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RESEARCH ARTICLE

Reinforcement concrete beams with external steel elements

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Abstract: The reinforcement of structural elements is widely practiced worldwide. It can be applied due to deterioration of the concrete, either due to age, change of use, extensions, or updating of the design code. However, it is sometimes used with inappropriate materials or without technical supervision or structural design. The main purpose of this paper is to investigate the method of strengthening based on the external addition of steel elements and to determine its influence on the flexural load-carrying capacity of reinforced concrete (RC) beams. For the same area of external steel, two types of beams are defined: the first one with cold-formed angle sections at the bottom corners, and the second one with a steel plate in the center of the tension face of the beam. The behavior of a total of 12 beams under monotonic and cyclic loading is experimentally studied. The connection was made with post-installed expanding bolts, without adhesives. The configuration that presents adequate results in terms of strength, flexibility, and energy, this obtained with the addition of a steel elements. On the other hand, the use of angled sections, contrary to expectations, reduces the load-carrying capacity and ductility of the section.

Keywords: Reinforcement, reinforced concrete, beams, plates, angles.

1. Introduction

The use of reinforced concrete structures is common in construction due to their economy, strength, tradition, and durability. However, over time, beams may be subjected to greater loads than initially anticipated, material deterioration, cracking due to seismic activity, etc. These variations compromise their structural capacity and jeopardize the safety of occupants and elements of a building.

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In response to this situation, external reinforcement of concrete beams has become an effective solution for increasing load capacity. This technique involves adding elements such as angle profiles, steel plates, or carbon fiber strips to the outer zone of the beam, increasing resistance to different stresses, and improving its structural behavior [1].

The application of external steel members began in the 1960s due to their cost-effectiveness and versatility. Since then, efforts have been made to demonstrate that reinforcing structures externally with steel is an effective technique for increasing strength and achieving suitable performance, to minimize the need to demolish structures with deficiencies [2]-[4].

Primarily, the use of plates and angle profiles for external reinforcement has been of interest. Some studies have focused on analyzing post-reinforcement load capacity, deflection, and the durability of external reinforcement, among other variables, to ensure its effectiveness and long-term durability [5]-[7].

Adding plates has shown significant benefits in responding to different stresses based on certain factors: position, joining method, thickness, plate type, facility, etc. As indicated by [8] and [9], placing lateral plates on reinforced concrete beams allows for a reduction in the quantity and extent of shear cracking. Alfeehan A and Alkerwei H [10], evaluated plate anchorage to a concrete beam using bolts with and without epoxy adhesive and observed that the load capacity effectively increased. However, beams without adhesive failed due to pull-out or connector yielding, not the plate. Aykac and Ozbek [11] tested T-section concrete beams reinforced with perforated steel plates and post-tensioned anchors, obtaining positive results in strength and ductility. Additionally, Oh et al [4], report that both shear stress and tension normal in the layer between the plate and the beam is the main cause of possible premature failure.

On the other hand, adding angle profiles has also demonstrated benefits. For example, Tayeh and Abusharar indicate that reinforcing beams for shear with steel angles improves strength and deflection, delaying shear failure but not preventing it [12].

Considering that external reinforcement with steel elements is widely used today, sometimes even by non-professionals without appropriate materials or technical control, this study focuses on examining the experimental behavior of reinforced concrete beams by adding the same area of external steel, using both plates and L-type profiles (angles). The objective is to experimentally determine the solution that presents the highest load capacity and appropriate structural response. Bolts are used as an anchoring technique without epoxy adhesive. This helps identify the level of safety and structural performance when using this technique and reduces the risks associated with possible structural failures.

2. Materials and methods

To determine the behavior of external reinforcement in reinforced concrete beams, three configurations were tested: i) without external reinforcement (UR) for control, ii) beam with external reinforcement with angles (RL), and iii) beam with external reinforcement with a plate (RP).

2.1 Concrete

The concrete was designed using the ACI [13], method, with a water-cement ratio of 0.46, GU-type cement, coarse aggregate N67 following ASTM C33-18 [14] and fine aggregate. The proportions are provided in Table 1. The nomenclature used to define the materials corresponds to: W for water, C for cement, A for sand, and R for gavel.

Compressive strength tests of the samples were conducted on the day of beam tested, following ASTM C39 [15], [16], for cylindrical specimens of 100 x 200mm diameter and length, respectively. The average compressive strength was 29.09 MPa, with a standard deviation (S) of 1.75 and a coefficient of variation (CV) pf 6%.

Table 1. Dosage.

Material	Kg/cm^3 of concrete	Kg/bag of cement	Dosage by weight
W	220.8	25.2	8.28
C	438.58	50	16.44
A	717.33	81.8	26.89
R	924.14	105.4	34.64
Total	2300.85		

To address the need for bending reinforcement representation, all beams incorporate a minimum of 4 longitudinal corrugated rods, each with a 6mm diameter (2 at the top and 2 at the bottom). Additionally, 6mm diameter stirrups, spaced 23cm apart, serve as transverse reinforcement, as illustrated in **Figure 2**.

2.2 Reinforcement

To assess the impact of external elements, an equal area of reinforcement is added to the beams. Consequently, two black cold-formed steel angles with equal sides, measuring 40mm in width and 2mm in thickness (L40 x 2mm), and a steel plate, 78mm wide and 4mm thick (PLT 78.0 x 4mm), are selected. The cross-sectional area for each type of reinforcement is 3.12cm^2. The lengths of both the plate and angles are 90cm, with 5cm reserved at each end until the base support.

Both the angles and plates are anchored to the beams using 8mm diameter, 6.3cm long expander bolts, as depicted in **Figure 1**.

Figure 1. Expanding bolt.

- *Test specimens*

A total of 12 beams, each with a cross-section of 10 x 15cm and a length of 120cm, were manufactured. After the reinforced concrete beams underwent 28 days of pool curing, they were dried for 24 hours before proceeding with the placement of the reinforcement.

Four specimens, designated UR-1, UR-2, UR-3, and UR-4, were used as control beams without any additional reinforcement. Another four beams were reinforced in bending with angles at the bottom corners and are identified as RL-1, RL-2, RL-3, and RL-4. Finally, four beams were reinforced with steel plates at the bottom center and are referred to as RP-1, RP-2, RP-3, and RP-4. Each configuration is illustrated in **Figure 2**, **Figure 3** (a) and (b).

- *Experimental study*

The prismatic specimens were tested in flexure as simple beams with a load at one-third of the free span, following ASTM C78-18 [17]. All beams were tested on day 34, counted from the date of fabrication.

The beams were painted white, and marked, and a grid with 2.5cm spacing was generated to easily identify the development of cracks. Additionally, supports were placed 10cm from each end, leaving 1m of free span. Deformations were recorded using a dial gauge located on the top face of the beam. The mounting of the beams in a hydraulic press is detailed in **Figure 3** (c).

Specimens UR-1, RL-1, and RP-1 were tested under monotonic loading, applying load progressively until failure to determine the maximum strength and the material behavior under pseudo-static loading.

The remaining beams were subjected to "cyclic" loading (loading and unloading, non-reversible) to identify the response of each configuration to fatigue and strain accumulation over time, simulating seismic events or constant vibration conditions [18], [19].

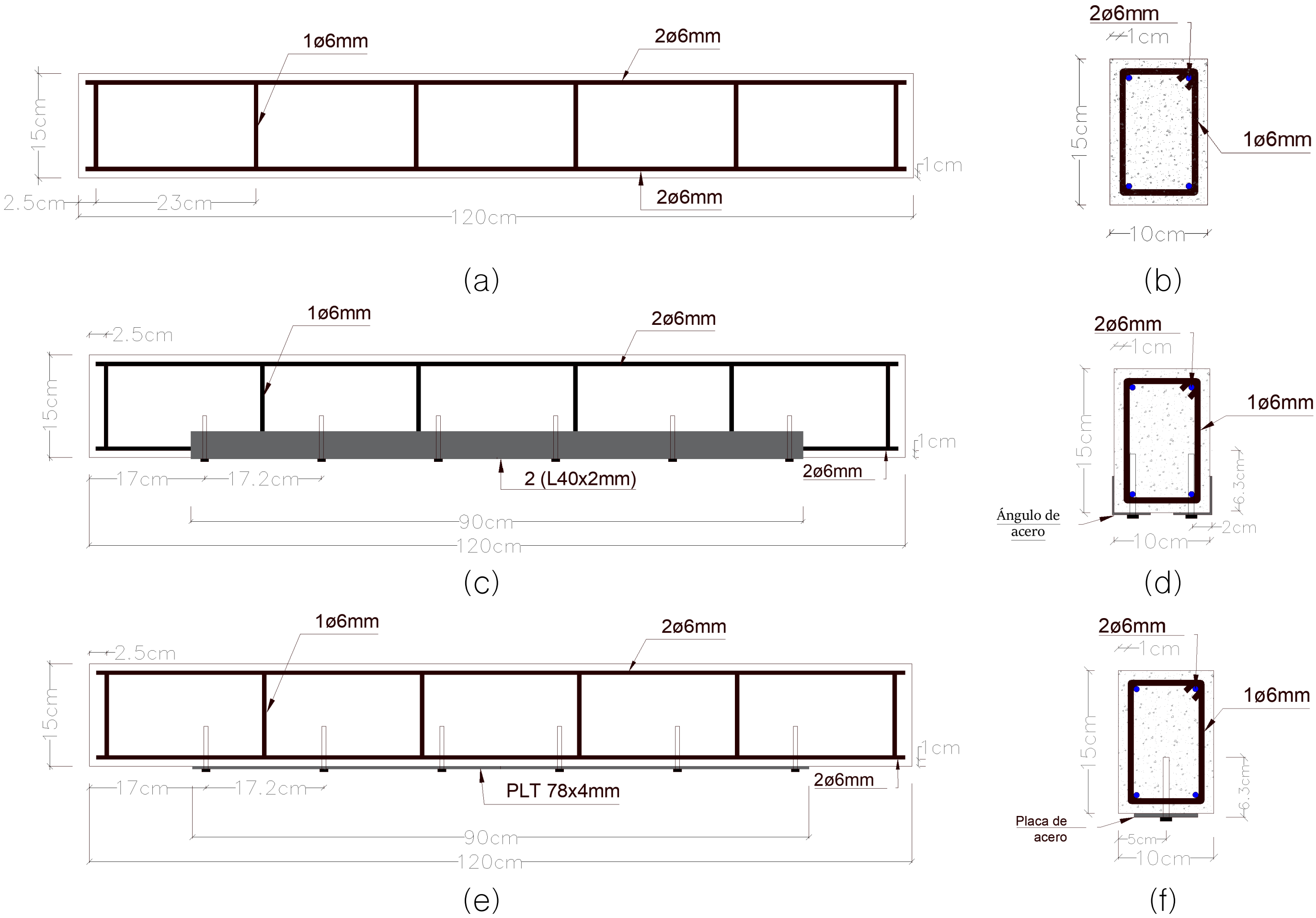


Figure 2. Test specimens: (a) longitudinal section UR, (b) cross-section UR, (c) longitudinal section RL, (d) cross-section RL, (e) longitudinal section RP, (f) cross-section RP.

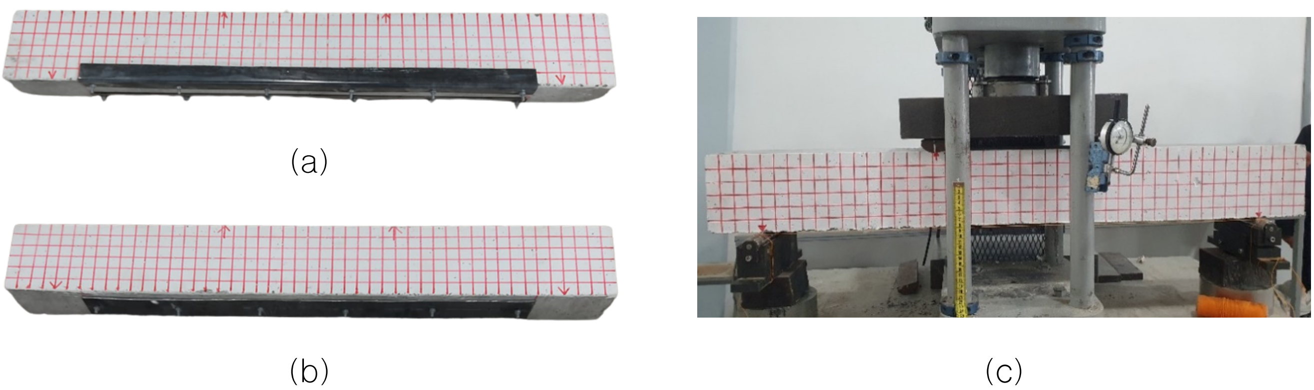


Figure 3. Experimental study: (a) RL beam, (b) RP beam, (c) test setup.

3. Analysis of results

3.1 Monotonic test

The UR-1, RL-1, and RP-1 beams underwent monotonic loading. During each experimental test, the approximate loads at which the first crack occurred were recorded (Cpf) and displacements were recorded as shown **Table 2**.

Table 2. Experimental results for load and displacement values.

Identification	Cpf	Δ
	kN	mm
UR-1	19.18	1.18
RL-1	23.19	1.47
RP-1	24.65	1.92

The decrease in the load-carrying capacity of beam RL-1 is attributed to the damage to the section caused by the drilling of the concrete for the anchorage of the reinforcement, which is located in double rows on the bottom face, as shown in **Figure 3** (a). These drill holes weaken the beam in the tension zone, resulting in concrete cracking and stress concentration points.

The experimental results are detailed in **Table 3**, the displacement at which failure occurs, Δmax, moment capacity (Mn), and ultimate stiffness (Ku). In addition, the bilinear representation proposed by FEMA-356 [20], **Figure 4**, allows the estimation of yield load (Cy), yield point displacement (Δy), stiffness in the linear range (Ke), ultimate displacement, and ductility ratio for each type of beam.

Table 3. Experimental results for load and displacement values.

Identification	Monotonic curve						Bilinear representation				
	Lpeak	Variation of Lu	Lpeak0/Lpeak	Δmax	Mn	Ultimate stiffness Ku=(Cmax/Δmax)	Cy	Δy	Elastic stiffness Ke=(Cy/Δy)	Δu	Ductility μ
	kN	%		mm	kN.m	kN/mm	kN	mm	kN/mm	mm	
UR-1	31.73	-	1	7.5	5.29	4.23	24.6	0.89	27.64	6.00	6.74
RL-1	29.57	-6.80	0.93	12	4.93	2.46	19.8	0.55	36.00	3.00	5.45
RP-1	35.74	11.84	1.13	10	5.96	3.57	27.85	0.97	28.71	8.50	8.76

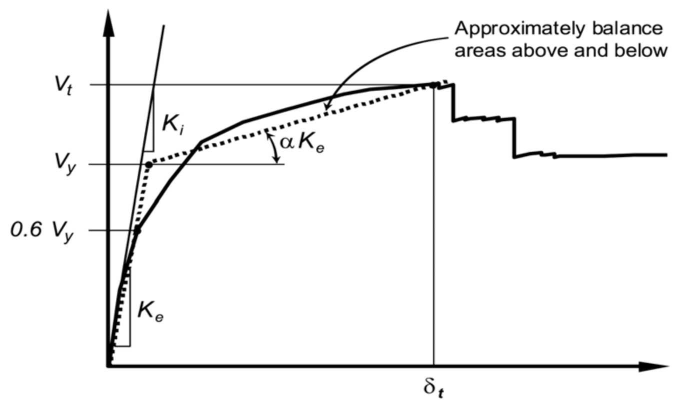


Figure 4. Bilinear representation of the capacity curve [20].

The results of the monotonic tests are depicted in the Load vs Displacement curve for the three specimens and are presented in Figure 5. Beam UR-1 demonstrates brittle failure, with cracks and fissures in the central third. Similarly, beams RL-1 and RP-1 showed cracks at the bottom that propagated toward the upper zone as the load increased. However, as shown in Figure 5, the beams with RL-1 and RP-1 reinforcement develop greater displacement to failure, thus exhibiting increased ductility compared to UR-1. In particular, beam RL-1 fails in a slow and controlled manner, losing strength as it deforms, and even experiences some stiffening. This indicates that, despite not increasing bearing capacity, this reinforcement provides ductility benefits.

The increase in the load-bearing capacity of the RP-1 beam is attributed to the fact that the number of holes is less than that of the RL beams, enhancing the anchorage between the plate and concrete. This improvement arises because only one row is required on the bottom face, as detailed in Figure 3 (b). This configuration enhances both load-carrying capacity and ductility.

Additionally, the bilinear idealization allows us to determine and compare the energy dissipated in the linear range and up to the maximum load of each type of beam analyzed by calculating the area under the curve. The results are shown in Table 4.

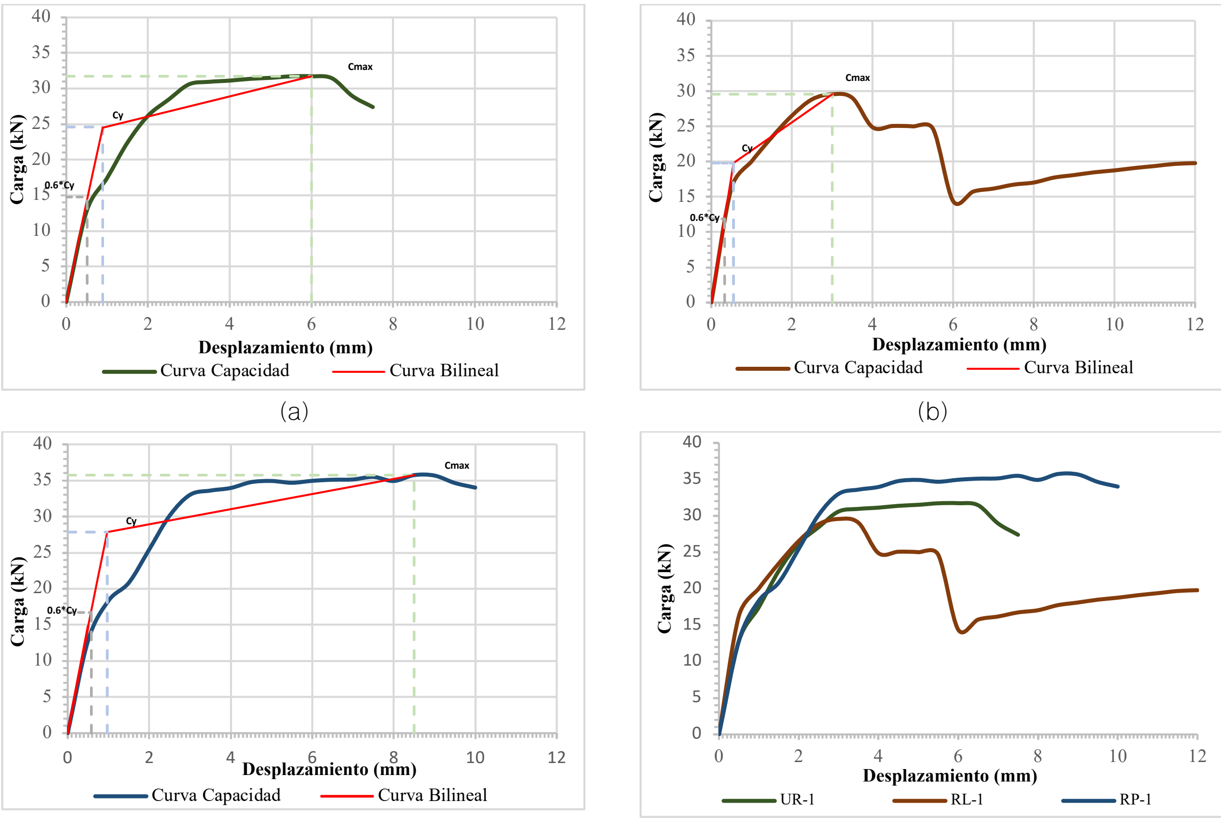
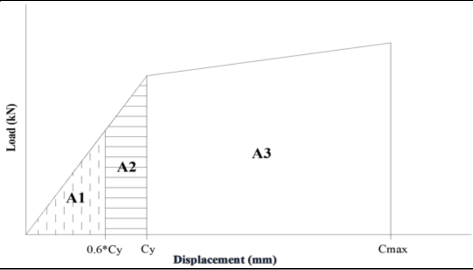


Figure 5. Monotonic response curve: Load vs Displacement (a) UR-1, (b) RL-1, (c) RP-1, (d) comparison of the three types of beams.

Table 4. Energy accumulated

Identification	Energy Dissipated (J)				
	Energy 0.6Cy	Energy Cy	Energy Lu	Range linear	Total Energy
	A1	A2	A3	A1+A2	A1+A2+A3
UR-1	3.76	7.18	143.93	10.95	154.87
RL-1	1.96	3.48	60.48	5.45	65.92

	RP-1	4.85	8.66	238.47	13.51	251.98

The configuration that dissipates the most energy is RP-1, followed by UR-1, and finally RL-1. The selected idealization considers straight lines only up to the maximum load, ensuring equal areas above and below these lines. Therefore, in the case of RL-1, the zone of increased deformation as it loses strength, prior to its fracture, is not considered.

3.2 Cyclic testing

The experimental charge and discharge, or cyclic, test is performed three times for each type of configuration and under displacement control. The process consists of the approximate displacement value at which the first crack, Δ, four stages are established (0.25Δ, 0.5Δ, 0.75Δ and 1Δ) that represent the linear or elastic zone. This stage was carried out for three cycles. The process of charging up to one stage and then proceeding to full discharge is referred to as cycling. For the nonlinear or inelastic zone, stages were also defined starting at 2Δ and advancing in 1Δ. For this zone, two cycles were performed in each stage.

Table 5, shows the results of the maximum load reached by each configuration (Lu), maximum displacement (Δmax), moment (Mn), load variation regarding (UR), and ultimate stiffness (K).

The tests conducted on specimens UR-2, UR-3, and UR-4 show a tendency and ductility approximately equal to the monotonic curve UR-1, exhibiting an average maximum load of 31.17kN with a maximum displacement of 7.08mm. **Figure 6** presents the results of each cyclic test counterbalanced with the monotonic UR-1 curve. Additionally, in **Figure 6** (d), the average cyclic response and its envelope are shown.

Samples RL-2, RL-3, and RL-4 show lower deformation and elasticity compared to RL-1. At stage 3Δ, data collection was interrupted by a jump in the deformation meter, attributed to the fracture of the internal corrugated steel rods. It should be noted that at no time did the external steel elements lose connection with the concrete. This configuration and the monotonic test showed a reduction in its load-carrying capacity of 15.27%, 22.87%, and 3.96% compared to UR-2, UR-3, and UR-4, respectively. The maximum average load is 26.80kN, with a maximum displacement of 5.88mm. **Figure 7** shows the cyclic results.

Beams RP-2, RP-3, and RP-4 demonstrate a similar trend to RP-1, increasing the load-carrying capacity by 14.25%, 16.36%, and 2.34% compared to beam UR-2, UR-3, and UR-4, respectively. At stage 3Δ, failure occurs due to the fracture of the internal corrugated steel rods. However, the external plate experiences creep and maintains contact with the concrete. An average maximum load of 34.58kN and a maximum displacement of 7.68mm are estimated. **Figure 8** shows the load vs displacement plots of the RP beams.

Table 5. Experimental results for load and displacement values.

Identification	Mn (kN.m)	Lu (kN)	Lu0/Lu	Δmax (mm)	Ultimate load variation (%)	Ultimate stiffness (kN/mm)
	1	2		3	4	5 = (2 / 3)
			Cyclical test 1			

UR-2	10.15	30.46	1	5.90	-	5.16
RL-2	8.60	25.81	0.85	4.41	-15.27%	5.85
RP-2	11.60	34.80	1.14	7.68	14.25%	4.53
Cyclical test 2						
UR-3	10.49	31.48	1	7.08	-	4.45
RL-3	8.09	24.28	0.77	4.41	-22.87%	5.51
RP-3	12.21	36.63	1.16	5.76	16.36%	6.36
Cyclical test 3						
UR-4	10.52	31.57	1	7.08	-	4.46
RL-4	10.11	30.32	0.96	5.88	-3.96%	5.16
RP-4	10.77	32.31	1.02	5.76	2.34%	5.61

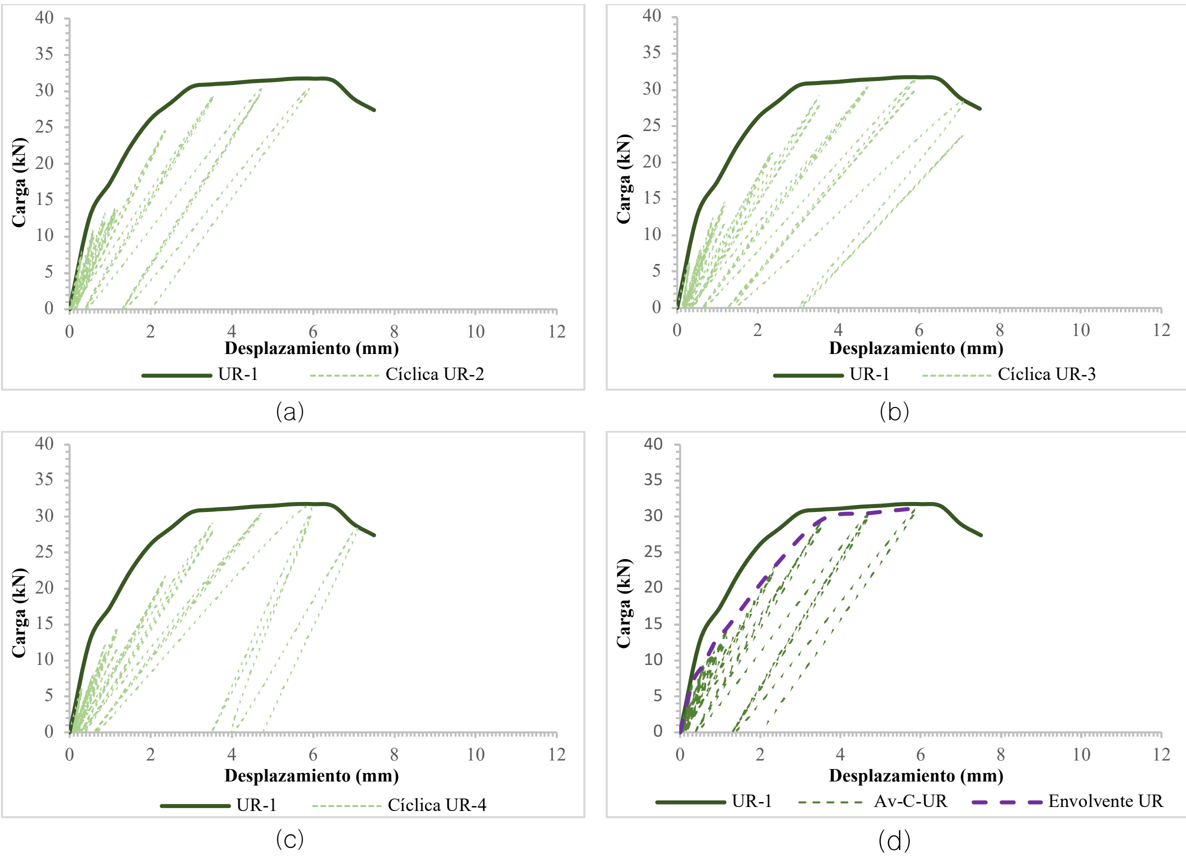


Figure 6. Load vs displacement curve of UR beam: (a) cyclic test 1, (b) cyclic test 2, (c) cyclic test 3 and (d) comparison: average curve of cyclic, envelope, and monotonic tests.

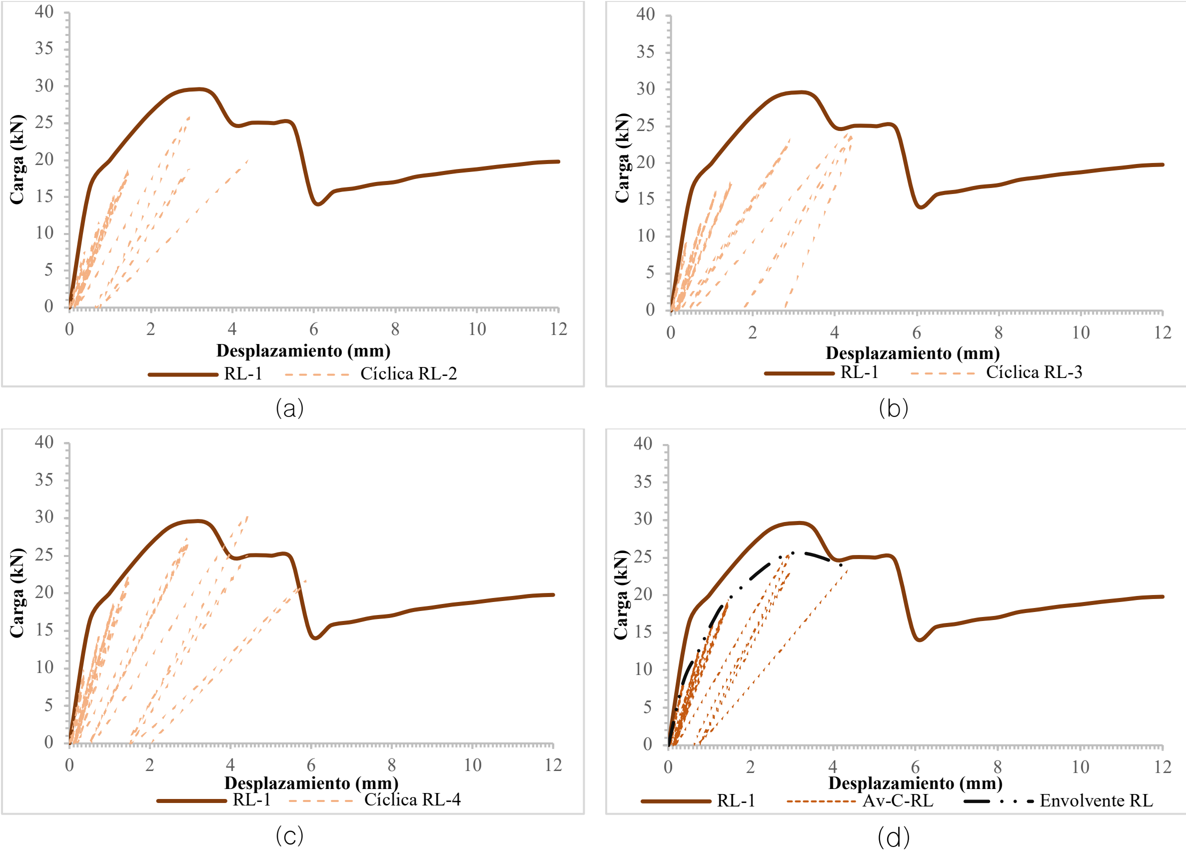


Figure 7. Load vs displacement curve of RL beam: (a) cyclic test 1, (b) cyclic test 2, (c) cyclic test 3 and (d) comparison: average curve of cyclic, envelope, and monotonic tests.

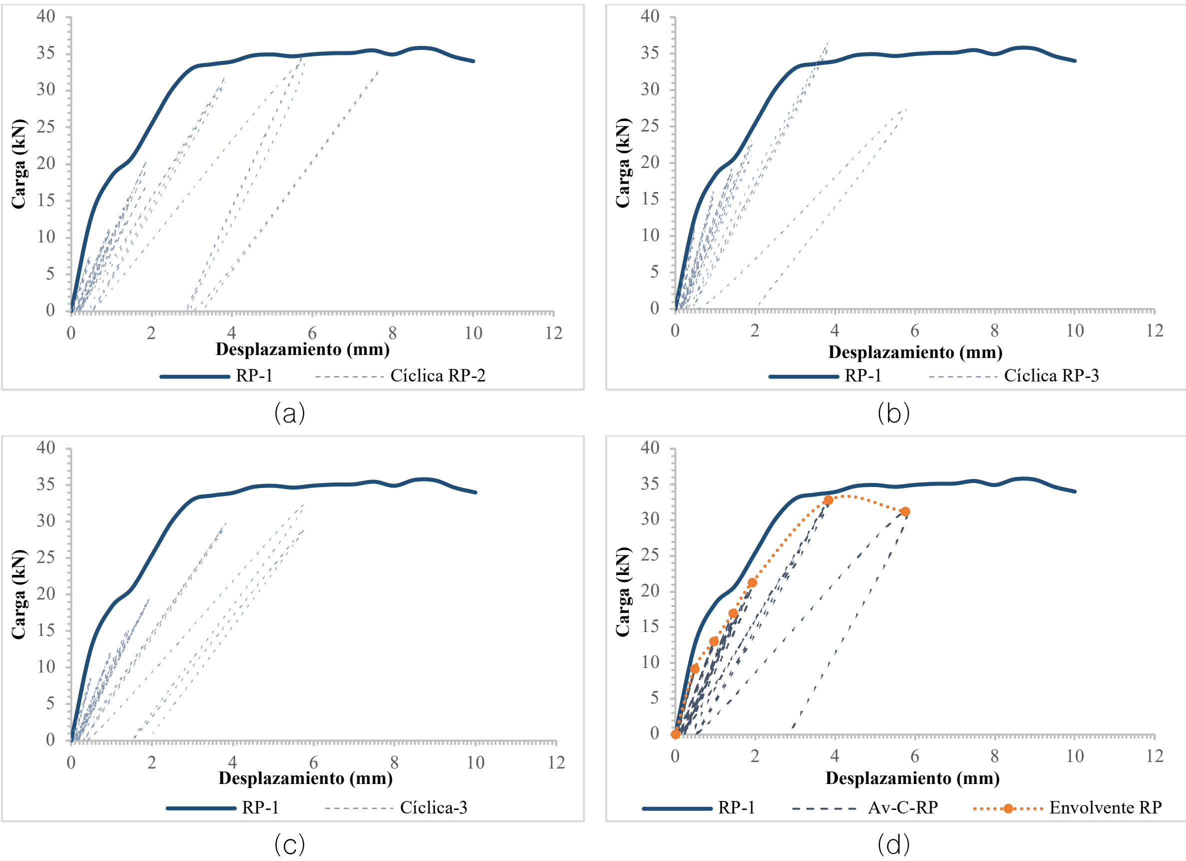


Figure 8. Load vs displacement curve of RP beam: (a) cyclic test 1, (b) cyclic test 2, (c) cyclic test 3 and (d) comparison: average curve of cyclic, envelope, and monotonic tests.

Figure *9*, presents the Load vs Deformation curve of beams under monotonic loading and the envelope of the average cyclic response for each type of beam.

It can be observed that the RP-1 beam reaches the highest load capacity both under monotonic and cyclic loading. Furthermore, its pre-failure displacement is greater than that of UR-1. Even during cycling testing, its deformation is similar to that achieved by the UR envelope, with the advantage that the external plate flows next to the concrete beam without damage, even though the internal corrugated rebar reinforcement fails.

The RL-1 beam exhibits greater displacement before reaching failure when subjected to a monotonic load. However, in the cyclic tests, it develops less deformation compared to the UR and RP envelopes. Particularly, this configuration, despite being reinforced, does not increase the load capacity concerning the UR beam under both monotonic and cyclic loading. In this way, it is demonstrated that, despite being a reinforcement technique, it does not directly contribute to flexural resistance.

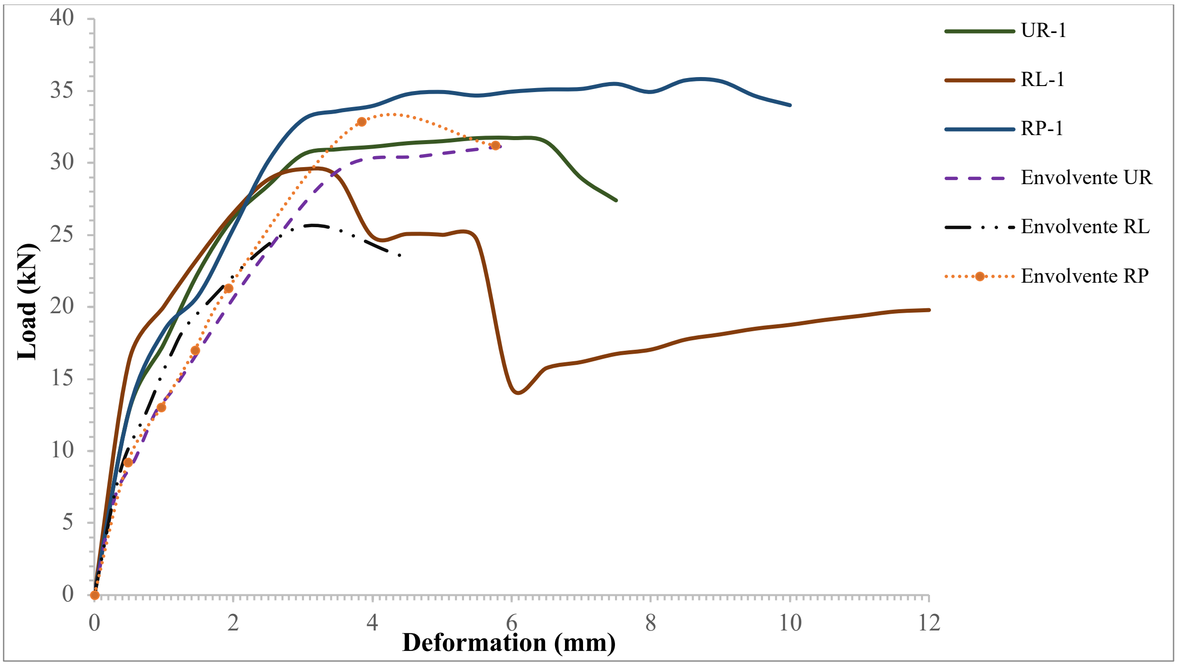


Figure 9. Comparison of monotonic testing with the average envelope of cycling testing.

3.3. Failure patterns

At the end of each experimental test, the failure modes of each specimen were recorded, as shown in Figure 10. It is clarified that the concrete beams satisfy the minimum shear reinforcement; however, they do not comply with the stipulations in the current regulations regarding the maximum separation of the transverse reinforcement. This is done to demonstrate the need for reinforcement.

The UR beams fail in bending, generating a main crack in the central third, accompanied by additional cracks and the consequent yielding and fracture of the internal corrugated steel rods, as shown in Figure 11.

The beams reinforced with external angles, RL-1 and RL-3, fail in bending, presenting fissures and crack of lesser thickness compared to the UR. However, in the cyclic tests RL-2 and RL-4, they fail in shear, with cracks beginning in areas close to the anchor drilling and extending even to the place where the loas is applied. This result is attributed to multiple bolt holes in a small area, generating a concentration of stress in the surrounding areas, weakening the material, and leading to brittle failure. Additionally, it is observed that the lateral wings of the profile, lacking anchoring, buckle locally and separate from the sides of the RC beam. This particularity is indicated in **Figure 12**.

On the other hand, the beam reinforced with an external plate. RP-1 and RP-3, experiences shear failure, resulting in fractures in the net area of the connection. Specimens RP-2 and RP-4 fail in flexure during the cyclic tests. Although numerically this configuration provides greater load capacity and ductility, the failure mode is uncertain.

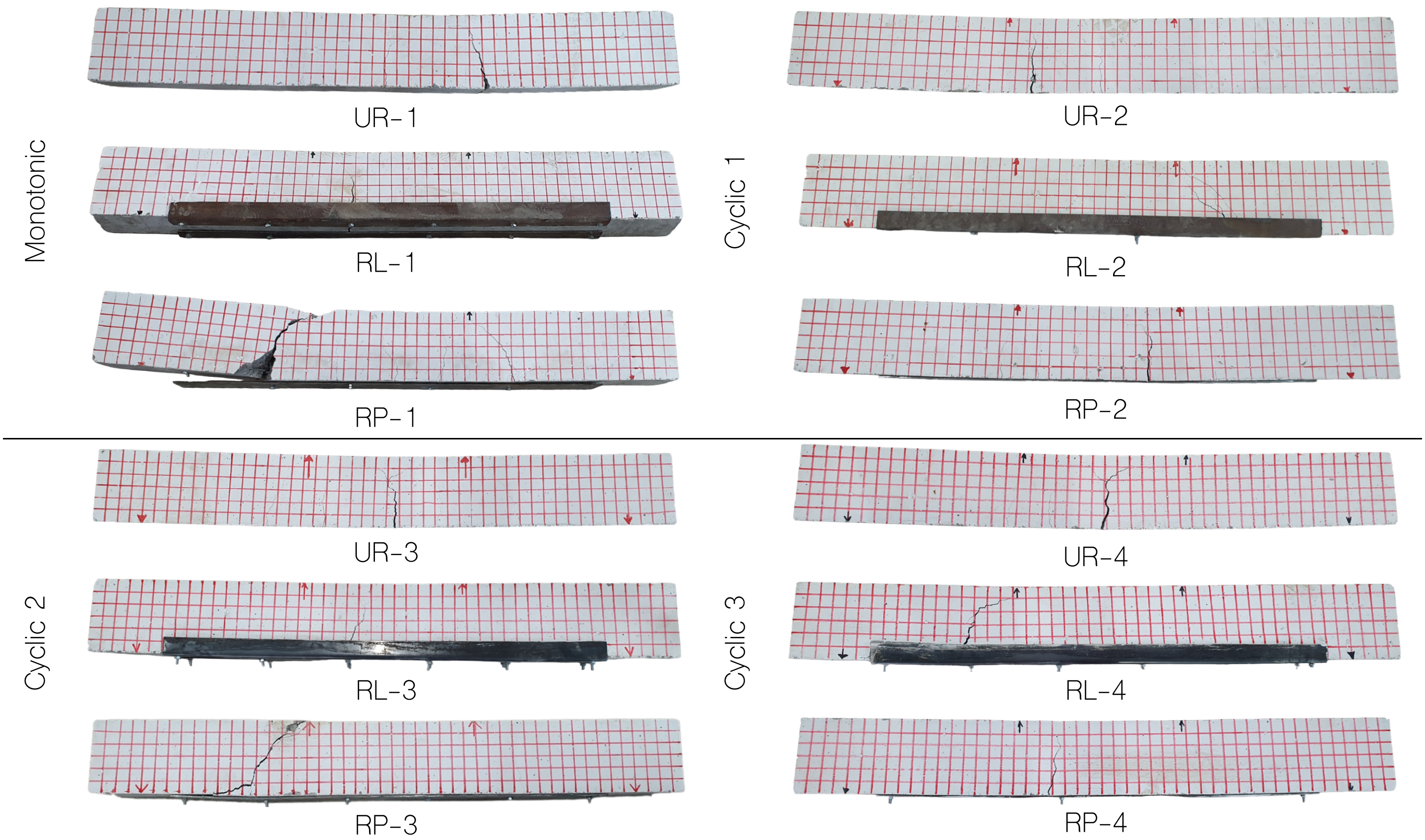


Figure 10. Failure mode of the specimens.

Figure 11. Failure of steel bar.

Figure 12. Flange buckling in RL beam.

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4. Discussion

The discussion of this study highlights that the use of metallic external reinforcement in reinforced concrete (RC) beams can significantly improve their load carrying capacity and ductility. An increase in load carrying capacity and ductility was observed in the RP beam, reinforced at the bottom center, compared to the RL beam, which showed a decrease due to perforations for anchorage of angles. However, although the RP beams performed better under cyclic loading, deficiencies were still observed in the transverse reinforcement that limited ductile failure. These findings highlight the need to optimize the location and methodology of reinforcement to ensure adequate structural response in RC beams.

In addition, the estimation of the energy dissipated during the tests highlights the effectiveness of the RP beam in absorbing extreme loads and prolonging the durability of the structure. However, the importance of addressing deficiencies in transverse reinforcement to improve the response to cyclic loading and ensure the long-term safety of reinforced concrete structures is highlighted. In conclusion, this study emphasizes the need for careful planning and design in the implementation of external steel reinforcement to maximize its effectiveness and ensure the structural integrity of RC beams.

5. Conclusions

To identify the contribution to the safety and load capacity of RC beams with the addition of external metal reinforcements, two types of beams, denoted as RL and RP, were analyzed through monotonic loading and cyclic loading tests. Based on the results and observations obtained in this experimental study, the following conclusions can be deduced:

- Under monotonic loading, the beam reinforced with a plate in the center of the bottom face, RP, increases the load capacity by 11.84% and the ductility by 1.3%. this behavior is attributed to the fact that it is a non-invasive method, requiring a smaller number of perforations for anchoring the plate.
- In the monotonic test, the RL beam demonstrates a los in load capacity and ductility of approximately 6% and 19%, respectively, due to the damage caused by the number of perforations in the concrete for anchoring the angles, which weakens the section and affects its resistance.
- Under cyclic loading, the RP specimens exhibit better behavior compared to the RL-type beams. They show increased resistance and displacement before failure. However, due to the deficiency in transverse reinforcement of the RC beams, it is not possible to guarantee ductile failure with this configuration.
- Through bilinear idealization, it is estimated that RP, with 251.98J, dissipates more energy due to its deformation capacity, while RL, with 65.92J, presents less energy dissipation than the UR control beam with a value of 154.87J.
- The RP reinforcement method demonstrates superior structural behavior compared to the RL configuration. Therefore, it is recommended to optimize the plate reinforcement methodology to prevent the formation of brittle failures and make it a safe technique applicable to reinforced concrete structures.

6. Recommendations

As a complementary study, it is a recommended to investigate the behavior of RL beams with a reduced number of anchors in the tension zone, including the exploration of lateral anchors to enhance the beam-reinforcement connection. On the other hand, another option is test with other kind of anchors such as adhesive admixtures that allow the steel elements to be joined to the concrete beam in a continuous bond.

Author's contributions: The contribution of the author, W.M, stands out for his crucial role in the execution of experiments, strategic planning, data analysis and writing of the article, demonstrating an ethical commitment at each stage. P.N and X.N, contributed their experience in the bibliographic search, data review and improvement of the writing, thus strengthening the quality and credibility of work. P.I improvement of the writing. The synergy between student and teachers resulted in an article that effectively combines practical experience and academic knowledge, offering a solid contribution to the field of study.

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Conflicts of interest: The authors declare that they have no conflict of interest.

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