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Efficacy of Plastic Waste Strips Towards Enhancement of Shear Capacity of Reinforced Concrete Beams

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Abstract

The amount of plastic waste produced worldwide has been steadily rising. Manufacturing processes, service industries, and municipal solid waste produce a significant amount of waste plastic. One common construction and industrial waste that could be employed as shear reinforcement in concrete beams for specified purposes is the plastic waste strips, since they have relatively high tensile strength. Such plastic strips are used to tie clay bricks, floor finishing tiles, walkway finishing blocks, curbstones, and so on in different industrial products. This study examines an approach that uses plastic waste strips in place of conventional stirrups to enhance the shear performance of reinforced concrete (RC) beams. A set of shear tests was performed on carefully constructed 150 mm width × 225 mm depth × 1400 mm length beam specimens to evaluate failure mechanisms, modes of failure, crack patterns, and shear strength. All beams have the same flexural requirements, so they were ensured to fail by exceeding their shear strength under the applied load. This study examined five concrete beams that were reinforced internally using plastic waste strips in the shear region, as well as one control beam. The tested beams were reinforced using various strip spacings and configurations. The results of the tests indicated that increasing the plastic waste strips improved the concrete section shear strength. As the number of plastic strips in the section increases, the distance between each strip is drastically reduced, increasing the shear capacity of the beam. The experimental results indicate that the beam with six vertical plastic waste strips in its section has a 75% higher shear strength capacity than the reference beam without any transverse reinforcement. In addition, shear resistance is higher in the beam with plastic strips at 45° and 135° inclined angles than in the beam with vertical plastic strips in the same amount of plastic strips. Based on these findings, reinforced concrete beams can be utilized for specific purposes by employing plastic waste strips as transverse reinforcement to resist internal shear forces.

Keywords: Plastic Waste Strips; Improvement Shear Strength; Shear Failure; Strips Configurations; Reinforced Concrete Beams.

1. Introduction

In order to solve issues related to excessive use of natural resources, environmental contamination, and the production of significant amounts of solid waste, the construction sector was included in the development of the sustainability concept in recent years. The concrete industry is a major global consumer of natural resources and has a significant environmental impact [1]. New technology and human lives have led to the generation of waste materials. Plastics are in great demand worldwide because of their advantages, which include their affordability and suitability for various applications. It has been noted in recent years that there are excessive amounts of waste plastic in the world [2].

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The extensive use of plastics has led to an increase in the quantity of solid waste. Polyethylene makes up most plastic waste, whereas polyethylene terephthalate (PET) is the second most prevalent form. In recent decades, utilizing plastic waste to study the flexural behavior of concrete has shown promise. Several research studies have examined the use of plastic waste to improve the flexural behavior of concrete [3]. Abdulridha et al. [4] added waste rope fibers (WRF) to concrete. WRF was added to the concrete mixture in different amounts by the researchers, namely 0%, 0.25%, 0.5%, and 1% by weight of the concrete. The effect of adding these fibers on the mechanical properties of concrete, as well as the structural performance of concrete components, was investigated by the researchers. According to one of the study's most important findings, the addition of WRF increased the concrete's flexural strength by up to 4.3%. Polyethylene terephthalate fibers were added to concrete beams at two different volumetric percentages, 0.5% and 1%, by Khalid Ali et al. [5]. The effect of adding PET fibers to the concrete layer on the flexural behavior of the beams was evaluated. They found through test results that the ultimate load was considerably increased when PET fiber concrete was used with a layered distribution. Furthermore, they stated that concrete beams reinforced with PET fiber stacks showed greater deflections before failure. In the tension zone of concrete members, conventional reinforcing was applied in the form of plastic strips that were installed near the surface. The application of NSM by fiber-reinforced polymer materials to improve reinforced concrete structures has had a global focus of attention throughout the last 20 years [6-8]. To increase the resistance of reinforced concrete beams under flexural and shear loads, NSM FRP strengthening technology is frequently used. Several experimental and numerical studies have been carried out to investigate the use of bars or strips attached near the concrete member's surface to reinforce concrete beams. The results of these tests show that even though NSM FRP and concrete have a rather strong bond, debonding at the ends of NSM FRP flexural-strengthened RC beams is nevertheless a common cause of failure [9-11].

In the past, the primary prerequisite for a structural design was safety. These days, a structural design optimizes the structural dimensions while also taking sustainability and economic needs into account [12-14]. Understanding the behavior of materials and structures is essential to achieving ideal dimensions. To improve the behavior of materials and structures, innovations are also required [15]. The common forces applied to beams in frame structures, bending and shear stress, are quite dangerous. In order to withstand these stresses, beams must maintain safety limitations. Certain stresses, including shear failure or diagonal tension failure, can cause sudden and disastrous failures that are more hazardous and unpredictable and may differ from shear failure [16-18]. However, as pure shear stress is probably never seen in concrete structures, the authors feel that no other study has correctly assessed concrete's resistance to pure shear stress. However, inclined cracks, often referred to as diagonal or shear cracks, always appear in concrete members when they are subjected to shear stresses at ultimate load. These cracks are known as web shear cracks because they usually start in the web of beams, which has the maximum shear stress. When shear stresses exceed the concrete's tensile strength, shear failure happens [19]. Numerous research studies, such as those conducted by Ostovarzijerdi et al. (2019) [20] and Matta et al. (2013) [21], have examined the impact of size factor on the shear strength of FRP straight beams. Even when the beams are reinforced with various kinds of FRP bars and are exposed to various loading circumstances, all of these experiments consistently confirm that an increase in effective depth results in a decrease in normalized shear strength.

A study by Shewalul [22] examined the application of steel scrap and waste metal to increase the strength of concrete. The author experimented with different amounts of steel scrap in relation to the weight of the concrete mix. After much testing, it was found that there was a 5.3% drop at 1.5%, a 26.8% rise at 0.5%, and a 30.7% increase at 0.75%. Likewise, Gabule [23] investigated the use of steel chips to improve the concrete beams' shearing characteristics. Different amounts of steel chips were used in the study to evaluate their behavior. The findings showed an increase in steel fiber at 1% but a decrease at 0.5% and 1.5%. Steel stirrups and wire mesh of equivalent weight were used by Ghosh & Mukhopadhyay [24] on various beams. After testing was completed, it was discovered that adding wire mesh for shear reinforcement yields better results compared to using stirrups alone. Seshu et al. [25] reinforced the core zone of the beams in their investigation using welded wire mesh. To achieve shear failure, the authors placed the welded wire mesh at 160 mm intervals. The beams that were primarily intended for flexural failure failed with shear. According to the author, there was just a 3% improvement in shear strength. This enhanced resistance to shear and diagonal cracks resulted from the presence of welded wire mesh transverse reinforcement in the core zone. Several investigations and approaches have been carried out to increase the shear strength of RC beams, either by utilizing wire mesh or merely steel chips. According to the literature currently in publication, both strategies have been shown to increase the reinforced concrete beams' shear strength. Nevertheless, there is a study gap about using strapping plastic belts as stirrups to increase the shear capacity of reinforced concrete beams.

This study aimed to fill this knowledge gap, investigate the behavior of beams under shear, and determine the potential improvement in shear strength that could be brought about by using strapping plastic belts as stirrup reinforcement in the shear zone. The effectiveness of plastic strips in increasing the shear capacity of reinforced concrete beams is investigated in this research. To improve the shear performance of reinforced concrete (RC) beams, this study used plastic waste strips in place of traditional stirrups to conduct experimental testing on six beams with different inclination angles and cross-sectional areas. The results of the experimental study will be presented, with an emphasis on using different strip spacing and configurations. The results will also be thoroughly discussed. The analysis of the tests showed that adding more plastic waste strips increased the shear strength of the concrete section, and the results will be compared with previous research. Key findings will be outlined in the conclusions, along with possible uses for this dual approach in concrete beams that resist internal shear forces by using plastic waste strips as transverse reinforcement. Future research directions will also be suggested. According to the suggested framework shown in Figure 1, this study was a laboratory-analytical investigation that was conducted to improve the shear performance of reinforced concrete (RC) beams by substituting plastic waste strips for traditional stirrups.

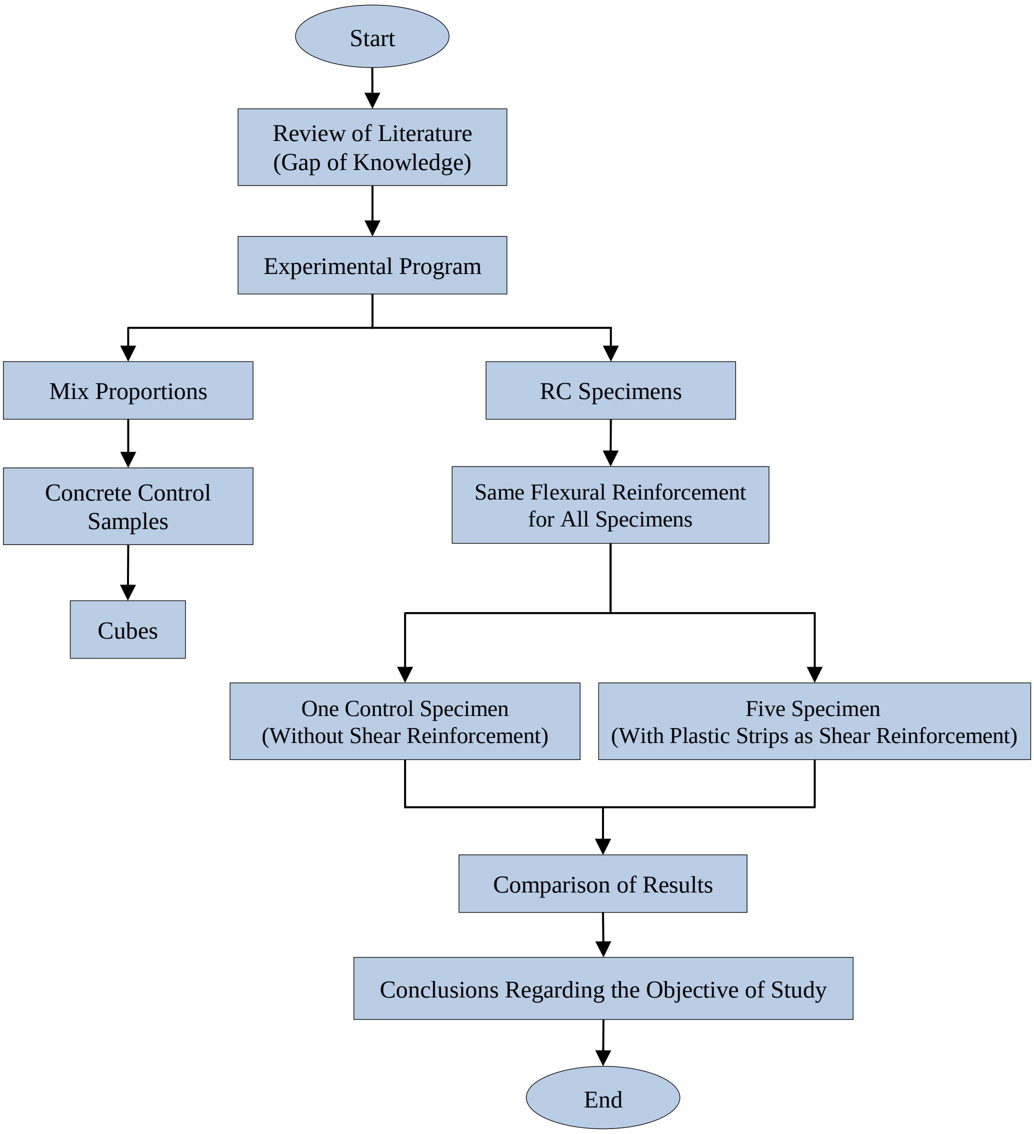


Figure 1. The proposed framework's scheme

2. Experimental Program

2.1. Materials

2.1.1. Cement

Ordinary Portland cement (type I) was used in the experiment work. It was stored in airtight plastic containers to avoid exposure to humid air conditioning and to maintain constant quality. For ordinary Portland cement, the cement characteristics meet the ASTM C150 specification limitations [26].

2.1.2. Sand

Al-Akhaidher natural sand provides the graded fine aggregate used in concrete, which having a particle size that is suitable for a 4.75 mm filter. Fine aggregate is tested in accordance with ASTM C33 [27] specifications. The grading of the sand confirmed the requirements of ASTM C33 [27], as shown in the Figure 2.

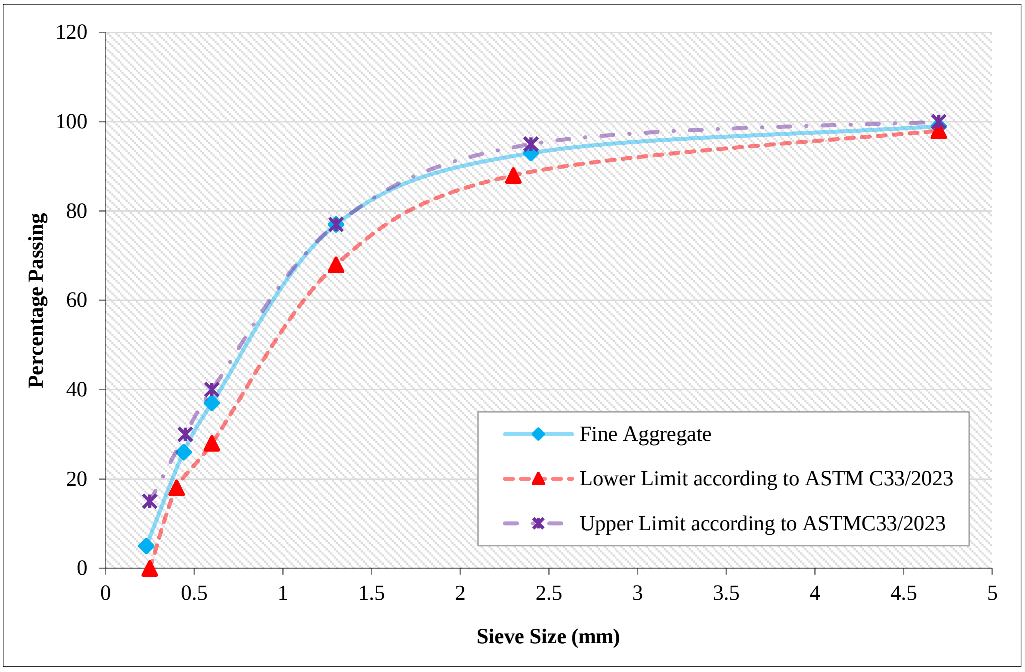


Figure 2. The fine aggregate grading curve

2.1.3. Coarse Aggregate

The coarse aggregate was crushed gravel up to 14 mm in size. The best coarse aggregate to utilize is one that is 100% crushed, clean, typically cubical or angular, and has at least some flat and elongated particles. The gravel was cleaned with water from the duct and then left to air dry before use. ASTM C33 requirements are confirmed by the gravel's grading [27], as shown in the Figure 3.

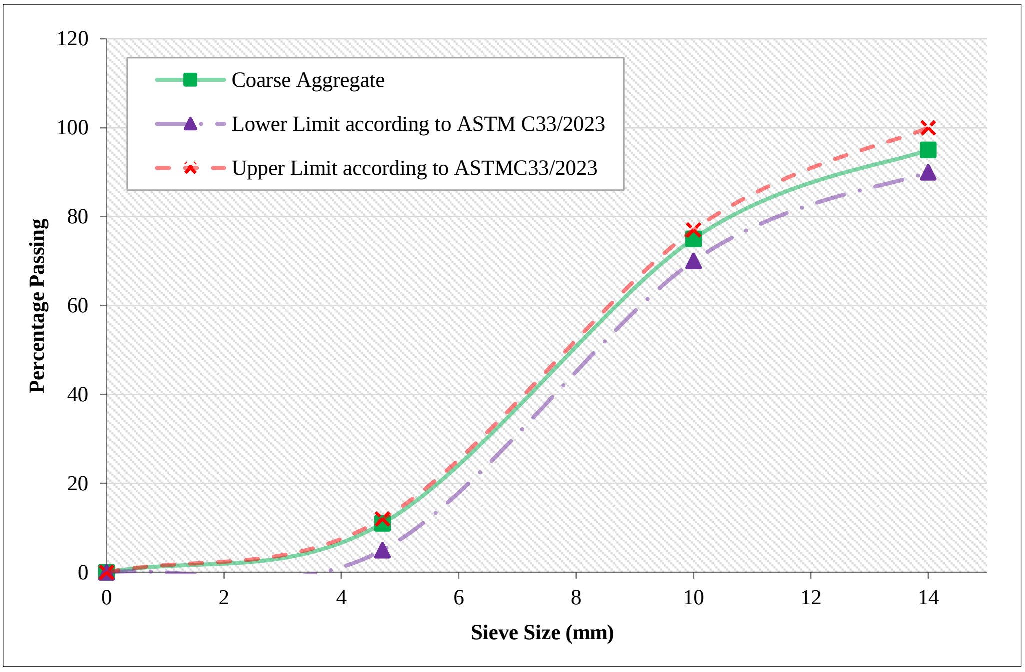


Figure 3. The coarse aggregate grading curve

2.1.4. Plastic Waste Strips

Waste Plastic strapping belts, as shown in Figure 4-a were used instead of traditional stirrups as shear reinforcement in reinforced concrete (RC) beams. Three specimens of plastic strips were tested in the laboratory using a MTS 150 universal testing machine, as shown in Figure 4-b. When tested, the ties' average tensile stress was 214 MPa, as indicated in Table 1. Figures 5 illustrate the stress-strain performance of plastic waste strips specimens.

(a) Plastic waste (b) Experimental test setup

Figure 4. Plastic waste strips under test

Table 1. Tensile strength of strapping ties

Sample 1×16 mm	1	2	3	Average
Tensile strength MPa	213.5	214.8	213.6	214

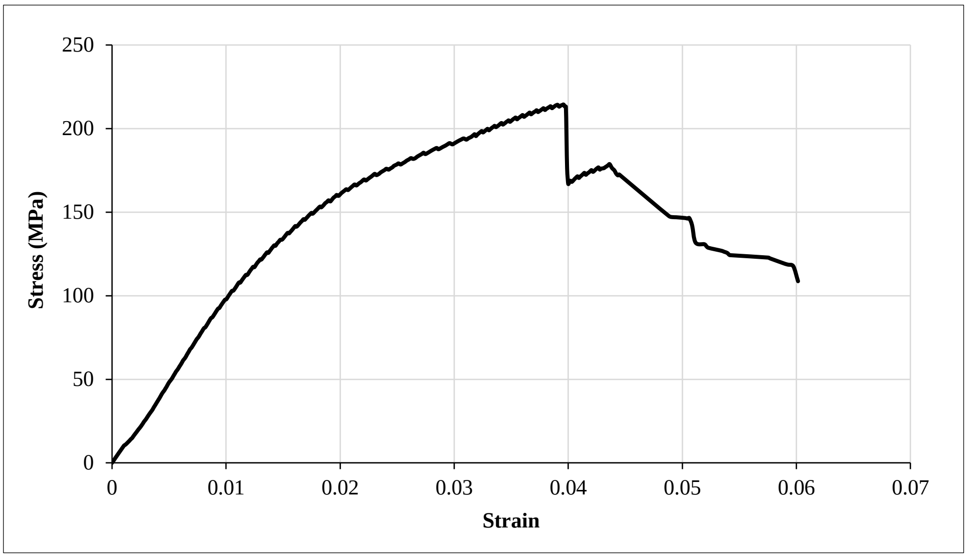


Figure 5. Plastic strip stress-strain

2.1.5. Steel Reinforcement

Steel bars with nominal diameters of 16 mm and 12 mm at the bottom and 10 mm at the top were utilized as longitudinally deformed bars to reinforce all concrete beams. Three steel stirrups only were made from 10 mm deformed bars distributed along the beam to install longitudinal reinforcement in location. For the 16 mm bars, the average yield stress and ultimate strength were 658 MPa and 723, respectively, whereas the values for the 12 mm bars were 640 MPa and 707 MPa. Furthermore, the 10 mm's maximum strength and average yield stress were 660 and 590 MPa, respectively. These findings complied with ASTM-A615 [28].

2.2. Concrete Mix Preparation

According to the British design approach BS 5328 part 2: 1991 requirements, a mix was created to produce concrete with a 28-day compressive strength of 25 MPa [29]. With a maximum aggregate size of 14 mm and a water/cement ratio of 0.48, the concrete mix was created using the following weight-based proportions: 1 (cement), 1.8 (fine aggregate), and 2.95 (coarse aggregate). A medium workable slump range of 80 mm to 100 mm was employed in this experiment in accordance with ASTM C143 [30]. Following mixing, the concrete was poured into two-layer molds, and each layer was compacted using a plunger mechanical vibrator (3000 vibrations per minute) equipped with a 50 mm-diameter metal rod for five seconds each time, or until no air bubbles appeared on the concrete's surface. In the lab, the molds were covered with polyethylene sheets for roughly twenty-four hours after being leveled by hand trawling. The details of the mix proportion are shown in Table 2.

Table 2. Mix proportion of concrete mix (kg/m^3)

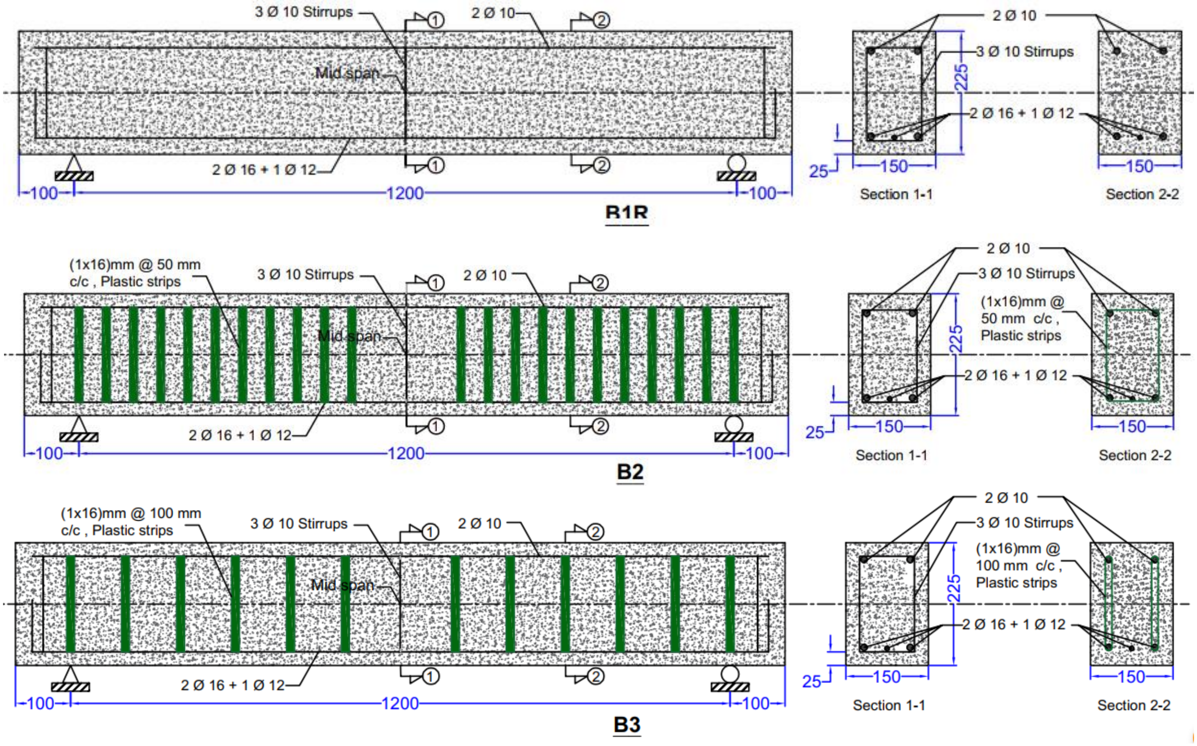
Mix	Cement	Fine Agg.	Coarse Agg.	*W/C* ratio %	Target Compressive Strength (MPa)
NC	390	700	1150	0.48	25

2.3. Specimens Details

There were six reinforced concrete beams in the experimental program. The beam's measurements were 1400 mm long, 225 mm deep, and 150 mm wide. Steel reinforcement, comprising two 16 mm diameter steel bars, one 12 mm diameter steel bar at the bottom of the beam, and two 10 mm diameter steel bars at the top, was installed for all beams. Along the beam, only three 10 mm-diameter stirrups were positioned: two at the end and one in the center. To prevent shear failure, the plastic belts are arranged as stirrups with varying spacing between 50 mm and/or 100 mm centers. The details of all beams are illustrated in Table 3. The dimensions and configuration of plastic belt details of the tested beams are highlighted in Figure 6. The reference beam, which was one of the six specimens (marked as B1R), doesn't have waste plastic strips for shear reinforcement. The shear reinforcement in the other five was made of waste plastic strips in various patterns. Waste plastic strips were arranged in a ring pattern spaced 50 mm apart for the B2 beam, much like traditional steel stirrups. So, two vertical plastic strips were used to resist the internal shear force. Four plastic strips, positioned vertically on the longitudinal reinforcement and spaced by 100 mm and 50 mm, served as shear reinforcement in the beams known as B3 and B4, respectively. Plastic strips in B5 were angled by 135° and 45 degrees. 50 mm is the typical angled separation between strips. The plastic strip of 45° at the specimen's left end is parallel to the shear cracks, but the strip of 135° is perpendicular to them, so plastic strips of 135° resist the internal shear force. At the other end, the situation is reversed. Six plastic strips, spaced 50 mm apart, were affixed vertically to the longitudinal reinforcement of the specimen known as B6 in order to resist internal shear force. Here, two of the six plastic strips were fixed by adding an additional 10 mm diameter bar to the top bars. In order to have a shear failure mechanism, all specimens were longitudinally reinforced.

Table 3. Beam test variables

Specimen Designation	Description
B1R	Reference beam without plastic belts for stirrups
B2	Every 50 mm, the plastic belts similar to the traditional stirrups.
B3	Every 100 mm, the plastic belts stabilized as two separate stirrups
B4	Every 50 mm, the plastic belts stabilized as two separate stirrups
B5	Every 50 mm, the plastic belts stabilized at a 45° and 135°
B6	Every 50 mm, the plastic belts stabilized as three separate stirrups



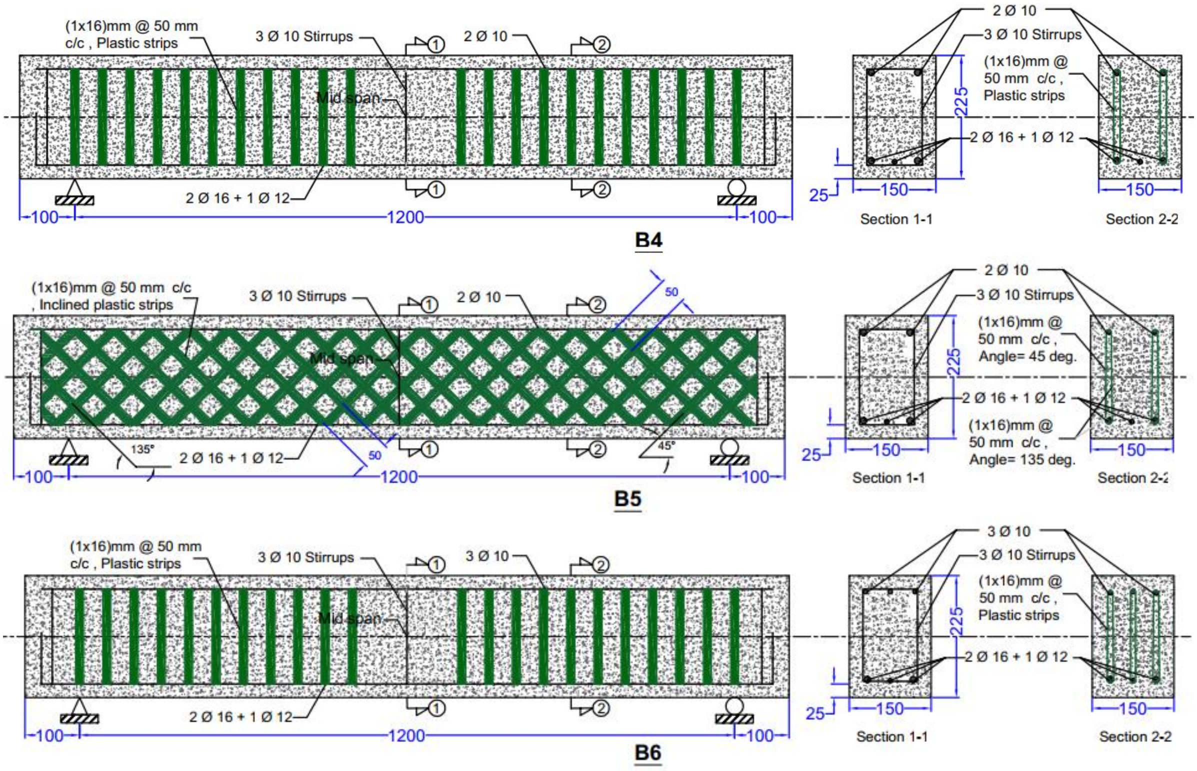


Figure 6. Details of configuration waste plastic strips stabilize as stirrups in the test beams

2.4. Preparing the Beam Specimen

Six simply supported reinforced concrete beam specimens were cast and cured in a lab setting at Kerbala University's construction materials laboratory, which is part of the civil engineering department. After the reinforcing bars were cut to the appropriate length, each bar's ends were shaped into 90-degree hooks, as shown in the Figure 7. Once the internal surface of the wooden molds had been cleaned with a thin layer of lubricating oil, the reinforcing bars were placed within the mold to form a 25 mm concrete cover over them. Three 100 × 100 × 100 mm concrete cubes were included in each control model. A polyethylene covering was placed over the beams to prevent plastic shrinkage cracks within 24 hours of the concrete being cast. After that, the beams were covered with burlap sacks and wetted down. While the other beams were strengthened with plastic belts as stirrups in the shear zone, the first beam served as a control sample without plastic belts.

Figure 7. Plastic belts configured as shear zone stirrups (Note: B1R has the same details but without plastic strips)

2.5. Testing Procedure

Each beam was tested using a hydraulic testing machine with a 2000 kN capability in Kerbala University's construction materials laboratory. The applied loads are distributed over two points by a solid steel beam at the top of the specimen. A view of the machine during beam testing is depicted in Figure 8. Every beam underwent monotonic load shear testing till failure and was tested as simply supported. The testing machine's load cell recorded the load after it was increased by 5 kN. Additionally, the displacement was recorded by a data acquisition system. The beams were loaded in a four-point loading system with a shear span of 450 mm on each side and a clear span of 1200 mm between the supports, as shown in Figure 9. One linear variable differential transducer (LVDT) was placed at the mid-span of the beam and connected to the data logger in order to monitor the deflections in the beams. Crack patterns were also investigated. The loads and cracks on the side face of each specimen were labelled.

Figure 8. A hydraulic testing machine with a test configuration

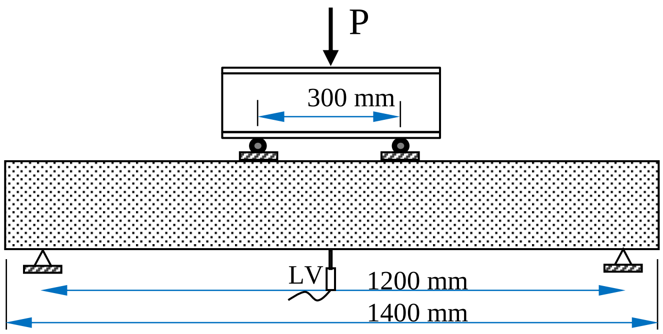


Figure 9. Beam test setup

3. Results and Discussion

As previously stated in section 2.3, six RC beams were made and evaluated under the influence of four-point loads until they failed by shear as adapted in previous studies [6, 10, 11, 31]. All beams have the same dimensions and longitudinal reinforcement. Plastic waste strips were used as shear reinforcement; however, the beams don't have steel transverse reinforcement.

3.1. Failure Mechanism and Mode of Failure

Every specimen was tested while being loaded with four points. Shear failure occurred after the stress was applied and increased gradually. All specimens exhibit elastic behavior with a linear load-deflection relation at the early loading stage. At or close to the mid span at the maximum bending moment zone, concrete flexural cracks develop when the load is gradually increased. As the load increases, diagonal tension-induced shear cracks begin to form close to the supports. There is one shear crack that has become wider. Eventually, the specimen fails where the specimen shear strength is exceeded as force is steadily raised. All specimens fail owing to exceeding the shear strength of concrete in diagonal tension, with the exception of specimen B6, which appears to have a combined mechanism of failure due to both exceeding the shear strength and yielding of flexural steel bars. Figure 10 shows cracking patterns and failure mode for all tested specimens.

Figure 10. Tested beams

3.2. Cracking and Ultimate Loads

Every specimen was examined while being loaded with four points. Shear failure occurred after the load was applied and increased progressively. The ultimate shear capacity loads, the first visible shear crack, the first visible flexural crack and the deflection values were recorded. The percentages of change in ultimate and cracking loads were then calculated. These test results are displayed in Table 4. The values of the first visible cracking shear loads are higher than those of the first visible cracking flexural loads, as seen in Table 4. This is because shear cracks are caused by diagonal tension close to supports, but flexural cracks are caused by horizontal tension at the bottom fiber. However, in order to ensure shear failure, all specimens were reinforced longitudinally; as a result, the specimens are stiffer in flexure than in shear. Cracking and ultimate loads are qualitatively represented in Figure 11. It is evident that there is little variation in the cracking load values. This is because every specimen was made using the same concrete mix. Visually, every tested beam showed signs of crack start and propagation under load. In Figure 9, the crack pattern of every beam is depicted. This Figure shows that the mode of failure in the beams was due to shear failure. Furthermore, it is clear that the crack pattern is the same in every beam with the exception of beam (B5), which shows a more increase in both the quantity and width of cracks due to the plastic waste's inclination in comparison to other beams with vertical plastic strips.

Table 4. Cracking, ultimate loads capacity and deformations

Specimen Designation	P_{cr} *flexure* (kN)	P_{cr} *shear* (kN)	P_u *shear* (kN)	P_{cr} Increasing [a] (%)	P_u Increasing [a] (%)	Δ_{cr} *flexure* (%)	Δ_u *flexure* (%)
B1R	50	90	100	-	-	3.1	5
B2	45	70	125	-10	25	1.57	5.7
B3	50	95	126	-	27	2.4	6.9
B4	45	90	140	-10	37	1.98	4.96
B5	55	78	127	10	27	2	4.45
B6	60	85	175	20	75	1.55	7

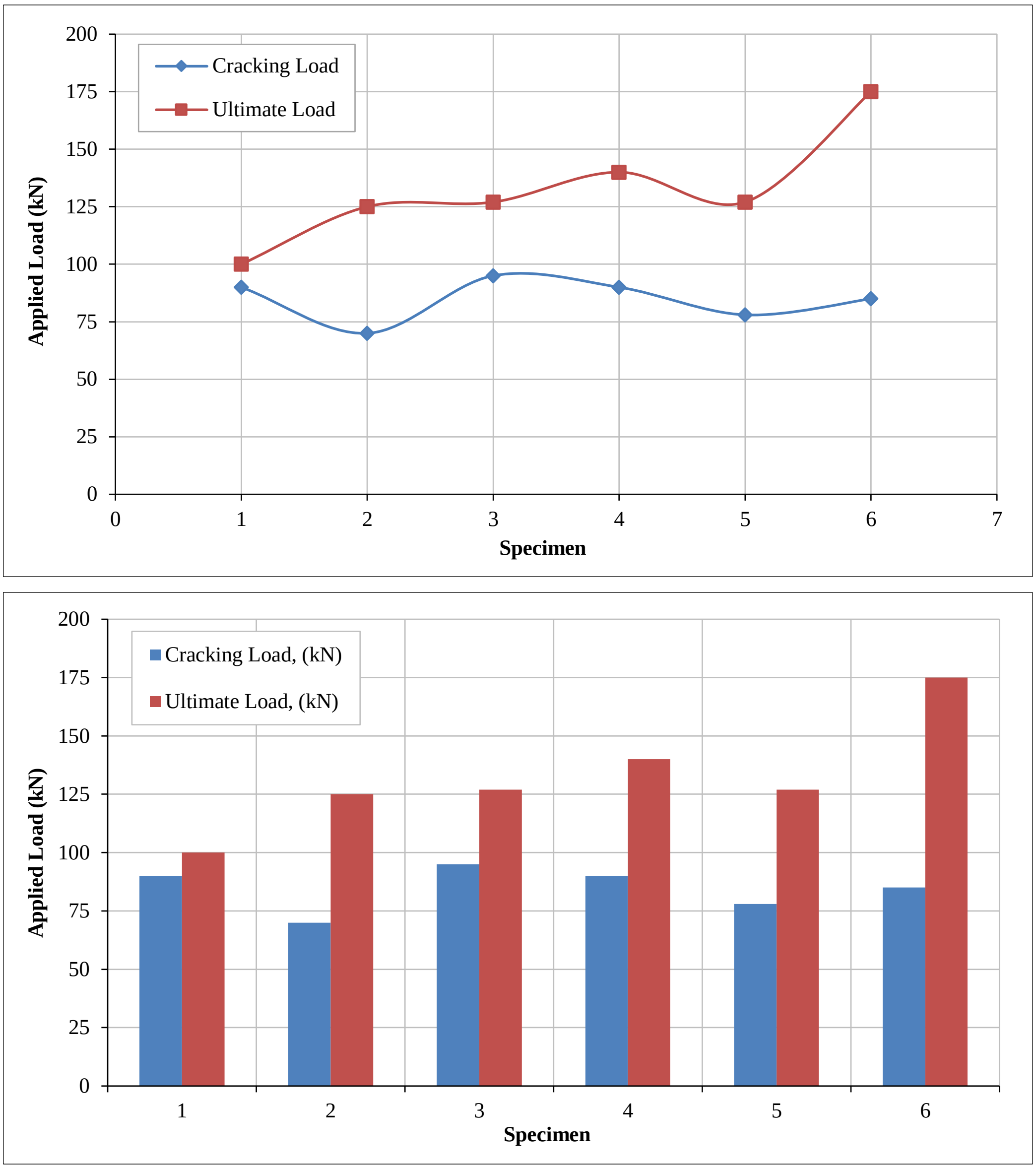


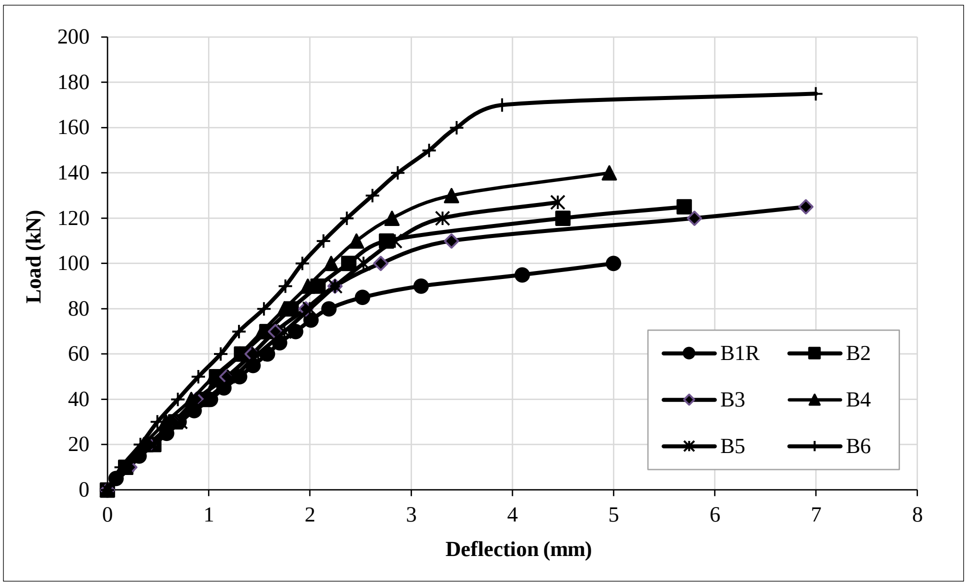
Figure 11. Shear cracking and ultimate loads

The fact that concrete is not homogeneous is the cause of the slight variations in their values. However, the quantity and design of plastic strips significantly increase the ultimate shear strength. At a load level of 100 kN, the reference specimen, B1R, fails due to shear. Specimens B2, B3, B4, B5, and B6 had shear strength capacities that are 25%, 27%, 37%, 28%, and 75% higher than those of the reference specimen. The use of plastic strips as shear reinforcement results in an increase in shear resistance. Shear resistance is roughly equivalent in specimens B2 and B3. This is because B3 has four vertical plastic strips placed 100 mm centers, whereas B2 has two vertical strips spaced 50 mm centers. Despite having the identical pattern of plastic strips, specimen B4 has a stronger shear strength capacity than B3 due to the reduction of the strip spacing to 50 mm. Because specimen B5 likewise features two plastic strips as inclined shear reinforcement, its shear resistance is almost identical to that of specimens B2 and B3. According to test results, specimen B6 exhibits the greatest resistance to applied shear. This outcome is due to the presence of six vertical plastic strips, which act as shear reinforcement.

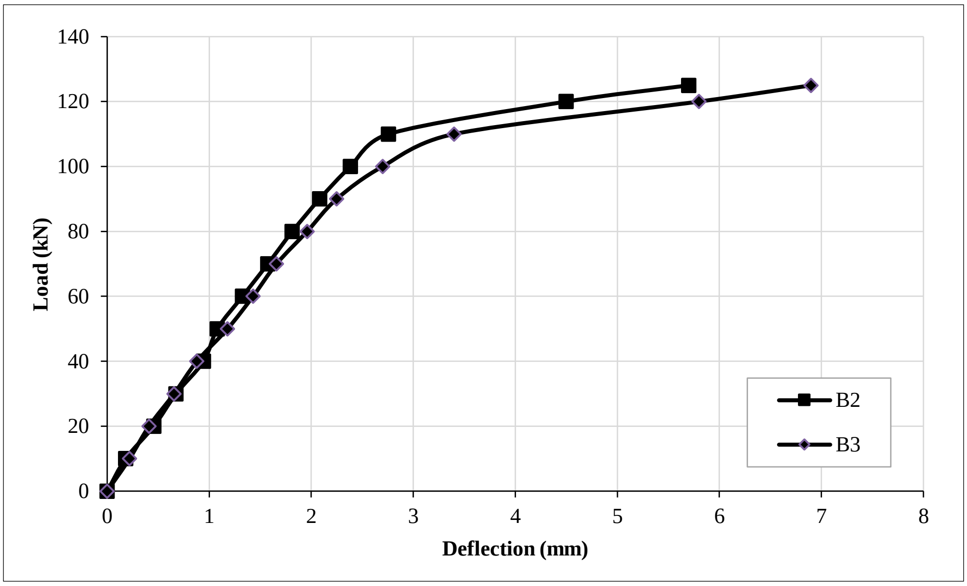
3.3. Load–Deflection Relation

The mid span deflection values for the initial flexural visible crack load and ultimate load are displayed for each tested specimen in Table 4. All specimens' load-deflection relation curves are plotted. Figure 12-a explains a comparison of behavior of specimens having plastic strips as shear reinforcement with respect to reference one, B1R, which have no plastic strips. Typically the deflection increases linearly with applied load until the first crack load is reached, after which the relationship tends to be nonlinear until the failure load is reached. In general, all specimens had almost the same deflection values at the initial cracking load, as illustrated in the Figure 12. This is because each specimen has almost the same flexural stiffness where they have the same flexural requirements. The non-homogeneous nature of the concrete may cause variations in flexural stiffness, which could be the cause of the slight variations in deflections at cracking load. However, they exhibit greater variations in deflection values at higher loading levels. Also the specimen’s containing plastic strips as shear reinforcement tend to have stiffer behavior. The inclusion of plastic strips as shear reinforcement, which delay cracks from starting at the shear flexural zone, gives B2, B3, B4, B5, and B6 a higher flexural stiffness than B1R. However, due to the fact that it has a greater number of plastic strips for shear reinforcement, B3 is slightly less stiffness than B2, as shown in Figure 12-b; this because of the plastic strip spacing in B2 is half that in B3.

Load-deflection relations for specimens B2, B3, and B5 are introduced in Figure 12-c. B5 is stiffer than B2 and B3 since it has two inclined plastic strips; that means normal to crack direction, whereas each of B2 and B3 has vertical plastic strips. It can be said that inclined plastic strips are more efficient. Specimen B4 is stiffer than B5, as shown in Figure 12-d; because it has four vertical plastic strips whereas B5 has two inclined ones; so it offers a higher shear strength. The load-deflection relation for B3, B4, and B6 is displayed in Figure 12-e. These specimens have same pattern but different number of vertical plastic strips. Specimen B4 is stiffer than B3 since it contains larger amount of plastic strips, spaced by 50 mm, as shear reinforcement than that of B3, spaced by 100 mm. Because it contains six vertical plastic strips spaced by 50 mm and this is greater than that of B3 or B4, specimen B6 is owing more stiffness than B3 and B4. In general, the presence of shear reinforcement restrains in-plane flexural deflection where specimens' resistance to flexural-shear deformation is increased.



(a)



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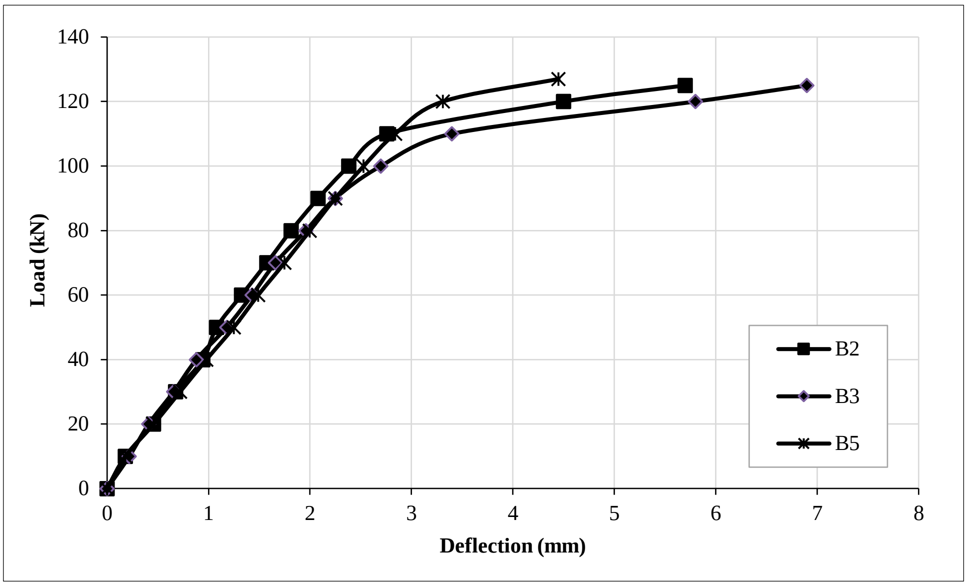

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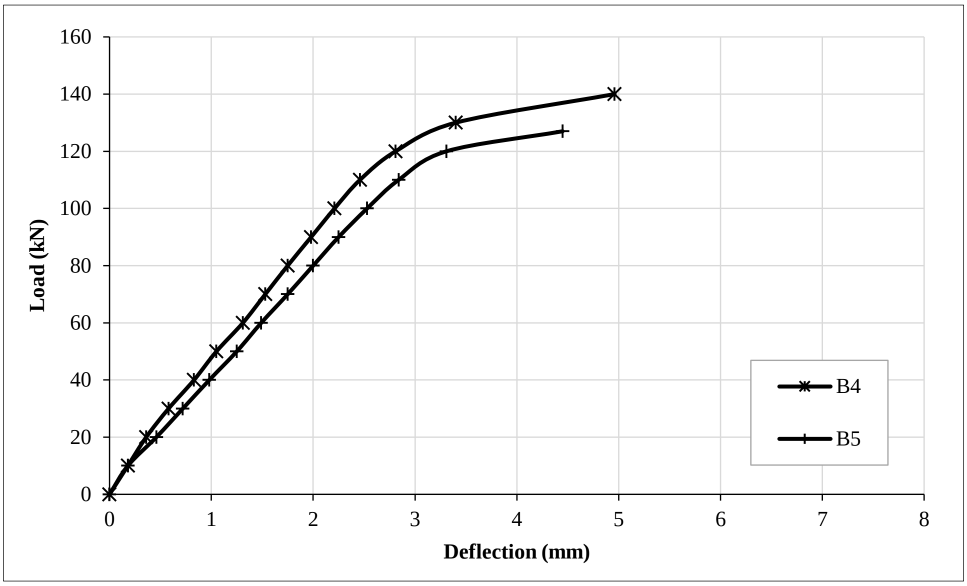

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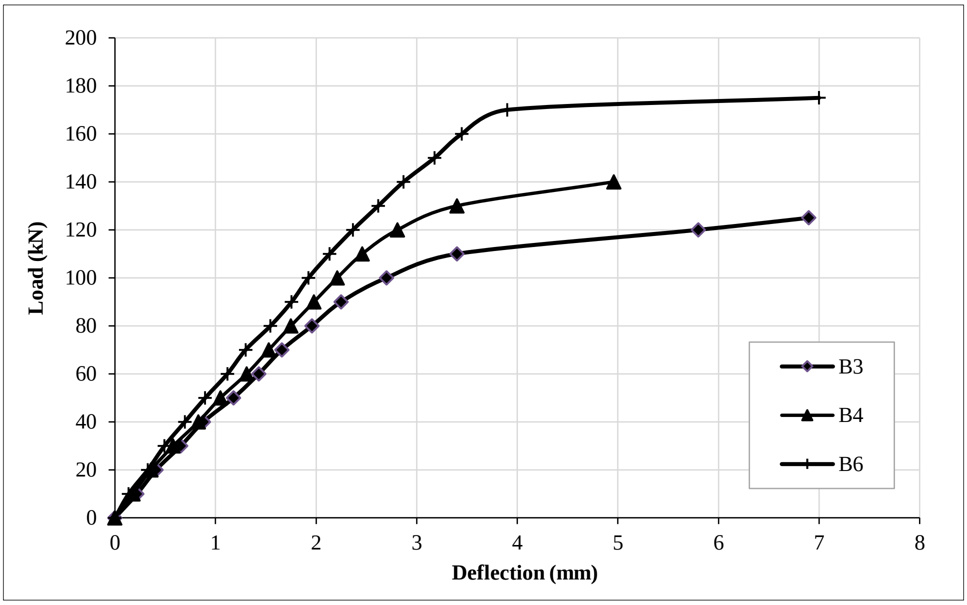

(e)

Figure 12. Load-deflection curves for tested shear beams

4. Conclusions

The current study's experimental results and discussion allow for the following deductions to be made:

- Making reinforcement out of recycled plastic strips is one way to address the environmental issue. Additionally, for some applications, reinforced concrete beams made using this technology will be more effective. These practices promote a sustainability-focused approach.
- The load-deflection curves show that the reinforced beams with plastic straps are stronger than the ones without them, where the shear strength capacities of beams with plastic straps are greater than those of the reference beam by 25-75%. Shear resistance increases when plastic strips are used as shear reinforcement.
- The shear strength capacity increased when plastic strips were used as stirrups. Compared to four plastic strips, six plastic strips which act as shear reinforcement exhibited greater stiffness and capacity.
- Despite having the same section amount of strips, the shear resistance of a beam with inclined plastic strips is higher than that of a beam with vertical plastic strips; this indicates that inclined strips that are perpendicular to the direction of the crack are more effective.
- Using plastic waste strips as transverse reinforcement to resist internal shear force tends to restrict the spread of flexural and web shear cracks, increasing the overall

4.1. Recommendations

- The procedure presented in this study can be applied for specified purposes like light loaded reinforced concrete beams such as lintels and other small precast beams.
- The effectiveness of using plastic waste strips to increase the reinforced concrete beams' flexural capacity.
- Using NSM FRP strengthening technology to increase the shear strength capacity for beams reinforced with plastic waste strips.
- Using plastic waste strips to increase the strength of concrete.
- Study the performance over the long-term, including under cyclic loading, sustained loads, and temperature changes.

5. Declarations

5.1. Author Contributions

Conceptualization, S.H.; methodology, S.H.; validation, S.H. and A.J.; formal analysis, S.H. and A.G.; investigation, S.H. and A.J.; resources, A.J. and N.M.; data curation, A.G. and A.J.; writing—original draft preparation, A.J. and N.M.; writing—review and editing, S.H. and A.J.; visualization, A.G. and S.H.; supervision, A.G. and S.H.; project administration, S.H., N.M., and A.J.; funding acquisition, N.M., S.H., A.G., and A.J. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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