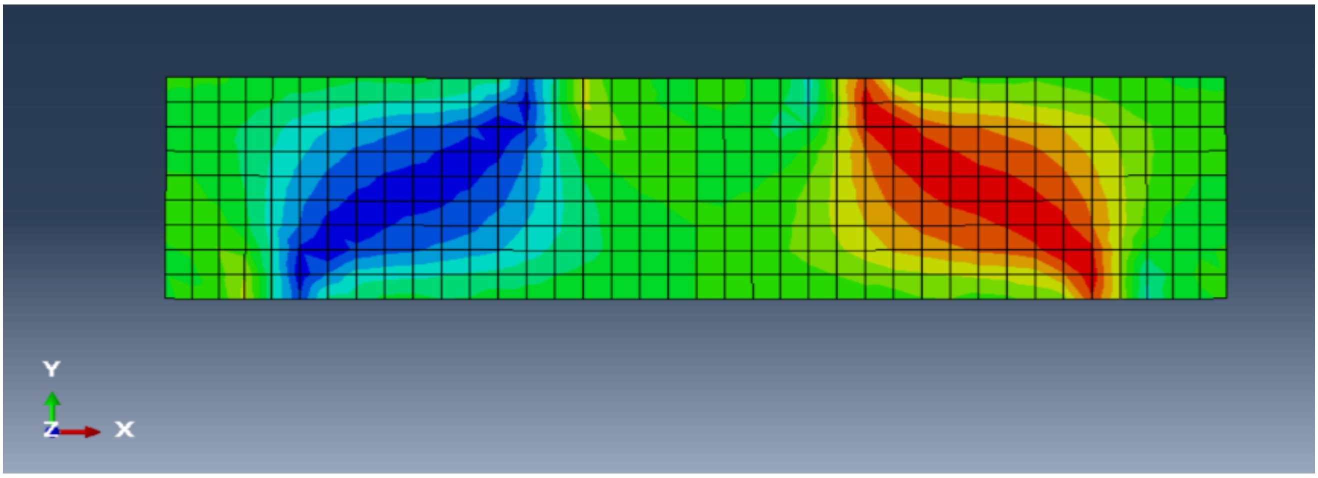

Figure 6. Plain Concrete Beam - Plastic Strain

The reinforced concrete beam model reached 0.0000226 for the plastic strain, which can be identified in the bottom region of the tension zone of the beam, represented by a green color (see Figure 9). In this case, the plastic strain has been decreased twenty-five times, which is so ordinary due to the provision of steel bars as reinforcement. Also, the shear stress has decreased for the same reason, enhancing both the flexural and shear strength.

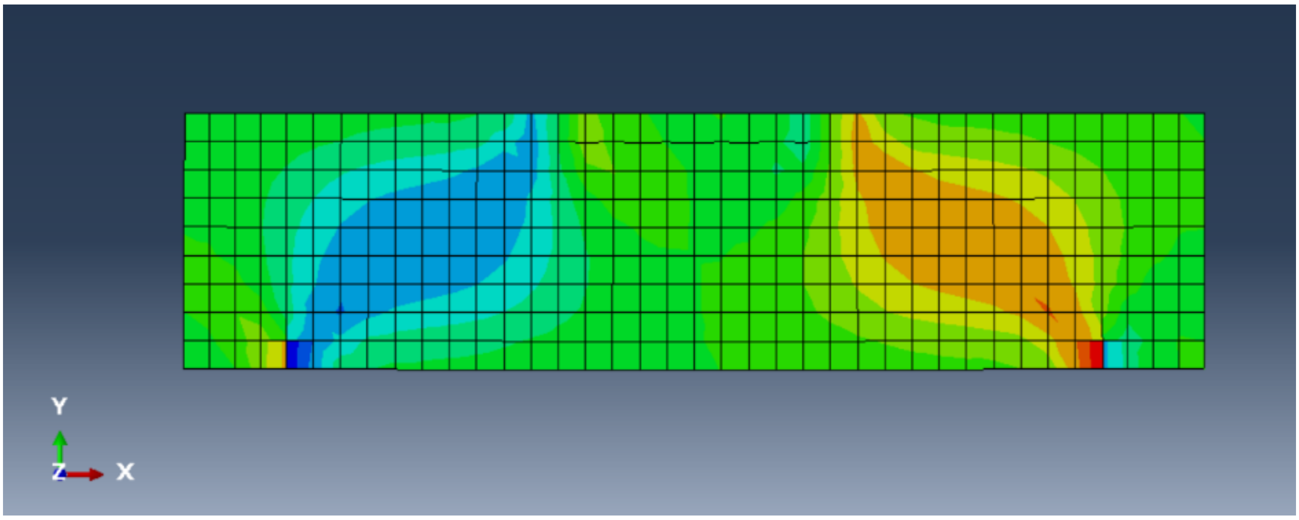

Figure 7. Reinforced Concrete Beam - Plastic Strain

The plastic strain for the spring-reinforced concrete beam model is 0.0000072, which decreased three times compared to the concrete beam model (see Figure 10). This means that the steel spring positioning has increased the flexural strength of the concrete beam very efficiently. Also, the shear stress has decreased, and the blue and red colors are getting lighter, indicating decreased shear stress. Consequently, the spring-reinforced concrete beam model has enhanced both the flexural strength and the shear strength of the beam to a very good extent.

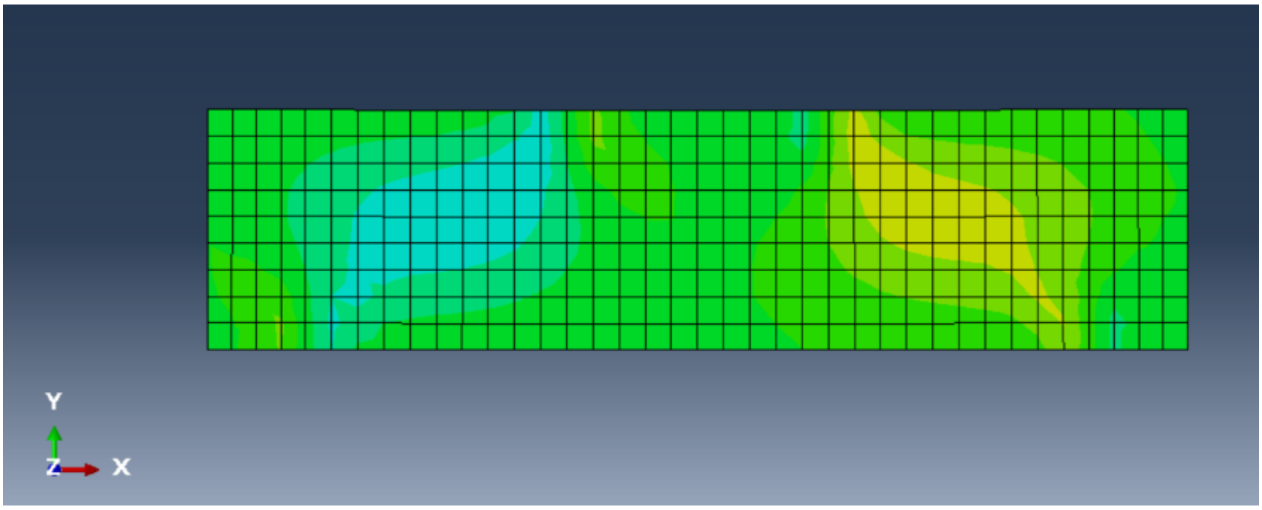

Figure 10. Spring Reinforced Concrete Beam - Plastic Strain

In the same way as the flexural stress, the relation between the three models is also non-linear. This is due to the proportional relation between the flexural stress and the plastic strain, which results in the same behavior under loading (see Figure 11).

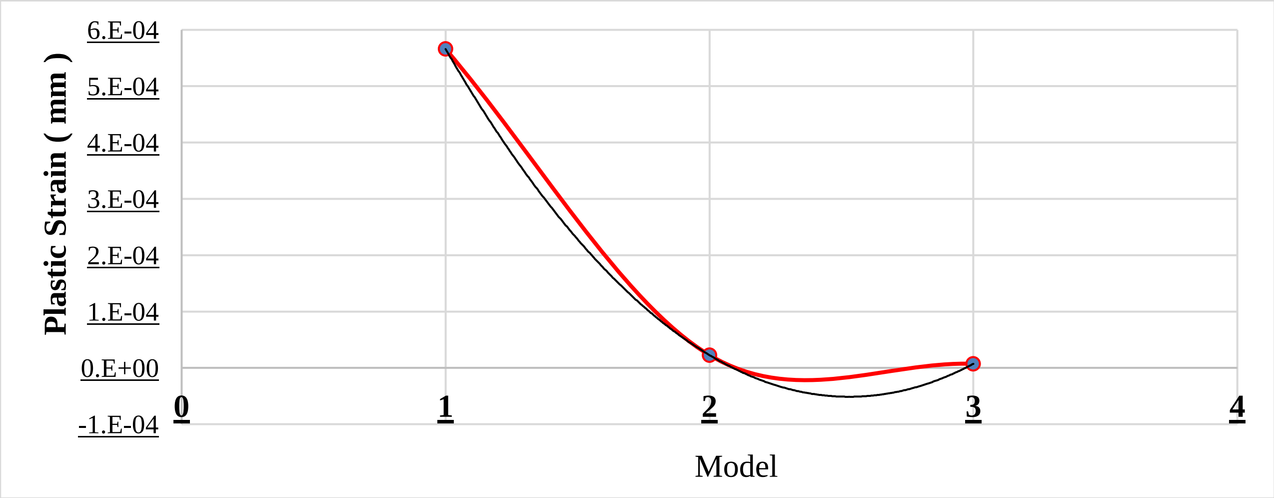

Figure 11. Relation between Models - Plastic Strain

5. Conclusions

The results and analysis have led to several key insights. Firstly, the ABAQUS program has effectively simulated the models' behavior under load, accurately predicting both flexural and shear stress for each model. This level of precision is particularly noteworthy. Furthermore, introducing spring reinforcement in concrete beams has marked a significant innovation, enhancing the flexural strength of structural beams by a factor of five compared to traditional reinforced concrete beams. This advancement is poised to influence the design of structural elements significantly. In addition, the spring-reinforced beams exhibited a threefold improvement in plastic behavior, suggesting a more robust resistance to the propagation of flexural and shear cracks under external loading. This aspect is critical for structural integrity. Lastly, the innovation of steel spring reinforcement is not just a technical achievement; it promises to revolutionize the economics of construction projects. By increasing the safety factor, this innovation ensures that designs are more economical, robust, and reliable, enhancing overall structural safety.

Declaration of Competing Interest:The author declare that he have no known competing of interest.

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