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Experimental study and assessment of the structural performance of laced reinforced concrete beams against reverse cyclic loading

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ABSTRACT

This experimental research evaluates the structural performance of laced reinforced concrete beams (LRC-45) in comparison to conventional reinforced concrete beams (RC-90) under reverse cyclic loading. Visual inspection revealed that LRC-45 exhibited superior crack resistance, even at high displacements, unlike RC-90, which displayed vertical cleavages and diagonal tension cracks. RC-90 demonstrated minimal ductility, initiating cracking at lower loads. Hysteresis response curves showed LRC-45 outperforming RC-90 in terms of cracking load and maximum load, with higher displacement capacity. The ductility factor of LRC-45 was 56.39% higher. Notably, LRC-45 exhibited a substantial 143.43% increase in cumulative energy dissipation, highlighting its superior energy-absorbing capacity. Additionally, stiffness analysis indicated significantly higher stiffness in LRC-45. The numerical analysis supported experimental findings, emphasizing the potential of laced reinforcement in enhancing structural resilience, energy dissipation, and stiffness. The novelty lies in the remarkable improvements offered by LRC-45, particularly its enhanced energy-absorbing capacity and stiffness, which are crucial for structures subjected to dynamic loads, such as seismic events.

Keywords: Laced reinforcement; reverse cyclic loading; ductility; energy dissipation.

INTRODUCTION

The design of reinforced concrete structures often necessitates the consideration of severe dynamic loads such as blasts or earthquakes [1]. Under typical loading conditions, the primary focus is on strength and stability criteria. However, during seismic events, the loads are significantly higher and short-lived. Consequently, building codes emphasize the importance of ductility criteria [2]. In the past two decades, there has been a growing emphasis on achieving higher levels of ductility through appropriate concrete mix proportions, the incorporation of steel fibres, and changes in reinforcement detailing [3]. Key objectives for a structure to exhibit strong ductile behaviour include ensuring adequate resistance, substantial inelastic deformation with sustained resistance, and preventing the local or early failure of structural components like columns, beams, and beam-column junctions [4]. Achieving full functionality of structures after events such as explosions, seismic forces, or impulsive loads is often impractical and cost-prohibitive. Instead, the primary goal for these structures is to contain the effects of such events, preventing their spread to nearby buildings and structures [5]. Laced Reinforced Concrete (LRC) beams are designed with transverse reinforcements continuously bent to effectively link the longitudinal reinforcements on both sides of beams, columns, or slabs. LRC elements exhibit a higher capacity of support rotation, enabling them to absorb and dissipate energy more effectively. For instance, particularly in dynamic scenarios like a blast explosion of charge weight of 75T and the separation distance between the test storage structures was reduced from 101 to 30 m [6].

The advantages of LRC elements, including increased support rotations, strain hardening beyond the yield plateau, reduced spalling after reaching the yield limit, and high shear resistance during transient blast loading, are detailed in the comprehensive manual TM 5–1300 [7]. Srinivasarao concluded that lacings can effectively achieve ductile failure even under high-cycle shear. The spacing of reinforcement has a minimal impact on cracking and ductility. The role of stirrups was explained by SALLAM and FAWZY [8]. The presence of stirrups in the constant moment region does not significantly affect the stiffness of tested RC beams [9]. However, including stirrups in this region results in a 10% reduction in ultimate load capacity [10].

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The extent of buckling in the compression reinforcement depends on the number of stirrups used, and all forms of discontinuous stirrups proved inadequate in preventing horizontal cracks at the interface between the tensile reinforcement and the core of the beam after yielding, leading to sudden and brittle failure [11]. ZHAO's *et al.* [12] investigation of RC Beams, both Normal and ECC specimens, with and without web reinforcement concluded that post-peak response is characterized by shear ductility in RC beams. ZAKARIA's *et al.* [13] study on shear cracking in RC beams revealed that the width of shear cracks is directly proportional to the spacing between shear cracks and shear reinforcement strain [13, 14]. The characteristics of shear and longitudinal reinforcement play a crucial role in determining diagonal crack spacing and openings [15]. Wider diagonal crack spacing and a limited ability to control shear crack openings occur as the side concrete cover around the stirrup increases [16]. The relationship between crack width and stirrup strain remains consistent regardless of the applied loading paths.

The inclusion of transverse reinforcement in reinforced concrete beams offers several benefits [17]. Transverse reinforcement effectively controls crack width by increasing aggregate interlocking on the crack surfaces [18]. Ductility at the ultimate state increases and shear strength significantly improves. The presence of transverse reinforcement ensures a smooth transfer of internal forces from concrete to steel reinforcement. Overall, transverse reinforcement positively affects crack control, shear strength, and the behaviour of reinforced concrete beams [19]. Transverse reinforcement becomes effective as soon as diagonal or inclined cracks begin to form. It starts resisting certain shear stresses even before inclined cracking becomes evident [20]. Once diagonal cracking occurs, the majority of the shear force is borne by the transverse reinforcement. The utilization of continuous reinforcements was discovered to enhance the ductility of structural elements [21]. The significance of employing wire ropes as shear reinforcement in concrete beams. The experimental findings revealed that concrete beams reinforced with continuous spiral-type wire ropes exhibited serviceability crack width limits at higher loading levels compared to beams reinforced with conventional stirrups. Furthermore, beams reinforced with wire rope displayed a reduced rate of crack width increase with increasing applied load when compared to conventional beams [22]. SHEIK and TOKLUCU's [23] study demonstrated that incorporating spiral steel reinforcement in a column leads to improved concrete strength and ductility. According to ANANDAVALLI *et al.* [24] research, structural components prepared using LRC can achieve support rotation as high as 4° while the conventional beams attain a support rotation of 2°. From the tests conducted at CSIR–SERC, it was concluded that LRC exhibited a plastic hinge rotation of 4° at support and 8° at the center for continuous construction [25]. The continuous lacings are inclined between 45° and 60° to horizontal. Several methods have been proposed to improve the energy dissipation capacities and durability of RC beam-column joints through reinforcement design and detailing [26, 27].

A significant amount of research has been conducted on seismic-resistant beams [28–32], but little is known about the laced reinforced concrete structural elements that are required to improve the performance of RC structures and reduce the likelihood of sudden structural failures. This work proposes LRC beams under reverse cyclic loads with laced reinforcements at 45 and 30 degrees. A typical reinforced concrete beam has also been tested under identical loading circumstances for comparison. This study examines the ductility behaviour, energy dissipation, failure mechanisms, crack pattern, and the load-deflection response of LRC beams under reverse cyclic loading. The LRC beams that were cast for the study were determined to have a shear span-to-depth ratio of 2.6.

2. MATERIALS AND METHODOLOGY

Concrete specimens were cast using standard concrete mix proportions following IS 456 guidelines [20]. Rectangular concrete beams with dimensions of 300 × 300 × 820 mm were cast for both LRC 45 and RC 90 [33]. The lacing angle was set at 45 degrees for LRC 45, while RC 90 had conventional 90-degree stirrups [34]. All specimens followed IS 456 guidelines. The concrete had a compressive strength of 30 MPa and a tensile strength of 3.38 MPa [35]. Four 12 mm diameter steel bars were used in both the tension and compression zones for all specimens. The lacing bars also had a diameter of 12 mm [36]. Reinforcement material properties included a yield strength of 500 MPa and Young's modulus of 210,000 MPa [36]. A hydraulic jack load cell with a capacity of 100 kN was employed to apply loads [37]. Reverse cyclic load tests were conducted using a hydraulic jack load cell [38]. Load cycles involved loading and unloading in upward and downward directions [39]. Displacement and strain measurements were recorded at various load levels. Displacement was measured using dial gauges and electrical resistance strain gauges were used to monitor strain in the reinforcement [40]. Nonlinear material models for concrete and steel were employed to predict stress, strain, deformation, and ultimate load-carrying capacity under higher reverse cyclic loads [41–43]. The properties of concrete and steel are shown in Table 1 and Table 2.

Table 1: Material properties of concrete.

Youngs modulus	27386 Mpa
Poisson ratio	0.2
Compression strength (uniaxial)	30 Mpa
Tensile Strength (Uniaxial)	3.38 Mpa
Biaxial compressive strength	34.7 Mpa
Dilatancy angle	30°
Ultimate effective plastic strain in compression	0.01
Plastic strain at uniaxial compressive strength	0.0012
Residual compressive relative stress	0.2
Relative stress at the start of nonlinear hardening	0.4
Residual tensile relative stress	0.2
Plastic strain limit in tension	0.01

Table 2: Material properties of reinforcement steel.

Young's modulus	210000 Mpa
Poisson ratio	0.3
Yield strength	500 Mpa
Tangent modulus	984.30 Mpa

3. EXPERIMENTAL PROGRAM

The experimental program consists of the evaluation of 45-degree and 90-degree reinforcements by maintaining the longitudinal reinforcement and the cross-section as the same [44]. The spacing of nodes in lacings is kept at 160 mm [45–48]. The cantilever beam was cast with a rectangular cross-section measuring 300 × 300 mm with a height of 0.82 m and the beam was securely fixed at the base as shown in Figure 1. The shear span-to-depth ratio for the rest specimens was set at 2.6 [49]. The design of the specimens followed the guidelines of IS 456. The diameter of the reinforcement rod used as lacing and the longitudinal bar was 12 mm in size. Reverse cyclic load testing was carried out on a mounted loading frame [50]. The vertical portion of the casted specimen (Column portion) was positioned at fixity by a hydraulic jack fixed rigidly to the mounting frame [51]. In a reverse cyclic test, loading and unloading in upward and downward directions is given alternatively upon the beam. The load is applied at the top surface of the beam by a hydraulic jack load cell (Actuator) of capacity 100 kN at a distance of 160 mm from the free end of the cantilever beam portion and unloaded after it [52, 53]. The dial gauge is located at the bottom of the beam exactly under the loading point to capture the displacement during the forward loading cycle and vice versa for the reverse loading cycle and it gets repeated until the ultimate load. An electrical resistance strain gauge with a length of 30 mm was slotted inside bars 2 of tensile reinforcement and compressive reinforcement and the lacing bar for all three beams [54]. To measure steel strain, a strain gauge device is connected to LVDT, and the strain for each load is noted. The geometric details of the test specimen are furnished in Table 3 and the instrumentation setup for reverse cyclic loading is shown in Figure 1. The LRC beam with 45-degree lacing is named LRC-45, RC beam with conventional stirrups is named RC-90 [55].

The load cycle of LRC 45 and RC 90 is shown in Figure 2(a) and Figure 2(b). In the first cycle, the load was constantly increased from 0 to 25 kN, with the load cell placed above the beam at a distance of 160 mm from the free end of the cantilever beam and the dial gauge positioned below, after which it was unloaded to zero kN during the forward cycle. The position of the dial gauge and the load cell is swapped and the load is applied again from the bottom up to 25 kN from zero kN during the reverse cycle. The same procedure is followed for the other cycles. The displacement was noted at each load point to draw the hysteresis loop. Strains in the reinforced bars were also monitored using an electrical resistance strain gauge [56].

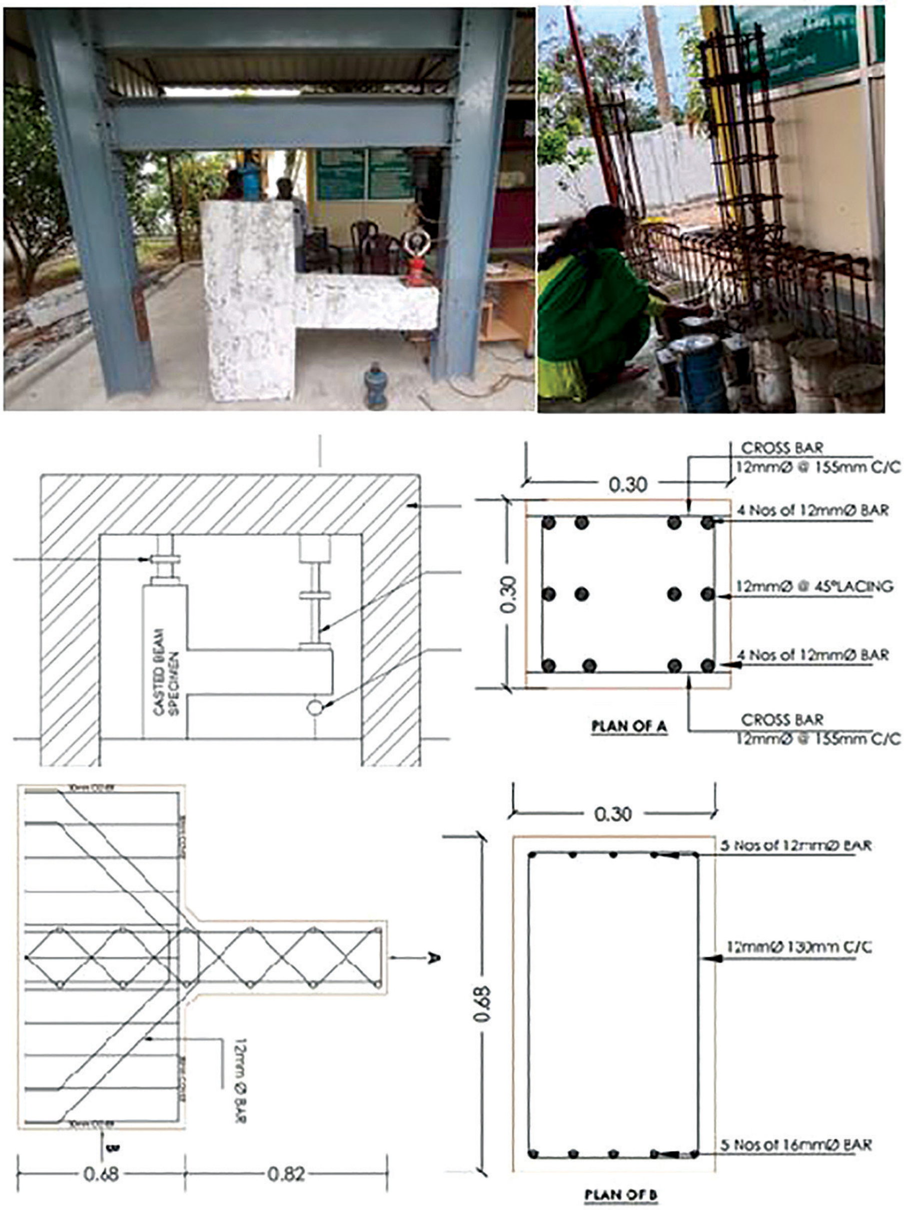
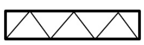
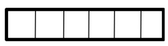


Figure 1: Test setup and reinforcement detail of LRC 45.

Table 3: Geometric details of the test specimens.

BEAM	LRC-45	RC-90
Total Length (m)	1.50 (0.68 + 0.82)	1.50 (0.68 + 0.82)
Width (mm)	300	300
Depth (mm)	300	300
Longitudinal reinforcement	4 numbers of 12 mm dia in tension and compression zone each (T and C)	4 numbers of 12 mm dia in tension and compression zone each (T and C)
Stirrups (mm)	12	12
Lacing angle	45°	Closed stirrups 90°
Diameter of cross rod (mm)	16	16
Span of beam (m)	0.66	0.66
Schematic figure of shear reinforcement		

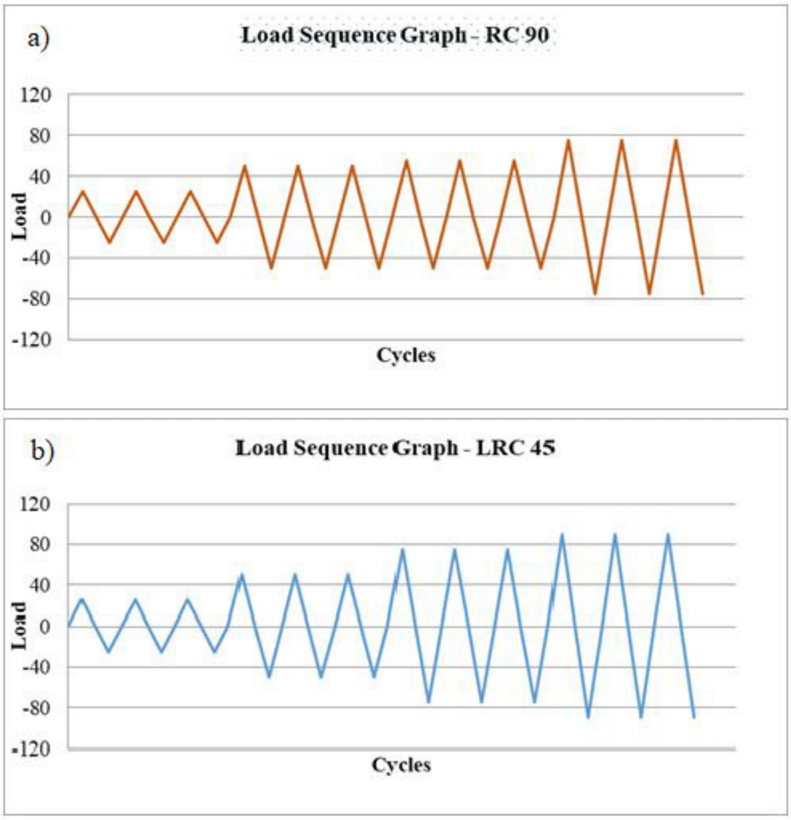


Figure 2: a) Load cycle of RC 90 b) Load cycle of LRC 45.

4. RESULTS AND DISCUSSION

4.1. Crack pattern

It is found that the interface between the column and beam has developed crack propagation and the failure pattern was consistent in all the test samples. Upon visual inspection, it was evident that at lower displacement levels, no significant damage was observed at the Beam column joint. As the displacement increases, a clear vertical cleavage has occurred at the junction of all the specimens except LRC-45 [57]. At higher displacement levels, diagonal tension cracks were developed in both the faces of the beam spanning across the tension and compression zone. It is found that minimum ductile behavior is observed in RC-90 which is depicted in Figure 3(a) and 3(b). However, no cracking was observed in the column at any stage of the experiment during an investigation [58]. For the specimen LRC-45, no cracks were noticed at the joint and the joint remained intact

Figure 3: a) Crack pattern of LRC 45 b) crack pattern of RC 90.

throughout the test. The first crack started at the load of 60 kN for LRC 45 and 35 kN for RC 90. The peak load of LRC 45 is 90 kN and 75 kN for RC 90. The crack width of LRC 45 is also less compared to other RC 90. For the conventional beam RC 90, the first crack started at 24 kN at the beam-column joint interface from the top. At 48 kN, the crack from the tensile zone and the compressive zone joined. As the load gradually increased, diagonal shear cracks were progressively formed along both sides of the specimen.

4.2. Hysteresis response curves

The beams LRC-45 and RC-90 are experimentally tested by reverse cyclic load testing and the load-deflection variations are figured as hysteresis response curve/Load deflection curve and are shown in Figure 4(a) and Figure 4(b). The forces and displacement vary in the push and pull directions due to Bauchinger effect. All the beams displayed nearly identical behavior, except the first cracking load and the maximum load [59, 60]. The first cycle load of LRC 45 and RC 90 is compared and shown in Figure 5 (a). The maximum load taken by LRC-45 is about 87.5 kN and the RC-90 is about 75 kN and the corresponding displacement is 25.8 mm and 14.85 mm as shown in Figure 5(b) The figure indicates that for each tested specimen, the pattern in both the push and pull directions is similar, with only a mild variation in values of ultimate load and displacement values between the positive and negative directions. Hysteresis loop at the initial cycle and the final cycle is graphed in the respective figures.

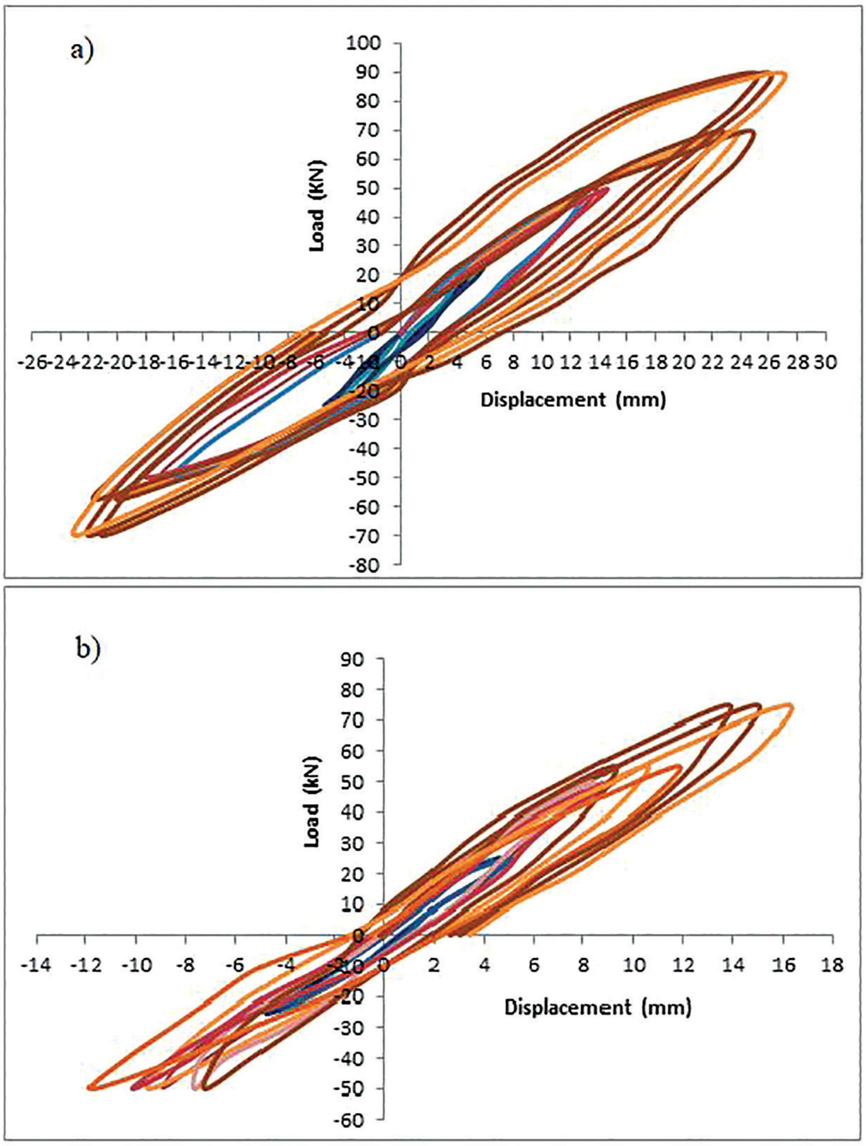


Figure 4: a) Load displacement curve LRC 45 b) load displacement curve RC-90.

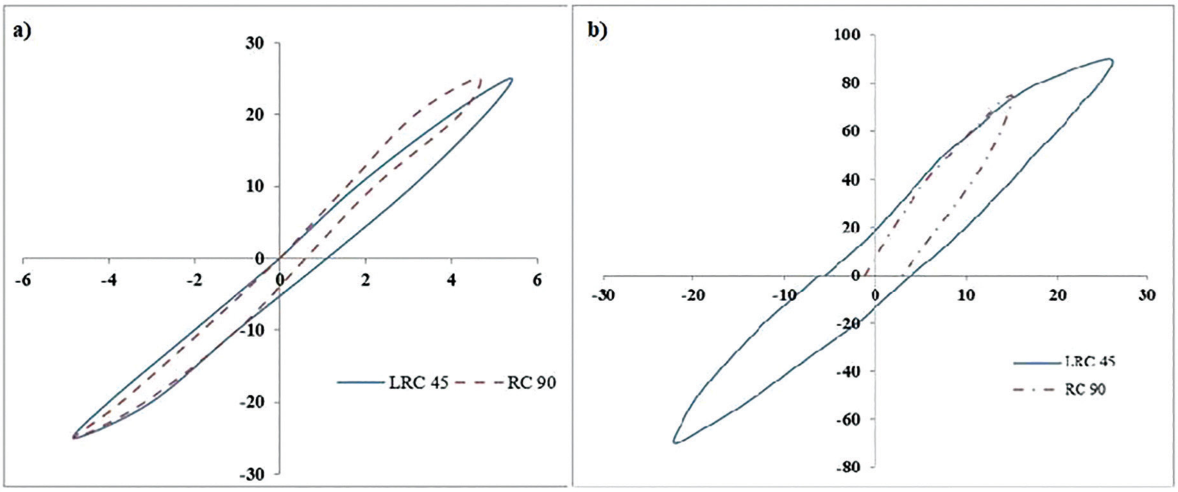


Figure 5: a) Comparison of first cycle load-deflection curve of LRC 45 and RC 90 b) comparison of last cycle load-deflection curve of LRC 45 and RC 90.

4.3. Ductility factor

The ratio between ultimate deflection (Du) and the yield deflection (Dy) is called as ductility factor. Load–tip deflection curves have been used to derive values of Du and Dy. In this study, the deflection value corresponding to 90% of the ultimate load in the descending branch of the load-tip deflection envelope curves is considered as Du [18]. The calculation of the cumulative ductility factor involves determining the ductility of the structure for each loading event or cycle and then summing these values to obtain the cumulative ductility. It is seen that the ductility factor of LRC 45 is 56.39 percent higher than the RC 90. Table 4 shows the ductility factor of LRC 45 and RC 90 and a comparison of the Cumulative ductility factor is shown in Figure 6.

Table 4: Ductility factor of LRC 45 and RC 90.

SPECIMEN	YIELD DEFLECTION Dy (mm)		ULTIMATE DEFLECTION Du (mm)		DUCTILITY FACTOR		AVERAGE DUCTILITY
	+ve	–ve	+ve	–ve	+ve	–ve	
LRC 45	12	11	25.8	22	2.15	2	2.08
RC 90	11	8	14.85	10.4	1.35	1.3	1.33

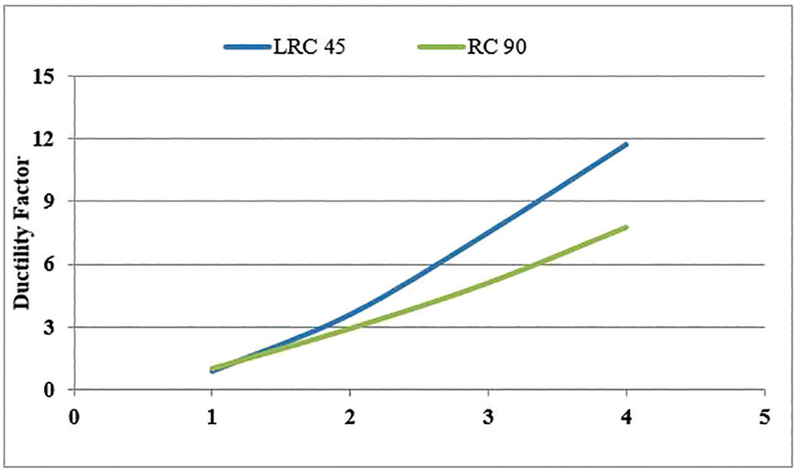


Figure 6: Comparison of cumulative ductility factor of LRC 45 and RC 90.

4.4. Energy absorption capacity

The assessment of energy dissipation in reinforced concrete beams subjected to cyclic loading is a crucial aspect of structural performance analysis. In this study, the energy dissipation was quantified by calculating the area enclosed within the hysteresis loop, representing the load-displacement behavior during loading cycles. The results indicate that energy absorption in both the positive and negative loading cycles exhibited a consistent trend of increasing with displacement and load amplitude. This behavior is expected as higher displacements and loads require more energy to deform and subsequently recover from loading. Remarkably, the cumulative energy dissipation for the LRC 45 beam was found to be 143.43% higher than that of the conventional RC 90 beam as indicated in Figure 7. This substantial increase in energy dissipation signifies the effectiveness of laced reinforcement in enhancing the beam's ability to absorb and dissipate energy during cyclic loading. It suggests that LRC 45 beams have superior energy-absorbing capacity, which is a critical attribute in structures subjected to dynamic loads, such as seismic events, where energy dissipation can help mitigate structural damage and ensure safety.

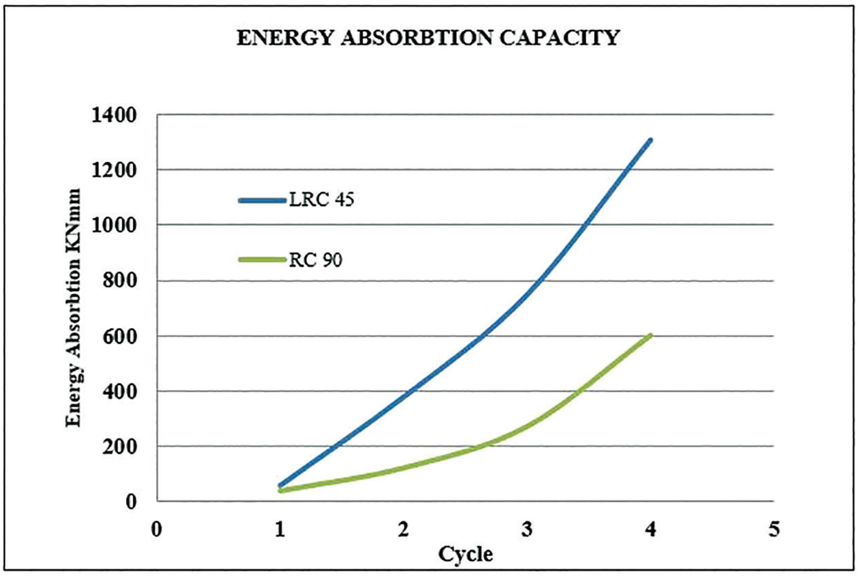


Figure 7: Comparison of cumulative energy absorption capacity of LRC 45 and RC 30.

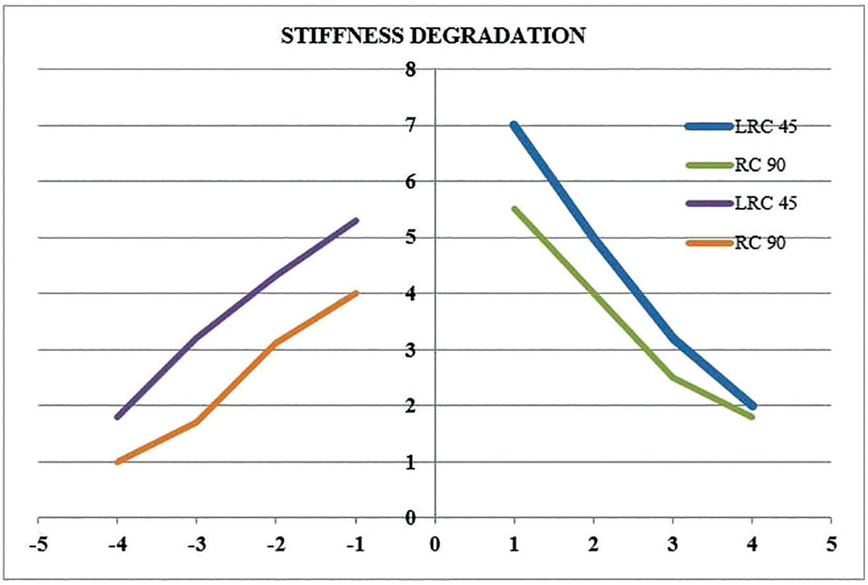


Figure 8: Comparison of stiffness degradation of LRC 45 and RC 30.

Table 5: Stiffness of LRC 45 and RC 90 in the forward and reverse cycles.

CYCLE NUMBER	LRC 45		RC 90	
	FORWARD CYCLE	REVERSE CYCLE	FORWARD CYCLE	REVERSE CYCLE
1	7	5.3	5.5	4
2	5	4.3	4	3.1
3	3.2	3.2	2.5	1.7
4	2	1.8	1.8	1

4.5. Stiffness

Laced reinforcement in a concrete beam is a structural technique that involves the incorporation of additional diagonal bars, known as lace bars, which intersect the primary longitudinal reinforcement. This arrangement creates a lacing pattern typically set at a 45-degree angle to the vertical axis of the beam. Scientifically, this lacing pattern serves to significantly enhance the overall stiffness of the concrete beam when compared to a conventional beam lacking lacing. The increase in stiffness can be attributed to several factors. Firstly, the introduction of diagonal lace bars effectively increases the moment of inertia of the beam's cross-sectional geometry. Moment of inertia quantifies a section's resistance to bending, and a higher value indicates greater stiffness. In this case, the lacing bars contribute to a larger moment of inertia, thus enhancing the beam's stiffness. Experimental findings, as indicated in Figure 8, demonstrate the significant impact of laced reinforcement on stiffness. The stiffness of the LRC-45 beam is notably higher than that of the RC-90 beam, both in the forward and reverse loading cycles. Specifically, LRC-45 exhibits a 27.27% higher stiffness in the forward cycle and a remarkable 32.5% higher stiffness in the reverse cycle. In Table 5, the Stiffness of the beam in each cycle is tabulated. For consecutive cycles, the load is directly proportional to deflection. Hence the stiffness is degraded.

5. CONCLUSIONS

- The experimental program under reverse cyclic loading carried out on 45-degree laced reinforcements and conventional RCC beam reveals the following points. In the experimental program, load-deflection response, crack pattern, failure modes, energy dissipation, and ductility were monitored and analyzed. It is observed that the first crack started at the load of 60 kN for LRC 45, and at 35 kN for RC 90. The peak load of LRC 45 is 90 kN and 75 kN for RC 90. The crack width of LRC 45 is also less compared to other RC 90. The ductility factor of LRC 45 is 56.39 percent higher than the RC 90.
- The cumulative energy dissipation of the conventional beam i.e., RC 90 is 1027 kN mm and the cumulative energy dissipation of the LRC 45 beam is 143.43 percent higher than the conventional beam. The stiffness of LRC-45 is 27.27% higher than the RC-90 in the forward cycle and 32.5% higher in the reverse cycle.
- As per Numerical analysis, the maximum stress taken by RC 90 at the final load is 372.21 MPa and is 18 percent higher than the LRC 45. The total deformation of RC 90 at the load of 500 kN is 338.96 mm and LRC 45 exhibits deformation of 259.76 mm thereby the conventional beam exhibits a deformation capacity 30 percent higher than the LRC 45 at 500 kN. Both LRC 45 and RC 90, the experimental and numerical result shows a good match. It is found that the inclined lacing at 45° to the horizontal performs well in ductility and provides sufficient shear strength under reverse cyclic as compared to conventional beam RC 90.

6. REFERENCES

[1] RAO, P.S., LAKSHMANAN, N., "Seismic behavior of laced reinforced concrete beams", In: *Eleventh World Conference on Earthquake Engineering*, 1996.

[2] SHAH, S.P., RANGAN, B.V., "Effects of reinforcements on ductility of concrete", *Journal of the Structural Division*, v. 96, n. 6, pp. 1167–1184, 1970. doi: http://dx.doi.org/10.1061/JSDEAG.0002601.

[3] PENDYALA, R.S., MENDIS, P., "Experimental study on shear strength of high-strength concrete beams", *ACI Structural Journal*, v. 97, n. 4, pp. 564–571, 2000.

[4] SARSAM, K.F., AL-MUSAWI, J.M., "Shear design of high-and normal strength concrete beams with web reinforcement", *Structural Journal*, v. 89, n. 6, pp. 658–664, 1992.

[5] LIN, C.H., LEE, W.C., "Shear behavior of high-workability concrete beams", *Structural Journal*, v. 100, n. 5, pp. 599–608, 2003.

[6] ANANDAVALLI, N., LAKSHMANAN, N., “Simplified approach for finite element analysis of laced reinforced concrete beams”, *ACI Structural Journal*, v. 109, pp. 91–99, 2012.

[7] KARAYANNIS, C.G., CHALIORIS, C.E., “Shear tests of reinforced concrete beams with continuous rectangular spiral reinforcement”, *Construction & Building Materials*, v. 46, pp. 86–97, 2013. doi: http://dx.doi.org/10.1016/j.conbuildmat.2013.04.023.

[8] SALLAM, H.E., FAWZY, K., “Stirrups in RC beams: facts beyond assumptions”, In: *Proceedings of the 5th ICCAE Conference*, 2004.

[9] AZIMI, M., PONRAJ, M., BAGHERPOURHAMEDANI, A., *et al*., “Shear capacity evaluation of reinforced concrete beams: finite element simulation”, *Jurnal Teknologi*, v. 77, pp. 59–66, 2015. doi: http://dx.doi.org/10.11113/jt.v77.6400.

[10] PANTELIDES, C.P., HANSEN, J., NADAULD, J., *et al*., “Seismic performance of reinforced concrete building exterior joints with substandard details”, *Journal of Structural Integrity and Maintenance*, v. 2, n. 1, pp. 1–11, 2017. doi: http://dx.doi.org/10.1080/24705314.2017.1280589.

[11] KAYA, E., KÜTAN, C., SHEIKH, S., *et al*., “Flexural retrofit of support regions of reinforced concrete beams with anchored FRP ropes using NSM and ETS methods under reversed cyclic loading”, *Journal of Composites for Construction*, v. 21, n. 1, pp. 04016072, 2017. doi: http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000732.

[12] ZHAO, D., LI, K., FAN, J., *et al*., “Shear behavior of RC beams strengthened with high-strength steel strand mesh reinforced ECC: Shear capacity, cracking and deformation”. *Engineering Structures*, v. 298, 2024. doi: https://doi.org/10.1016/j.engstruct.2023.117081.

[13] ZAKARIA, M., UEDA, T., WU, Z., *et al*., “Experimental investigation on shear cracking behavior in reinforced concrete beams with shear reinforcement”, *Journal of Advanced Concrete Technology*, v. 7, n. 1, pp. 79–96, Feb. 2009. doi: http://dx.doi.org/10.3151/jact.7.79.

[14] HAMRATET, M., BOULEKBACHE, B., CHEMROUK, M., *et al*., “Effects of the transverse reinforcement on the shear behaviour of high strength concrete beams”, *Advances in Structural Engineering*, v. 15, n. 8, pp. 1291–1306, 2012. doi: http://dx.doi.org/10.1260/1369-4332.15.8.1291.

[15] PANTELIDES, C.P., HANSEN, J., NADAULD, J., *et al*., *Assessment of reinforced concrete building exterior joints with substandard details, PEER report 2002/18*, Berkeley, Pacific Earthquake Engineering Research Center College of Engineering University of California, 2002.

[16] YANG, K.H., KIM, G.H., YANG, H.S., “Shear behavior of continuous reinforced concrete T-beams using wire rope as internal shear reinforcement”, *Construction & Building Materials*, v. 25, n. 2, pp. 911–918, 2011. doi: http://dx.doi.org/10.1016/j.conbuildmat.2010.06.093.

[17] FALESCHINI, F., HOFER, L., ZANINI, M.A., *et al*., “Experimental behavior of beam-column joints made with EAF concrete under cyclic loading”, *Engineering Structures*, v. 139, pp. 81–95, 2017. doi: http://dx.doi.org/10.1016/j.engstruct.2017.02.038.

[18] PARAMESWARAN, V.S., LAKSHMANAN, N., SRINIVASULU, P., *et al*., *Application of laced reinforced concrete construction techniques to blast-resistant structures: SERC Report No. RCC-SR-86-1*, Chennai, Structural Engineering Research Centre, 1986.

[19] SHABANLOU, M., MOFID, M., TAVAKOLI, A. “Experimental and Numerical Study on the Behavior of Reinforced Concrete Deep Beams with Normal-Strength and High-Strength Concrete After Being Exposed to Fire”, *Arabian Journal for Science and Engineering*, pp. 1–20, 2024. doi: https://doi.org/10.1007/s13369-023-08676-x.

[20] MADHESWARAN, C.K., GNANASUNDAR, G., GOPALA KRISHNAN, N., “Performance of laced reinforced geopolymer concrete (LRGPC) beams under monotonic loading”, In: *Advances in Structural Engineering*, pp. 355–367, 2015. doi: http://dx.doi.org/10.1007/978-81-322-2190-6_31.

[21] BUREAU OF INDIAN STANDARDS. *SP 34: 1987: Handbook on reinforced concrete and detailing*. New Delhi, India, Bureau of Indian Standards, 1999.

[22] BUREAU OF INDIAN STANDARDS, *IS 456: 2000. Plain and reinforced concrete - Code of practice*. New Delhi, India, Bureau of Indian Standards, 2000.

[23] SHEIKH, S.A., TOKLUCU, M.T., “Reinforced concrete columns confined by circular spirals and hoops”, *ACI Structural Journal*, v. 90, n. 5, pp. 542, 1993.

[24] ANANDAVALLI, N., LAKSHMANAN, N., NAGESH, R., “Behaviour of a blast loaded laced reinforced concrete structure”, *Defence Science Journal*, v. 62, n. 5, pp. 284–289, Sep. 2012. doi: http://dx.doi.org/10.14429/dsj.62.820.

[25] KRISHNASAMY, R., SHYAMALA, G., JOHNSON, S.C., *et al*., "Performance management of transmission line tower foundations against corrosion by nondestructive testing", *International Journal of Engineering and Advanced Technology*, v. 9, n. 3, pp. 443–447, 2020. doi: http://dx.doi.org/10.35940/ijeat.C4731.029320.

[26] PALANISAMY, G., KUMARASAMY, V., "Rehabilitation of damaged RC exterior beam-column joint using various configurations of CFRP laminates subjected to cyclic excitations", *Matéria (Rio de Janeiro)*, v. 28, n. 2, pp. e20230110, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2023-0110.

[27] MOHANRAJ, R., VIDHYA, K., "Evaluation of compressive strength of Euphorbia tortilis cactus infused M25 concrete by using ABAQUS under static load", *Materials Letters*, v. 356, pp. 135600, 2024. doi: http://dx.doi.org/10.1016/j.matlet.2023.135600.

[28] BINDHU, K.R., JAYA, K.P., VK, M.S., "Seismic resistance of exterior beam-column joints with non-conventional confinement reinforcement detailing", *Structural Engineering and Mechanics International Journal*, v. 30, n. 6, pp. 733–761, 2008.

[29] RAJESH, A.A., SENTHILKUMAR, S., SAMSON, S., "Optimal proportional combinations of rubber crumbs and steel slag for enhanced concrete split tensile strength", *Matéria (Rio de Janeiro)*, v. 28, n. 4, pp. e20230206, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2023-0206.

[30] KYTINOU, V.K., KOSMIDOU, P.M.K., CHALIORIS, C.E., "Numerical analysis exterior RC beam-column joints with CFRP bars as beam's tensional reinforcement under cyclic reversal deformations", *Applied Sciences (Basel, Switzerland)*, v. 12, n. 15, pp. 7419, 2022. doi: http://dx.doi.org/10.3390/app12157419.

[31] PRASANTHNI, P., PRIYA, B., DINESHKUMAR, G., *et al*., "Mechanical properties of coal ash concrete in the presence of graphene oxide", *International Journal of Coal Preparation and Utilization*, 2023. In press. doi: http://dx.doi.org/10.1080/19392699.2023.2284991.

[32] TAFSIROJJAMAN, T., FAWZIA, S., THAMBIRATNAM, D.P., *et al*., "FRP strengthened SHS beam-column connection under monotonic and large-deformation cyclic loading", *Thin-walled Structures*, v. 161, pp. 107518, 2021. doi: http://dx.doi.org/10.1016/j.tws.2021.107518.

[33] VELUMANI, M., MOHANRAJ, R., KRISHNASAMY, R., *et al*., "Durability evaluation of cactus-infused M25 grade concrete as a bio-admixture", *Periodica Polytechnica Civil Engineering*, v. 67, n. 4, pp. 1066–1079, 2023. doi: http://dx.doi.org/10.3311/PPci.22050.

[34] MAHINI, S.S., RONAGH, H.R., DALALBASHI, A. "Numerical modeling of CFRP-retrofitted RC exterior beam-column joints under cyclic loads", In: *4th International Conference on FRP Composites in Civil Engineering (CICE2008)*, Zurich, Switzerland, 22–24 July 2008.

[35] KRISHNARAJA, A.R., KANDASAMY, S., "Flexural performance of hybrid engineered cementitious composite layered reinforced concrete beams", *Periodica Polytechnica. Civil Engineering*, v. 62, n. 4, pp. 921–929, 2018. doi: http://dx.doi.org/10.3311/PPci.11748.

[36] COTSOVOS, D.M., "Cracking of RC beam/column joints: Implications for the analysis of frame-type structures", *Engineering Structures*, v. 52, pp. 131–139, 2013. doi: http://dx.doi.org/10.1016/j.engstruct.2013.02.018.

[37] PATTUSAMY, L., RAJENDRAN, M., SHANMUGAMOORTHY, S., *et al*., "Confinement effectiveness of 2900psi concrete using the extract of Euphorbia tortilis cactus as a natural additive", *Matéria (Rio de Janeiro)*, v. 28, n. 1, pp. e20220233, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2022-0233.

[38] WANG, G.L., DAI, J.G., BAI, Y.L., "Seismic retrofit of exterior RC beam-column joints with bonded CFRP reinforcement: an experimental study", *Composite Structures*, v. 224, pp. 111018, 2019. doi: http://dx.doi.org/10.1016/j.compstruct.2019.111018.

[39] JOHNSON, S.C., THIRUGNANAM, G.S., "Structural integrity assessment of transmission line tower foundations: a comprehensive approach", *CIGRE India Journal*, v. 4, n. 2, pp. 42–49, 2015.

[40] FAYAZ, Q., KAUR, G., BANSAL, P.P., "Numerical modelling of seismic behaviour of an exterior RC beam-column joint strengthened with UHPFRC and CFRP", *Arabian Journal for Science and Engineering*, v. 47, n. 4, pp. 1–16, 2022. doi: http://dx.doi.org/10.1007/s13369-021-06334-8.

[41] KRISHNASAMY, R., SINGARAM, C.J., PALANICHAMY, S., "Testing and evaluation of buckling and tensile performance of glass fiber-reinforced polymer angle section with different joints/connections", *Journal of Testing and Evaluation*, v. 52, n. 1, pp. 20230010, 2024. doi: http://dx.doi.org/10.1520/JTE20230010.

[42] SAGHAFI, M.H., GOLAFSHAR, A., "Seismic retrofit of deficient 3D RC beam-column joints using FRP and steel PT rods", *Materials and Structures*, v. 55, n. 8, pp. 210, 2022. doi: http://dx.doi.org/10.1617/s11527-022-02046-z.

[43] FARGHALY, A.S., BENMOKRANE, B., "Shear behavior of FRP-reinforced concrete deep beams without web reinforcement", *Journal of Composites for Construction*, v. 17, n. 6, pp. 04013015, 2013. doi: http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000385.

[44] HUNG, C.C., CHEN, Y.S., "Innovative ECC jacketing for retrofitting shear-deficient RC members", *Construction & Building Materials*, v. 111, pp. 408–418, 2016. doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.02.077.

[45] MOHANRAJ, R., SENTHILKUMAR, S., GOEL, P., *et al*., "A state-of-the-art review of Euphorbia Tortilis cactus as a bio-additive for sustainable construction materials", *Materials Today: Proceedings*, 2023. In press. doi: http://dx.doi.org/10.1016/j.matpr.2023.03.762.

[46] BOURGET, S., EL-SAIKALY, G., CHAALLAL, O., "Behavior of reinforced concrete T-beams strengthened in shear using closed carbon fiber-reinforced polymer stirrups made of laminates and ropes", *ACI Structural Journal*, v. 114, n. 5, pp. 1087, 2017. doi: http://dx.doi.org/10.14359/51700786.

[47] MURAD, Y.Z., ALSEID, B.H., "Retrofitting interior RC beam-to-column joints subjected to quasi-static loading using NSM CFRP ropes", *Structures*, v. 34, pp. 4158–4168, 2021. doi: http://dx.doi.org/10.1016/j.istruc.2021.10.024.

[48] JOHNSON, S.C., THIRUGNANAM, G.S., "Experimental study on corrosion of transmission line tower foundation and its rehabilitation", *International Journal of Civil & Structural Engineering*, v. 1, n. 1, pp. 27–34, 2010.

[49] KRISHNASAMY, R., JOHNSON, S.C., "Experimental investigations on glass fibre reinforced polymer composite pultruded sections and transmission line towers modules", *Water and Energy International*, v. 62, n. 10, pp. 33–37, 2020.

[50] CHALIORIS, C.E., KOSMIDOU, P.M.K., PAPADOPOULOS, N.A., "Investigation of a new strengthening technique for RC deep beams using carbon FRP ropes as transverse reinforcements", *Fibers (Basel, Switzerland)*, v. 6, n. 3, pp. 52, 2018. doi: http://dx.doi.org/10.3390/fib6030052.

[51] MOHANRAJ, R., SENTHILKUMAR, S., PADMAPOORANI, P., "Mechanical properties of RC beams With AFRP sheets under a sustained load", *Materiali in Tehnologije*, v. 56, n. 4, pp. 365–372, 2022. doi: http://dx.doi.org/10.17222/mit.2022.481.

[52] CHALIORIS, C.E., KYTINOU, V.K., VOUTETAKI, M.E., *et al*., "Repair of heavily damaged RC beams failing in shear using U-shaped mortar jackets", *Buildings*, v. 9, n. 6, pp. 146, 2019. doi: http://dx.doi.org/10.3390/buildings9060146.

[53] HAJI, M., NADERPOUR, H., KHEYRODDIN, A., "Experimental study on influence of proposed FRP-strengthening techniques on RC circular short columns considering different types of damage index", *Composite Structures*, v. 209, pp. 112–128, 2019. doi: http://dx.doi.org/10.1016/j.compstruct.2018.10.088.

[54] MORADI, E., NADERPOUR, H., KHEYRODDIN, A., "An experimental approach for shear strengthening of RC beams using a proposed technique by embedded through-section FRP sheets", *Composite Structures*, v. 238, pp. 111988, 2020. doi: http://dx.doi.org/10.1016/j.compstruct.2020.111988.

[55] LOGANATHAN, P., MOHANRAJ, R., SENTHILKUMAR, S., *et al*., "Mechanical performance of ETC RC beam with U-framed AFRP laminates under a static load condition", *Journal of Construction*, v. 21, n. 3, pp. 678–691, 2022. doi: http://dx.doi.org/10.7764/RDLC.21.3.678.

[56] RAVIKUMAR, K., PALANICHAMY, S., SINGARAM, C.J., *et al*., "Crushing performance of pultruded GFRP angle section with various connections and joints on lattice towers", *Matéria (Rio de Janeiro)*, v. 28, n. 1, pp. e20230003, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2023-0003.

[57] SHANMUGASUNDARAM, S., MOHANRAJ, R., SENTHILKUMAR, S., *et al*., "Torsional performance of reinforced concrete beam with carbon fiber and aramid fiber laminates", *Revista de la Construcción Journal of Construction*, v. 21, n. 2, pp. 329–337, 2022. doi: http://dx.doi.org/10.7764/RDLC.21.2.329.

[58] GURUNAATHAN, K., JOHNSON, S.C., THIRUGNANAM, G.S., "Anticipated and actual performance of composite girder with pre-stressed concrete beam and RCC top flange", *Structural Engineering and Mechanics International Journal*, v. 61, n. 1, pp. 117–124, 2017.

[59] KRISHNARAJA, A.R., ANANDAKUMAR, S., JEGAN, M., *et al*., "Study on impact of fiber hybridization in material properties of engineered cementitious composites", *Matéria (Rio de Janeiro)*, v. 24, n. 2, pp. e12347, 2019. doi: http://dx.doi.org/10.1590/s1517-707620190002.0662.

[60] RAJESH, A.A., SENTHILKUMAR, S., SARGUNAN, K., *et al*., "Interpolation and extrapolation of flexural strength of rubber crumbs and coal ash with graphene oxide concrete", *Matéria (Rio de Janeiro)*, v. 28, n. 4, pp. e20230179, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2023-0179.