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Welcome letter!

It is a great honor and privilege to stand before you today as the Editor-in-Chief of the prestigious journal, "Steps for Civil, Constructions, and Environmental Engineering" (SCCEE). I am deeply humbled to have been entrusted with this important role, and I would like to extend my gratitude to the editorial board, our reviewers, authors, and the entire team that makes this journal possible.

SCCEE serves as a vital platform for the exchange of knowledge, innovation, and advancements in the fields of civil engineering, construction engineering, and environmental engineering. This journal has facilitated the dissemination of groundbreaking research, influential studies, and critical developments. We have played an integral role in shaping the discourse and the direction of these disciplines, and I am committed to continuing this tradition of excellence.

Civil engineering, construction engineering, and environmental engineering are fields that underpin the development and sustainability of our society. From the construction of critical infrastructure to the preservation of our environment, our work has a profound impact on people's lives. It is essential that our journal continues to reflect the most cutting-edge research, the latest technologies, and the evolving challenges that our industries face.

As we embark on this journey, I want to emphasize our dedication to maintaining the highest standards of academic integrity, peer review, and ethical publication practices. We will continue to foster collaboration among researchers, practitioners, and experts in our fields, ensuring that the knowledge we publish is both rigorous and applicable.

Our commitment to open access, diversity, and inclusivity will be unwavering. We aim to engage with a broad and global audience, welcoming contributions and perspectives from around the world. Our goal is not only to disseminate knowledge but also to create a space where voices from different backgrounds can be heard and respected.

I invite all researchers, academics, practitioners, and students to be part of this exciting journey. Your work, your insights, and your dedication are the lifeblood of this journal. Together, we will push the boundaries of our fields, address pressing global challenges, and make a lasting impact on the world we live in.

In closing, I wish to express my profound gratitude for your trust and support as we move forward in this vital role. I look forward to working together with all of you to maintain SCCEE's reputation as a beacon of excellence in the realms of civil, construction, and environmental engineering.

Thank you.

Dr. Ali Jahami

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Research Article

An Experimental and Numerical Evaluation of the Structural Performance of Concrete Beams Containing Bamboo Shear Reinforcement

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Abstract

Alternatives to steel reinforcement in concrete are being actively investigated for environmental, economic, and durability concerns. Several studies suggest that bamboo is a potential substitute for steel reinforcement. In this study, the shear behavior of five reinforced concrete beams incorporating bamboo strips as shear reinforcement at different spaces and configurations were assessed. Structural concrete having a compressive strength of 25 MPa was used for this purpose. The experimental program involved applying four point bending test to the beams to determine their load deflection curves, crack pattern, and strain distribution. In addition, a numerical analysis was conducted for validation and prediction purposes. It was observed that including bamboo strips as shear reinforcement influenced a more brittle behavior with marginal differences when changing their spacing. On the contrary, the spacing was decisive for the load carrying capacity, as smaller spacing caused higher capacity. Strain distribution results followed a similar pattern to that of the deflection. All the curves exhibited a brittle shear failure evidenced by the crack propagation process. Further, the numerical study performed produced accurate results in comparison with the results obtained experimentally, in terms of both the load deflection curves and the crack pattern.

Keywords: *Bamboo-reinforced concrete, low cost construction, shear behavior, deflection, crack pattern, numerical analysis.*

*** Correspondence Author**

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Introduction

Steel reinforcement is an integral part of concrete structures. It is often implemented to support the tension zone of a concrete section due to its extremely high tensile strength. Steel reinforcement is also essential for resisting shear forces in the form of stirrups or ties. Nevertheless, steel is considered a high-cost material and it contributes to a considerable amount of greenhouse gases emissions worldwide. In addition, and apart from its economic and environmental drawbacks, steel reinforcement is a major cause of concrete degradation through corrosion. In fact, corrosion is the most important durability concern in reinforced concrete structures (El-Dieb and El-Maaddawy, 2018). When steel bars corrode, rust is formed and their volume increases, causing undesirable internal stresses within the concrete section. Consequently, this results in the formation of cracks and thus the spalling of concrete around the steel bars.

Responding to the mentioned demerits of steel reinforcement, a number of alternatives are being actively evaluated. Among these alternatives, bamboo emerges as a valid choice for many reasons. With more than a thousand species, bamboo belongs to the Gramineae family of plants and it is tremendously abundant in Africa, Asia, and Latin America, with India being the highest producer worldwide (Lobovikov *et al*. 2007). Conversely to steel, bamboo requires minimal energy for its production, reaching 50 times less than that required to produce steel (Ghavami, 2005). CO_2 emissions from steel production reaches 2 kg of CO_2 per 1 kg of steel, whereas bamboo could sequester CO_2 during its lifespan (Churkina *et al*. 2020, Zachariah *et al.* 2016). Also, bamboo has a high tensile capacity in the direction parallel to its fibers and exhibits brittle failure that generally occurs at its nodes (Javadian *et al.* 2019, Gauss *et al.* 2019) It was reported that the tensile strength of bamboo could reach 572 MPa (Wang and Shao, 2014). When employing proper techniques, bamboo has decent durability properties with marginal mechanical degradation with time (Lima *et al*. 2008). In addition, bamboo is a lightweight material, with density ranging from 500 to 800 kg/m^3.

A few number of studies considered replacing steel reinforcement with bamboo in reinforced concrete members. Agarwal *et al.* (2014) reported that concrete columns reinforced with 8% bamboo reached comparable axial load carrying capacity to that reinforced with minimum steel reinforcement but with improved ductility and energy absorption. It was also established in the same study that bamboo reinforced concrete beams achieved slightly higher load carrying capacity and more deflection than steel reinforced concrete beams. Qaiser *et al.* (2020) revealed that different types of bamboo reinforcement yielded different results concerning the ultimate load carrying capacity of reinforced concrete beams depending on the type of bamboo. A corrugated bamboo resulted in a higher load carrying capacity than wired bamboo or plain bamboo. Mali and Datta (2018) proposed a treatment method for bamboo reinforcement by creating a grooved bamboo sections that improved the flexural strength and ductility of concrete slabs in comparison with untreated bamboo reinforcement and steel reinforcement. Mali and Datta (2020) also detected a similar trend when assessing bamboo reinforced beams, where the ultimate load and energy absorption of reinforced beams containing “grooved” bamboo achieved comparable results to that of steel reinforced beams. Tirai and Minami (2011) reported that the prediction of the fracture behavior and the load capacity of bamboo reinforced beams is possible using existing formulas concerned with steel reinforced beams.

It is evident that using bamboo strips as shear reinforcement in concrete beams was not adequately addressed in the literature. The aim of this paper is to assess the structural performance of reinforced concrete beams containing bamboo strips as shear reinforcement. The load carrying capacity of the beams, the load deflection curve, and the strain distribution were addressed. In addition, the performance of the beams was modeled using ABAQUS 6.14 for validation and prediction purposes. Such study would further the knowledge of the use of bamboo strips in concrete structural elements by different means.

Methods

Concrete mixture design and casting

Ordinary Portland cement (OPC) class CEM I in accordance with EN 197-1 was used in this study. The cement was provided by Sibline Cement Factory, Chouf, Lebanon. Natural sand passing through sieve #4 (4.75 mm) was used as fine aggregates. Crushed stone was used as coarse aggregates at two nominal maximum sizes: 9.5mm and 19 mm. The natural sand and crushed stone are locally available in Lebanon. Sika Viscocrete 20HE was used as high range water reducer (HRWR). A single concrete mixture was used in this study having a binder content of 450 kg/m^3 and a water to cement (w/c) ratio of 0.45 for a target of 25 MPa compressive strength at 28 days. The HRWR was used at 1% of the cement weight to improve the workability of the mixture. The concrete mixture details are presented in (Table 1).

Table 1. Concrete mixture details (Kg/m^3).

OPC	Fine aggregates	Coarse aggregates (9.5mm)	Coarse aggregates (19mm)	Water	HRWR
450	415	692	692	200	4.5

A standard pan mixer was used for the concrete mixing procedure. The dry materials were first mixed for 2 minutes before adding half the amount of free water to the dry mixture and mixing for another 2 minutes. After that, the other half of the free water was added containing the HRWR and mixing resumed for further 2 minutes. Vibration was performed to ensure proper casting of the concrete into the molds with minimum voids (Figure 1). The mixture was then poured into molds. Steel cylindrical molds of size 300 × 150 mm were used for testing the compressive strength of the concrete at days 7, 14, and 28. Timber molds were prepared for beams with size of 150 × 170 × 1000 mm. The specimens were demolded after 24 hours and were placed in water tanks at 20° C until testing.

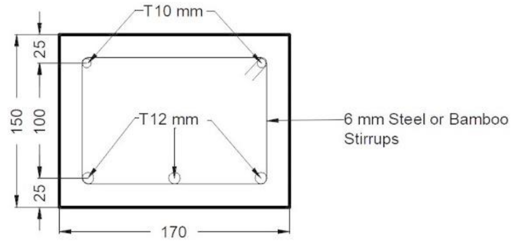
Figure 1. Vibration of concrete inside the molds.

Reinforced concrete beams

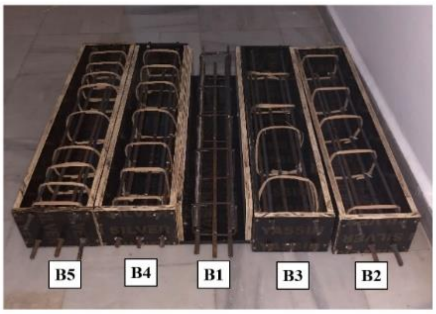
Five concrete beams, with dimensions of 150mmx170mmx1000mm were prepared to study the effect of bamboo links on the structural behavior. The flexural reinforcement of all beams consisted of steel reinforcement arranged as follows: three 12 mm rebars at the bottom (tension zone) and two 10 mm rebars at the top (compression zone). This is better illustrated in (Figure 2). The steel reinforcement was hot rolled deformed steel bars having a tensile strength of 420 MPa. The beams were designed to be over reinforced in flexure to ensure a shear failure. As for the shear reinforcement, beam B1 had steel stirrups of the same grade of diameter 6mm spaced at 180 mm. Beams B2, B4, and B5 had bamboo stirrups of diameter 6mm with a spacing of 180, 90, and 60 mm, respectively. B3 had bamboo stirrups of the same diameter (6mm) and a spacing of 180mm but the stirrups were inclined at an angle of 45°. The bamboo stirrups implemented were bought from a local furniture workshop in Beirut, Lebanon and have tensile strength of 550 MPa. The concrete cover at all sides of the beams was kept at 2 cm. (Table 2) shows the reinforcement details of the beams under study.

Table 2. Reinforcement details of the beams

ID	Flexural reinforcement			Shear reinforcement			
	Type	Bottom	Top	Type	Diameter	Spacing	Configuration
B1	Steel	3φ12 mm	2φ10 mm	Steel	6 mm	180 mm	Normal
B2		3φ12 mm	2φ10 mm	Bamboo	6 mm	180 mm	Normal
B3		3φ12 mm	2φ10 mm		6 mm	180 mm	45° inclination
B4		3φ12 mm	2φ10 mm		6 mm	90 mm	Normal
B5		3φ12 mm	2φ10 mm		6 mm	60 mm	Normal



(a)



(b)

Figure 2. (a) Reinforced concrete beams dimensions and reinforcement (dimensions in mm), (b) Beams inside timber molds before casting.

Experimental program

The compressive strength of the concrete mixture was determined in accordance to BS EN 12390-3 at 7, 14, and 28 days of curing. At each age, three concrete cylinders were tested, and the average value was reported.

Four-points bending test was performed for the beams after 28 days of curing. An increasing load was applied on the beams. Two steel rollers were used to transfer the load to the beams from a steel I-section beam that in turn transferred the load from the testing machine. The full test setup is shown in (Figure 3). While loading, the central deflection was automatically recorded by the machine. The machine was stopped at loads 32, 64, and 96 KN to measure the strain distribution at predefined positions, 20, 40, 110 and 130mm from the top face as shown in (Figure 4). Two demountable mechanical strain gauge (DEMEC) discs were affixed onto the beam's surface to assess the strain at specific locations using a mechanical strain gauge. The strain is determined by calculating the elongation between the two DEMEC points, divided by the initial spacing of 200 mm between them. A similar procedure was reported in literature (Manikandan *et al.* 2015, Khatib *et al.* 2019, Bawab *et al.* 2021). Loading was then resumed until failure.

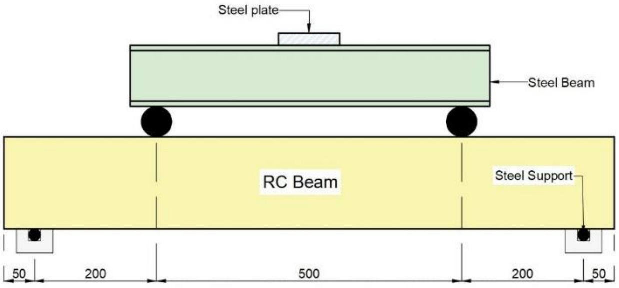


Figure 3. Four point bending test setup (dimensions in mm).

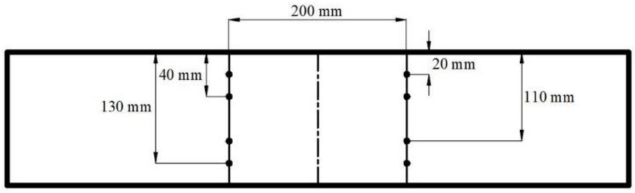
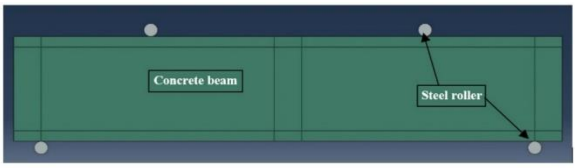


Figure 4. DEMEC points positions for strain distribution.

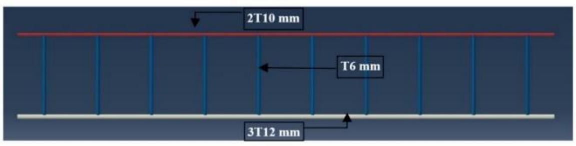
Numerical modelling

Numerical analysis was conducted on the five beams using ABAQUS 6.14 finite element software (Temsah *et al.* 2021, Jahami *et al.* 2021). The concrete body was modeled using 8-node linear brick elements with a mesh size of 1 cm, which was determined after conducting a mesh sensitivity analysis. The steel rebars and bamboo strips were modeled as 2-node linear 3-D truss elements. The contact between the steel supports and the concrete body was modeled as a "general contact" type, incorporating both "hard" normal contact and a tangential contact with a coefficient of friction of 0.7 between steel and concrete.

In addition, the cylindrical supports and loading rods were modeled as rigid bodies due to their significantly higher stiffness compared to the concrete body in contact (Temsah et al. 2018). It was assumed that all reinforcements were fully embedded inside the concrete body. For further information and visual representation of the beam modeling, please refer to (Figure 5).



(a)



(b)

Figure 5. Software modeling of the (a) beam and (b) reinforcement.

Concrete material was defined using the built-in concrete damage plasticity (CDP) model, which accurately captures the nonlinear behavior of concrete under various loading conditions. The CDP model takes into account the damage accumulation and plastic deformation of the concrete material. The main parameters required by the CDP method, such as the tensile strength, compressive strength, Elasticity modulus, and dilation angle, are presented in (Table 3). These parameters were carefully selected based on experimental data and previous studies to ensure the accuracy of the numerical analysis (Temsah *et al.* 2021, Jahami *et al.* 2021).

On the other hand, steel rebars and bamboo strips were modeled as elastic-perfectly plastic materials, as they exhibit linear elastic behavior until reaching their yield point, followed by plastic deformation. (Table 4) provides the relevant properties for steel and bamboo materials, including the Young's modulus, yield strength, and plastic strain. These properties were defined to accurately represent the mechanical response of steel and bamboo within the numerical model.

By considering the appropriate material models and defining their corresponding parameters, the numerical analysis aimed to capture the realistic behavior of the composite beam system, accounting for the nonlinear response of concrete while representing the elastic-plastic behavior of steel and bamboo materials.

Table 3. CDP parameters adopted in modeling.

Parameter	Symbol	Values
Elastic Modulus (MPa)	E	22995
Poisson's ratio	υ	0.2
Density (Kg/m^3)	ρ	2400
Compressive strength (MPa)	f'_c	24.5
Tensile Strength (MPa)	f_t	2.45
Dilation angle (°)	ψ	36
Eccentricity	ε	0.1
Bi-axial to Uni-axial strength ratio	f_{b0}/f_{t0}	1.16
Second stress invariant ratio	K	0.67
Viscosity parameter	μ	0

Table 4. Elastic-perfect plastic parameters for steel and bamboo materials.

Material	Young's modulus (MPa)	Tensile strength (MPa)	Plastic strain
Steel	200000	420	0
Bamboo	30000	550	0

Results and discussion

Compressive strength

(Figure 6) illustrates the noteworthy progress in compressive strength observed in the concrete mixture over the curing periods of 7, 14, and 28 days. As the curing time increased, there was a notable enhancement in the compressive strength values. At 7 days of curing, the concrete exhibited a compressive strength of 13 MPa, which further improved to 16.3 MPa after 14 days of curing. The most substantial gain was observed at the 28-day mark, where the compressive strength reached an impressive value of 24.5 MPa. These results demonstrate the progressive development and maturation of the concrete mixture over time.

Notably, the achieved compressive strength at 28 days satisfies the minimum requirement for structural concrete as prescribed by the ACI 318 standard, which mandates a compressive strength of at least 21 MPa. This finding indicates that the concrete mixture under investigation possesses sufficient strength to meet the structural demands and can confidently be employed in various construction applications. It is worth highlighting that surpassing the minimum requirement demonstrates the excellent performance and durability potential of the concrete mixture, providing an added advantage in terms of structural integrity and long-term stability.

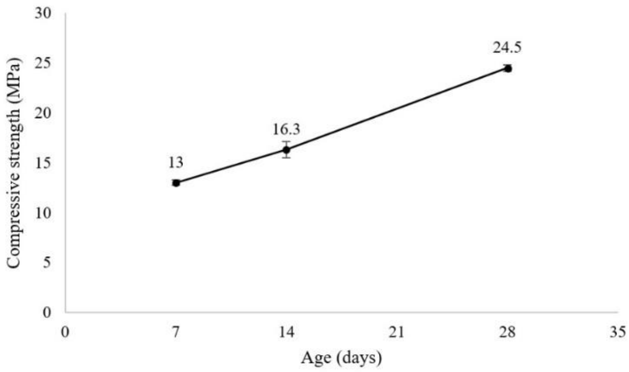


Figure 6. Compressive strength of the concrete mixture.

Load – deflection

In (Figure 7), the load-deflection curve for beams B1-B5 at 28 days of curing is depicted, providing valuable insights into their structural behavior. Initially, all beams exhibited a linear curve, indicative of elastic deformation, until the occurrence of the first crack. Following the initial crack, the curve maintained linearity; however, the slope differed compared to the pre-cracking phase. This linear behavior persisted until the beams reached their maximum carrying load capacity. At this point, the concrete experienced crushing, leading to a brittle shear failure in all the beams under investigation.

Analyzing the maximum deflection of the beams equipped with bamboo strip shear reinforcement (B2-B5), it was observed that they exhibited a maximum displacement ranging between 3 and 3.8 mm. In contrast, beam B1, reinforced with steel, exceeded this value and reached a maximum deflection of 4.4 mm. These findings suggest that the inclusion of bamboo strips as shear reinforcement resulted in a more brittle behavior of the reinforced concrete beams. The bamboo strips, although contributing to the overall strength, demonstrated a reduced capacity to accommodate flexural deformations, ultimately leading to a stiffer response and a more abrupt failure mode.

Furthermore, examining the effect of varying the spacing of bamboo strip shear reinforcement on the maximum displacement of beams B2-B5, it was observed that the change had only a marginal impact. The maximum deflection values remained relatively consistent across the different beam configurations, indicating that altering the spacing of the bamboo strips within the studied range did not significantly affect the overall structural response in terms of deflection.

These findings provide valuable insights into the performance and behavior of bamboo strip shear reinforcement in reinforced concrete beams. It highlights the need for careful consideration and evaluation when utilizing bamboo as a substitute for traditional steel reinforcement, as the resulting structural response may exhibit more brittle characteristics. Future research could focus on optimizing the design and arrangement of bamboo strip reinforcement to enhance the flexibility and ductility of the beams, ultimately leading to improved structural performance and resilience.

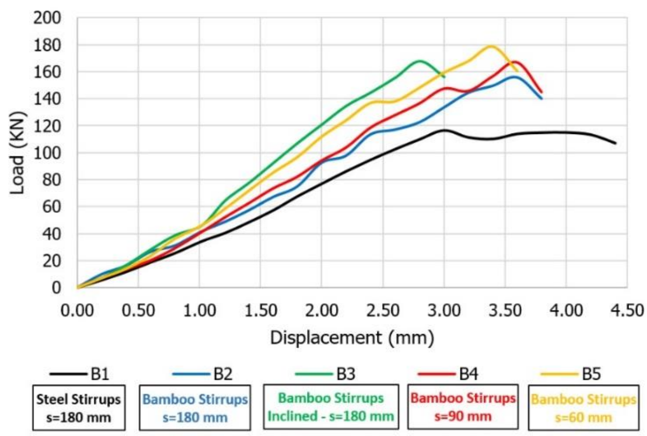


Figure 7. Load-deflection curve of beams B1-B5.

The maximum load carrying capacity of the beams ranged between 116 and 178 KN. Reducing the spacing of the shear reinforcement largely contributed to the increase of the load carrying capacity of the beams despite using bamboo strips as an alternative. An increase of 30% in the maximum load when using Bamboo links instead of steel links (B1 and B2). However, further decrease in the spacing did not have a remarkable impact. In addition, comparing B2 and B3 having the same spacing (180 mm) but different configuration of the bamboo strips, the 45° inclination caused a noticeable increase in the maximum load, from 155 to 167 KN. The maximum shear capacity of the beams is detailed in (Figure 8) and was calculated by dividing the load capacity over two (half for each support).

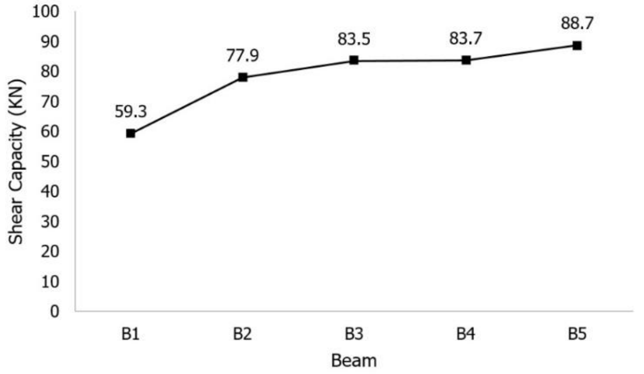
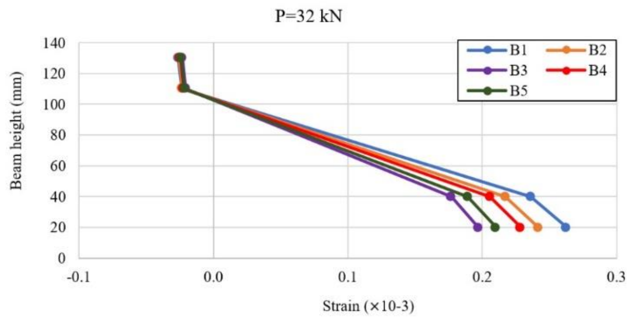


Figure 8. Shear capacity of beams B1-B5.

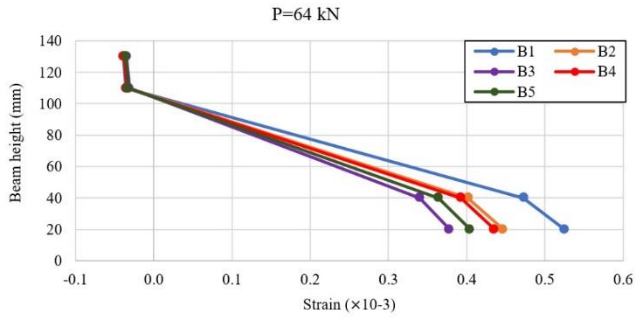
Strain Distribution

(Figures 9(a-c)) provide insightful visualizations of the strain distribution within beams B1-B5 at various locations (20, 40, 110, 130 mm from the bottom face of the beam) under different load levels (32, 64, 96 KN). As expected, the bottom zone of the beams experiences tensile strain (positive strain), while the upper zone undergoes compressive strain (negative strain). Additionally, it is observed that larger loads result in greater strains across the beams.

A consistent trend is noticeable among all beams at every load level, where Beam B1 exhibits the largest deformation, while Beam B3 displays the least deformation. This indicates that the characteristics of each beam, such as the type of reinforcement or arrangement of materials, contribute to its overall structural response. The substantial tensile strains observed in the beams correspond to significant displacements, as demonstrated in (Figure 9).



(a)



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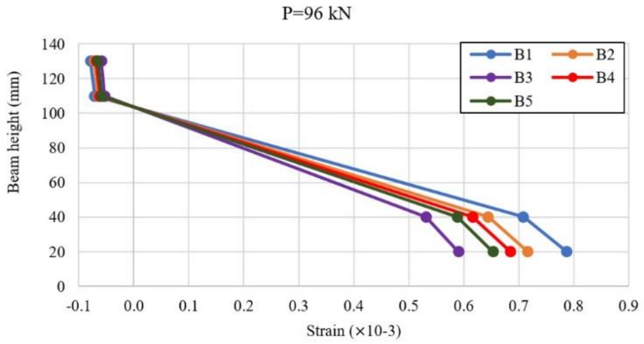


(c)

Figure 9. Strain distribution plots at (a) 32 kN, (b) 64 kN, (c) 96 kN.

Crack pattern

(Figures 10(a-e)) provide a comprehensive depiction of the failure mode and crack propagation observed in beams B1-B5. The examination of these figures revealed the presence of both flexural and shear cracks in all beams. The shear cracks primarily initiated near the supports and exhibited their widest extent at the bottom surface of the beams. On the other hand, the flexural cracks originated in the tensile zone and propagated vertically upward, with their maximum width also observed at the bottom of the beams.

Upon comparing the failure modes of beams B1 and B5, a notable observation emerges. As the shear capacity of the beam increased, there was a visible increase in the number of flexural cracks observed. This comparison highlights the influence of shear capacity on the structural response of the beams and the resulting crack patterns.

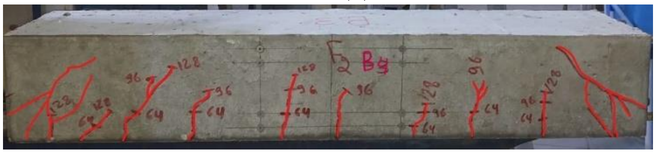
Despite their slight differences in shear reinforcement or design details, all beams exhibited similar crack propagation behavior. This finding suggests a consistent failure mechanism in which the beams experienced a brittle shear failure. The occurrence of brittle failure mode is indicative of limited ductility and reduced energy dissipation capacity within the beams.

The comprehensive analysis of the failure mode and crack propagation in beams B1-B5 contributes to a better understanding of the structural behavior and performance of the reinforced concrete beams under consideration. The observed crack patterns and failure modes can serve as valuable information for further design improvements and engineering interventions aimed at enhancing the ductility and overall resilience of concrete structures. Future research could focus on exploring innovative reinforcement techniques or modified beam designs to mitigate the occurrence of brittle failure and promote more desirable crack patterns, thereby improving the structural performance and durability of reinforced concrete beams.

(a)

(b)

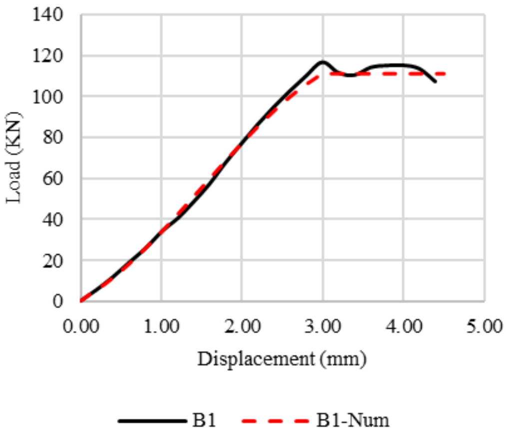
(c)



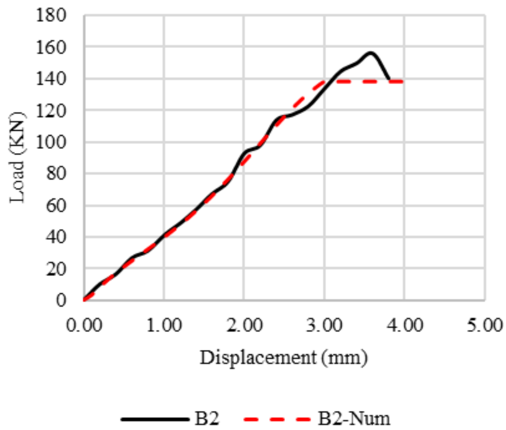
(d)

(e)

Figure 10. Crack propagation for beams (a) B1, (b) B2, (c) B3, (d) B4, and (e) B5.



(a)



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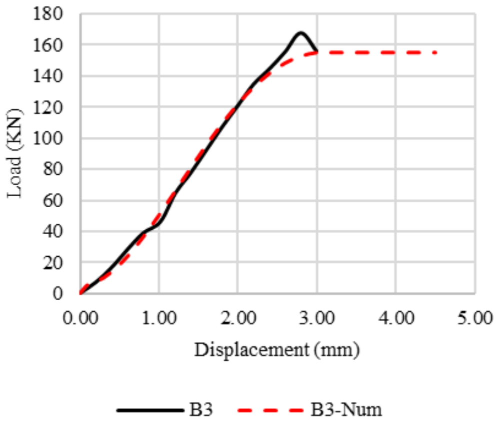

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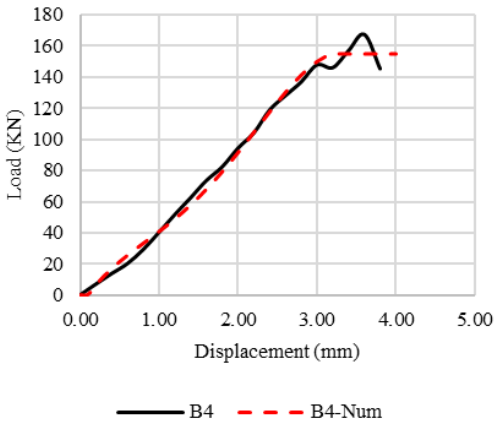
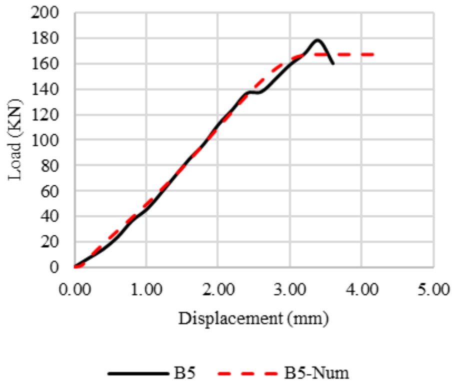


(d)

Numerical analysis

(Figures 11(a-e)) provide a comprehensive comparison between the experimental load-deflection curves and the numerical simulations performed using ABAQUS 6.14 for beams B1-B5, respectively. The results demonstrate that the software exhibits a commendable level of reliability in predicting the load-deflection behavior of the beams, irrespective of their respective reinforcement configurations. The numerical simulations closely match the experimental curves, exhibiting similar trends from the initial loading stages until failure. These findings align with similar studies reported elsewhere (Bawab *et al.* 2021, Khatib *et al.* 2020, Khatib *et al.* 2021), further validating the accuracy and consistency of the software in capturing the structural response of reinforced concrete beams.

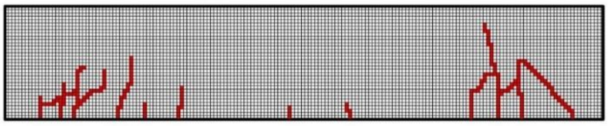
However, it is important to note that the software tends to slightly underestimate the load carrying capacity of the beams, as observed in all cases. Conversely, the maximum deflection is often overestimated by the software, particularly for beams B3 and B5. This discrepancy may be attributed to the more brittle failure mode induced by the beams containing bamboo shear reinforcement, as well as the assumption of perfectly plastic behavior assigned to both steel and bamboo materials within the numerical model.



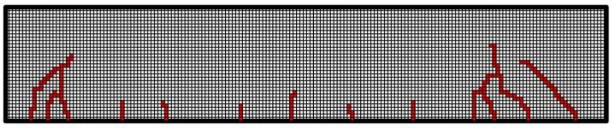
(e)

Figure 11. Numerical vs. experimental load-deflection curves for beams (a) B1, (b) B2, (c) B3, (d) B4, and (e) B5.

Moving on to (Figures 12(a-e)), the crack patterns generated by the software for beams B1-B5 are displayed. The crack patterns closely resemble those observed experimentally, further indicating the accuracy of the numerical simulations. The presence of multiple diagonal cracks concentrated near the supports indicates a shear failure mechanism. Additionally, for beams subjected to higher loads, the flexural cracks become more prominent, originating from the bottom face of the beam and propagating upwards. Consequently, the software provides further insight, revealing that beams B1-B3 exhibit fewer flexural cracks due to their earlier shear failure, while beams B4 and B5, carrying higher loads, exhibit more flexural cracks prior to experiencing shear failure.



(a)



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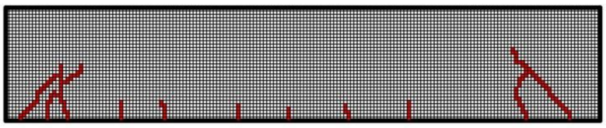

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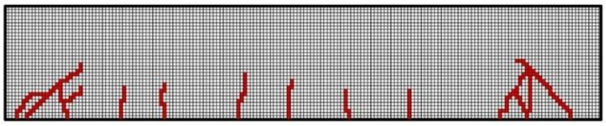

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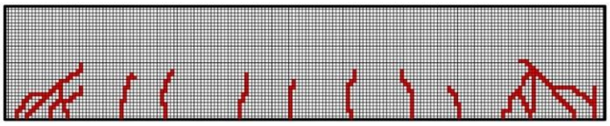

(e)

Figure 12. Crack pattern generated by the software for beams (a) B1, (b) B2, (c) B3, (d) B4, and (e) B5.

Conclusions

In this study, an assessment was conducted on the shear behavior of five reinforced concrete (RC) beams incorporating bamboo strips as shear reinforcement, considering different spacing and configurations. The beams were constructed using structural concrete with a compressive strength of 25 MPa. The experimental program involved subjecting the beams to a four-point bending test to evaluate their load-deflection curves, crack patterns, and strain distribution. Additionally, numerical analysis was performed to validate and predict the behavior of the beams. The key findings of this study can be summarized as follows:

1. The utilization of bamboo strips as shear reinforcement in RC beams resulted in a significant increase in the load carrying capacity, with an improvement of up to 30%. This noteworthy enhancement indicates the excellent performance of bamboo strips in resisting diagonal tension stresses generated by shear forces near the supports.

2. Among the different configurations examined, the beam incorporating inclined bamboo strips (at 45 degrees) demonstrated superior shear resistance compared to beams with vertical bamboo strips. This observation was supported by the ultimate load capacity, which exhibited an 8% increase in the beam with inclined bamboo strips.

3. The spacing of the shear reinforcement played a significant role in the damage pattern and shear capacity of the beams. As the spacing decreased, the shear capacity of the beams increased, and an increased number of flexural cracks were observed on the bottom surface, extending towards the top surface at the mid-span of the beams.

4. The finite element modeling demonstrated close agreement with the experimental results obtained from RC beams with bamboo strips. Both the load-deflection curves and damage patterns were successfully validated, thereby confirming the accuracy and reliability of the numerical simulations. These findings are of particular importance for future research endeavors focused on RC beams incorporating bamboo strips.

Overall, this study provides valuable insights into the use of bamboo strips as shear reinforcement in RC beams. The results highlight the enhanced load carrying capacity, the influence of inclined bamboo strips, the impact of spacing on shear capacity and damage patterns, and the successful validation of the numerical model. These findings contribute to the knowledge base for designing and optimizing RC structures incorporating bamboo strips as a sustainable alternative to traditional steel reinforcement.

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Research Article

Sustainable Restoration Techniques for Historic Buildings in Tyre City

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Abstract

The intervention of historic buildings is a complex and evolving phenomenon; all aspects of sustainability must be considered. The possibility of these restored buildings collapsing can cause significant damage to the economy, social life, environment, and cultural heritage due to inappropriate interventions and decisions. Therefore, an integrated approach to managing these historic buildings is needed to achieve a sustainable level of restoration. The responsibility to transmit cultural heritage to future generations makes sustainable construction even more important. In this article, common types of interventions are analyzed to create a guide for an integrated approach to sustainability and structural behavior according to international standards and methods. As a case study, the city of Tyre (Sour) was analyzed, and several cases have been studied to highlight the necessary aspects for sustaining historic buildings. By considering all structurally or pathologically important aspects explained below in two sections—macro and micro approaches—this article presents the main sustainability methods and techniques.

Keywords: Historic buildings, sustainable methods and techniques, concrete and waste plastic, restoration.

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Introduction

The tendency to neglect historic buildings is a concerning issue that often leads to their abandonment, dilapidation, and eventual destruction unless preservation efforts are proposed. These buildings hold significant cultural heritage value and form the basis of our culture, necessitating their conservation, structural restoration, rehabilitation, or at times, renovation of civil architecture. To ensure proper and internationally accepted methodologies for these processes, the Venice Charter was established in 1964, defining restoration standards and principles for monuments. The International Council on Monuments and Sites (ICOMOS) has continuously published charters, doctrines, and recommendations for the restoration and conservation of historic monuments. One of these publications, "Recommendations for the Analysis, Conservation, and Structural Restoration of Architectural Heritage" (ICOMOS Charter, 2003), outlines the necessary steps for restoring any historic building. These guidelines provide fundamental principles for conservation and discuss the rules and methodologies that engineers or architects should follow during restoration. They offer indispensable steps for preserving architectural heritage structures during rehabilitation. However, it is essential to acknowledge that while these charters offer general approaches and evaluation recommendations, specific problems observed in individual structures may vary, making selected interventions during rehabilitation not universally applicable.

In this article, various methods and techniques to address problems faced by historic buildings will be thoroughly examined through case studies in the city of Tyre (Soûr), located in southern Lebanon. The article aims to provide a comprehensive analysis of the types of issues encountered and suggest appropriate recommendations. Additionally, the article explores the use of concrete as a sustainable material in restoration techniques. Concrete is a popular choice due to its known benefits of strength, durability, and availability. However, it may have some flaws arising from the use of brittle natural resources. To overcome some of these flaws, some experts suggest substituting these resources with recycled waste plastic fibers, which can potentially enhance concrete's durability and behavior (Khatib, Jahami, et al., 2020). Several studies examining the effects of adding different types of waste plastic fibers to concrete will be briefly listed, along with their results. These fiber types include steel fibers, carbon fibers, recycled polyethylene terephthalate (PET) fibers, and macro polypropylene (PP) fibers. By exploring ways to improve the structural performance of concrete, the article aims to contribute to sustainable restoration practices for historic buildings.

2. Basic Expressions: Restoration, Renovation, and Preservation

In the literature, several expressions are used for interventions at the level of countering the neglect of historic buildings, such as adaptive reuse, restoration, renovation, preservation, reconstruction, conservation, and rehabilitation (E. Gracia, et al., 2023). In the following section, some of the main terms will be mentioned, focusing on the case study of Tyre city.

Restoration: The restoration of historic buildings is a complex process that requires a thorough understanding of the building's history, original structure, and materials used (John, 1903). This process involves repairing damaged walls and roofs, reinforcing foundations, and preserving the original structure. One of the critical aspects of restoring historic buildings is the use of natural and sustainable materials. Rehabilitation and restoration of heritage buildings are ways of sustainable development and an expression of culture (Gopinath & Ramadoss, 2021).

Renovation: Renovation of historic buildings involves updating the building to meet modern standards while preserving its historical integrity and our cultural heritage. This can involve updating the building's infrastructure, adding modern amenities, and improving accessibility. It is important to strike a balance between modernization and preservation to ensure that the building remains authentic (Chiara & Arian, 2018).

Preservation: Preserving the original structure of a historic building is fundamental to maintaining its cultural significance. The original structure includes the building's foundation, walls, roof, and decorative elements (Brebbia, 2002). These elements reflect the unique character and cultural significance of the buildings.

3. Building Materials and Sustainable Restoration Techniques

Interventions at the level of heritage/historical buildings are a complicated process that requires listing the main reasons and benefits for refurbishing the building and addressing the problems to be solved. Building risk assessment must be conducted to identify changes in building physics, such as variations in air penetration rate, moisture load, and moisture content throughout the year, which may increase the risk of decomposition of organic materials and architectural features (Torben, 2016).

Masonry structures of historic and listed buildings, such as strip foundations, walls, and vaults, are predominantly made of sandstone, limestone, granite, and fired brick wall units. Sandstone became a primary building material in the 15th century, gradually replacing sandy loam due to its high resistance to the elements. The collective term "building sandstone" includes several rock types of sedimentary origin with varying chemical composition, age, and physical properties (water absorption, hardness, porosity, frost resistance) (Wizany, et al., 2017).

Literature reviews reveal that most research has focused on structural and physical changes to buildings while retaining their previous function. This process is often combined with structural retrofitting and energy retrofitting interventions, aiming to elevate the building for better environmental performance while preserving its distinct character (Lidberg et al., 2015). In this field, many applications have been carried out by specialists. In 1936, Giovanni Dondini (Erder, 2005) identified four types of restoration: restoration by consolidation, restoration by decomposition "anastylesis," restoration by liberation, and restoration by completion or renovation. Specialists like Sherif, Murad, and Ashraf have applied mathematical modeling techniques to study the structural stability of archaeological buildings under the influence of different loads, both vertical and horizontal (Anwar, 2019).

Sustainable restoration techniques refer to methods that aim to minimize negative impacts on the environment while preserving historic structures (Turgay, et al., 2023). These techniques prioritize the use of environmentally friendly materials and energy-efficient practices. Examples of sustainable restoration techniques suitable for historic buildings, especially historic residential housing, include:

1. The Use of Natural and Sustainable Materials:

One of the most crucial aspects of sustainable restoration is the accurate selection of materials. Natural and sustainable materials such as wood, stone, and clay are preferred over synthetic materials that might harm the environment. These locally sourced materials have a low environmental impact. For instance, sandstone, limestone, and granite can be used for restoring historic walls, while natural paints and finishes can be used to preserve the original aesthetic of the buildings. Moreover, concrete, a commonly used material in construction, can be made more sustainable by replacing some natural resources with recycled or waste products such as waste plastic. This can have environmental and economic benefits, as waste plastic is often readily available in landfill sites and open spaces. Additionally, waste plastic can enhance concrete's durability and reduce the ingress of aggressive species by making it more ductile when combined with fibers such as rubber, glass, asbestos, plastic, or bamboo fibers. Several studies have focused on the mechanical and durability performance of rubberized concrete combined with macro polypropylene (PP) fiber, with positive improvements observed in fracture energy, compressive strength, and ultrasonic pulse velocity (UPV) (Wang et al., 2019).

2. Energy-Efficient Practices and Water Conservation Techniques:

Implementing energy-efficient practices can reduce energy consumption and carbon emissions. Strategies like utilizing natural lighting and optimizing ventilation can minimize the need for artificial lighting and heating. Solar panels can be used to generate electricity and hot water, reducing dependency on fossil fuels. Additionally, rainwater harvesting techniques can provide water for irrigation and non-potable uses.

3. Preserving the Original Structure:

Preserving the original structure of historic buildings is essential to maintain their cultural and historical significance. Sustainable restoration techniques prioritize repairing damaged walls and roofs, reinforcing foundations, and stabilizing structures to withstand natural hazards like earthquakes and floods, instead of demolishing and rebuilding.

4. Community Participation:

Community participation is vital for the success of sustainable restoration projects. Involving residents in the planning and implementation of projects enhances the social and cultural value of restoration work. This approach fosters a sense of ownership and pride in local heritage.

4. Tyre City Case Study

Tyre (Soûr) is located on the southern coast of Lebanon, 83 km south of Beirut. It holds the distinction of being one of the oldest continually inhabited cities in the world, dating back to the earliest Phoenician metropolises.

The modern town of Soûr consists of two distinct sites: one on the headland and the other being the Necropolis of El Bass on the continent. The town site boasts significant archaeological remains, a large part of which is submerged. The sector of Tyre El Bass, which served as the primary entrance to the town in ancient times, showcases the remains of the necropolis. Flanking a wide monumental causeway stands a Roman triumphal arch dating back to the 2nd century AD (UNESCO, 2022).

Figure 1: Map showing the location of Tyre city on the map of Lebanon, with an enlargement satellite map of Tyre city. (Source: www.googleearth.com, access in 2023)

Apart from the archaeological sites, the renowned old town represents the city of Soûr after the reconstruction of ancient Tyre in the 8th century AD. It comprises residential areas, markets, mosques, churches, and a small port, all built on the ruins of the historic city of Tyre using limestone and sandstone sourced from older buildings that are still in use.

An initial inventory of the stones used in the construction of these structures, regardless of the time they were built or their function, reveals a variety of stone types employed during different historical periods. These stones include sandstone (commonly referred to as *ramli*, which often transforms into a calcarenite), hard compact limestone, and soft, sometimes porous limestone. "These stones, all of sedimentary origin, are rich in calcium carbonate and possess favorable properties as dimension stones: they are easy to work with and sufficiently durable for the climate of South Lebanon. The stone known as *ramli* (sandstone in Arabic) derives its name from its sandy color, but its composition is that of calcarenite. It contains a mixture of bioclasts with fragments of other limestones and only small amounts of clay and sand" (Badawi, 2016).

4.1. Structural and Physical Changes (Problems and Solutions)

In the old city of Tyre, Lebanon, there are numerous historic buildings, especially residential ones, which have endured for centuries. However, natural and environmental factors, as well as human activity, have caused deterioration over time. The following problems have been observed:

1. Appearance of Cement Sheets on Main Elevations: Some buildings' stones have been renovated using cement to fill gaps.

2. Drainage Pipes on Main Elevations: Modern drainage installations have been added to the main elevations, affecting the original appearance.

3. Destruction of Some Balconies or Railings: Balconies and stairs of historic buildings have been damaged or removed.

4. Cracks in Brick Roofs: Brick roofs have developed cracks, potentially compromising their structural integrity.

5. Damages to Glass and Wood Openings: Glass and wooden openings, such as windows and doors, have suffered damages over time.

6. Spread of Plants: Plants have grown on the walls due to frequent exposure to weather factors and water penetration between joints.

7. Masonry and Stone Problems: Issues such as the appearance of black colors, bacterial growth, and holes in the masonry and stones have been observed.

Figure 2: Images taken at site in Tyre City showing Structural and Physical Changes (Problems). (A): Spread of Plants; (B): Appearance of Cements sheets on main elevations; (C): Masonry and Stone Problems (appearance of Black colors, Bacteria, holes…) (Source: Author)

The problems and reasons for plants growing on the walls are due to frequent exposure to weather factors (such as salt-laden winds and temperature differences near the sea) and the loss of mortar between the joints, which allows water to penetrate and create a suitable space for plant growth. As a result, maintenance involves uprooting and using chemical methods to eliminate these plants (Table 1).

Table 1. Maintenance or Repair Methods for the Growing Plants Problems

Maintenance or Repair Methods	Description	
1.Eliminating Plants by Uprooting	Uprooting has two side effects: the roots may still remain inside and could damage the building by removing a large amount of mortar between the stones.	
2.The Elimination of Plants Using Chemical Products	2.1. Climbing plants should be sprayed with a herbicide composed of "glyphosate." Additionally, the plants should be cut slowly by hand or with a trowel to keep the flowers clean and moisturized.	
	2.2. The gaps are cleaned with water, and the spaces between the stones are filled using white paint (clay) and mortar. Another method to remove shrubs and weeds is to cut them from the base.	
	2.3. The cut stem can be injected with a herbicide solution or punctured vertically to the center, allowing the herbicide to be inserted inside and effectively kill the main roots connected to the building structure.	

(Source: Author)

Exterior stone is a material subjected to the influence of various types of air pollution and undergoes several changes associated with hydration, leading to the deterioration of the elevation. Therefore, a proper diagnosis should be conducted to investigate the problem and identify the suitable cleaning methods, as mentioned in Table 2.

Table 2. Maintenance or Repair Methods for Exterior Stone Problems

Maintenance or Repair Methods	Description of the Maintenance or Repair Methods
1.Cleaning with Machine Tools and Rubbing	It is a simple, economical, and practical way based on cleaning the facades with a plastic brush. However, one negative aspect of this method is the potential for water leakage inside the gaps.
2.Cleaning by High Pressure of Cold or Hot Water	The surface must be cleaned before water treatment. The water pressure should be monitored carefully, especially on the main elevations that experience significant issues.
3.Cleaning by Scraping	This process consists of two methods: 3.1. Getting rid of sands (fine particles) using different pressures or refining the surface. However, this method is not preferable. 3.2. Chemical methods: This method is based on the use of chemical solvents to clean the surface and requires analysis in the laboratory. It helps in selecting the appropriate solvents for cleaning. The surface should be cleaned with water after exposing it to any chemical substances.

(Source: Author)

Like other materials, stone is also exposed to various factors that can cause damage, such as the separation of its constituent layers. Therefore, it is essential to polish and repair the main surface of the stone. The benefits of using this method lie in preserving the largest quantity of the stone's main substance. The repair process involves the following steps:

1. Outline the surface that requires repair and prepare the lime mortar.

2. Spray the surface with water, then apply a second layer of clay until it exceeds the surface of the gap. Allow it to dry.

3. Cover the finished surface with a damp piece of cotton and leave it to dry slowly.

4. Trim flat surfaces with a saw blade according to their final shape. Then, carve out the marked surface with a chisel and hammer to obtain a uniform recess of 15 cm in depth.

5. Hydrate the surface with water and use trowels to extend the plaster, filling half of the gap. Leave the plaster to dry for two or three days.

By following these steps, the main surface of the stone can be effectively repaired, preserving its original substance and enhancing its durability.

Figure 3. Diagrams Illustrating the Techniques for Preserving the Stone. (Source: Author)

4.2. Intervention Cases in Tyre City

The mentioned techniques were employed in numerous historic buildings observed in the city of Tyre after thorough site visits and individual case investigations. These methods were applied based on the specific type of intervention required for each building or area, such as restoration, preservation, or rehabilitation. The application of these techniques was supported by various reports from reputable sources, including UNESCO, the municipality, relevant organizations, and specialists (Ali Badawi, a PhD in archaeology and the scientific director of archaeological excavations in Tyre and South Lebanon). The utilization of these well-documented and expert-approved methods ensures the appropriate conservation and restoration of Tyre's valuable cultural heritage.

The first case study focuses on the restoration of the Archaeological Site in Tyre City, which holds the distinction of being one of the UNESCO World Heritage sites in Lebanon. Over time, the site has faced destruction and neglect during various periods of war, as well as exposure to local climatic conditions and biological growth occurring in the distinct four seasons.

To address the restoration needs, sustainable techniques were employed, including the use of natural stones like sandstone to replace missing or damaged parts of the structure. Additionally, an eco-friendly mortar made from lime and volcanic ash was utilized, reducing the carbon footprint of the restoration process. Advanced technology such as GIS scanning was employed to create 3D models of the site (Baratin & et. al., 2014), along with other methods like 3D X-ray micro-computed tomography (3D-μCT), Fourier transform infrared spectroscopy (FTIR), micro-X-ray fluoroscopy (μ-XRF), X-ray powder diffraction (XRD), and radiocarbon dating (C14) (Badde, et. al., 2020).

An illustrative example of the intervention conducted in 2014-2015 focused on a 69 sq.m area of the mosaic, within the framework of the Baʻalbek and Tyre Archaeological Project (BTAP I), as shown in figure 4 images № 1. The intervention served as an opportunity to train local building technicians and youth in the principles and techniques of mosaic conservation-restoration. It commenced with condition reporting, topographic survey, photo documentation, and digital mapping, followed by foil mapping of gridlines and lacunae, mapping of past repairs, and mortar sampling. The restoration process involved lifting the mosaic in sections, along with the top half of the cement substrates, and then removing the cement to clean the tesserae. The mosaic was then relocated in situ on a new hydraulic lime mortar substrate (Badde & MacKinnon, 2016).

By combining sustainable methods and advanced technology, the restoration of the Archaeological Site in Tyre City aimed to preserve its historical significance and cultural heritage for future generations.

Figure 4. Before (as shown in images №1) and after (as shown in images №2) Restoration of the Archaeological Site in Tyre City on site work (Source: Edited by Author based on Badde & MacKinnon, 2016)

Historic Buildings (commercial, residential, religious, and cultural): The interventions in various historic buildings, including commercial, residential, religious, and cultural structures, often involved a combination of technical and structural methods. Traditional building techniques and locally-sourced materials, such as sandstone, were utilized to ensure the preservation of the buildings' original appearance.

Local artisans (as shown in Figure 5, Image №1*) played a significant role in the intervention process. Their expertise and craftsmanship were employed in the restoration of the Al Mamluk Palace, renovation of the Maronite Church, restoration of the Sunna Mosque and Sharaf Eddine Mosque, and the conservation of AL Bitar House, among other projects. The involvement of these skilled artisans contributed to the authenticity and cultural continuity of the restoration efforts.

By employing local techniques and materials, and engaging the expertise of local artisans, the interventions aimed to safeguard the historical and cultural value of these buildings, preserving their significance for generations to come.

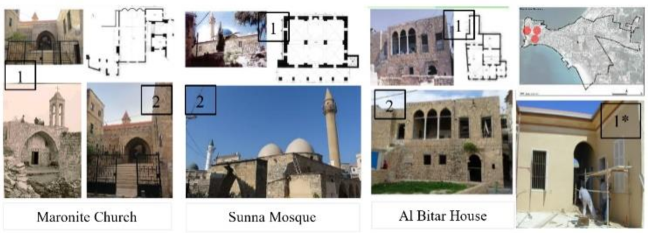

Figure 5. Historic Buildings in the Old City before (as shown in images №1/№1*) and after (as shown in images №2) Intervention.

(Source: Based on khoury study 2002; photos taken by the Author 2022-2023)

Mamlouk Palace: The Mamlouk Palace, constructed in the 13th century and located adjacent to the main archaeological site of the old city of Tyre, underwent extensive restoration. The restoration process involved repairing the damaged walls and roofs, reinforcing the foundations, and carefully preserving the original decorative elements (as seen in Figure 6, Images №1). Simultaneously, modern amenities were integrated into the building while ensuring the preservation of its historical and cultural significance.

One of the major challenges faced by the engineers during the restoration was replacing the damaged wooden beams and columns without compromising the integrity of the original stonework. To address this, they conducted a meticulous approach by cautiously removing the damaged elements and substituting them with new, durable, and sustainable materials. In this regard, the decision was made to remove the entire roof of the second floor and replace it with a roof composed of trusses, eliminating the use of wood (Concrete casting for the new slab). Additionally, the foundations of the building, which had weakened over years of neglect, required extensive reinforcement to ensure the structure's stability and longevity.

Through these carefully planned restoration efforts, the Mamlouk Palace was revitalized, safeguarding its historical and architectural heritage for future generations to appreciate and cherish.

Figure 6. Mamluk Palace Before (as shown in images №1) and After (as shown in images №2) Intervention.

(Source: Based on khoury study 2002, photo taken by the Author 2023)

CHUD Project (The Community Housing and Urban Development): The CHUD project was implemented in different stages and periods, funded through a loan agreement involving the World Bank, the Lebanese Government, the French Development Agency (AFD), and the Italian Cooperation, with support from local authorities (CHUD-PMU & ELARD, 2011). The primary objective of the project was to revitalize the old city by restoring its historic buildings, enhancing its infrastructure, and promoting tourism.

Restoration work was executed in a technical and structural manner, employing traditional techniques and materials to maintain the authentic appearance of the buildings (as depicted in Figure 7, Images №1). To ensure the safety of inhabitants, the restoration team also utilized modern techniques to reinforce the structures. For example, some buildings had their foundations and walls reinforced with steel and concrete to enhance earthquake resistance.

Incorporating innovative technologies, the CHUD project employed Building Information Modeling (BIM) and Geographic Information System (GIS). BIM facilitated the creation of accurate 3D models of the buildings, allowing the restoration team to identify any structural or design flaws before commencing restoration work. On the other hand, GIS was utilized to map the buildings and determine the most suitable sites for the project, considering factors such as accessibility and existing infrastructure (as shown in Figure 7, Images №1*).

Specifically, the project encompassed the restoration of buildings along the Cultural path, Souk Al Sayaghin (old Souk), and Al Bawaba, with collaboration from the General Directorate of Antiquities team. Through these concerted efforts, the CHUD project aimed to rejuvenate the old city, preserving its cultural heritage, and contributing to the community's sustainable development.

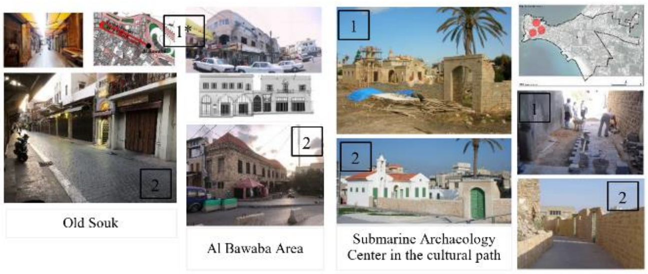

Figure 7. Cultural path, Old Souk and Al Bawaba before (as shown in images №1/№1*) and after (as shown in images №2) Intervention.

(Source: Based on khoury study 2002, photos taken by the Author 2022-2023)

While restoration projects for historic buildings in Tyre city have seen many successes, there have also been instances of failure due to various factors. Poor test techniques, inadequate implementation, and lack of funding are some of the main reasons for restoration failures.

One critical factor contributing to restoration failures is the lack of some test techniques, such as Load testing, Seismic evaluation, and Material testing. In some cases, buildings were not thoroughly tested, leading to incorrect intervention planning and oversights related to the original construction methods and materials. While visual inspections and non-destructive testing methods like ultrasonic testing and x-ray radiography were used in Tyre city, the implementation of more comprehensive techniques like GIS may have been overlooked, contributing to issues in the restoration process.

Inadequate implementation is another key reason for restoration failures, often stemming from a lack of proper training, expertise, or experience among the restoration teams. Although the CHUD project received funding from the European Union and local authorities, financial constraints still hindered the project's success. Insufficient funds allocated to major structural repairs caused delays in restoration work, while ineffective communication with the local community led to misunderstandings and disagreements.

Moreover, some of the techniques used in the CHUD project may not have been appropriate for the specific buildings or conditions in Tyre city. The use of eco-friendly materials that were unsuitable for the local climate and conditions resulted in decay and damage over time.

To ensure the success of future restoration projects, it is essential to address these issues by carefully planning, funding, and executing restoration initiatives with the appropriate expertise, techniques, and resources. Thorough testing, adequate training, community engagement, and the selection of suitable materials and methods are crucial to achieving successful restoration outcomes in preserving the cultural heritage of Tyre city.

5. CONCLUSION

The analysis of heritage building interventions in Tyre City reveals that a significant number of buildings underwent restoration processes, with 50% of them reusing materials. These interventions can be categorized into physical preservation procedures, aimed at improving the structural and architectural quality of the buildings, and adaptive reuse procedures, which enhance both the interior and exterior to accommodate modern use. However, it is observed that most of the buildings have not undergone any interventions to improve energy efficiency and energy-saving retrofits.

To ensure successful restoration projects, it is essential to consider sustainability and its elements in every phase of the process. Social, economic, and environmental aspects of sustainable restoration are interconnected, and the responsible professionals should be aware of these important concepts. Environmental actions and their impact on the structure and integration with nature are crucial indicators of a sustainable project. Moreover, social aspects must prioritize the satisfaction of inhabitants, address structural problems, and ensure the conservation of cultural heritage.

Choosing traditional techniques and materials is essential to respect the historical value and achieve the integrity and authenticity of historic monuments. Whenever possible, the replacement of deteriorated material with the same composition is preferred, and techniques used for vernacular architecture should satisfy safety requirements, making them the most sustainable solution for historic structures.

In the following article, the focus will be on differentiating between intervention actions, outlining the main steps of restoration for historic buildings, and exploring the possibility of improving the sustainability of concrete through the addition of waste plastic fibers. The article aims to promote the conservation of heritage and historic buildings while reducing the environmental impact of construction through sustainable techniques. By incorporating sustainable practices into restoration projects, Tyre City can preserve its cultural heritage and contribute to a more sustainable future.

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Review Article

Bio-Concrete and Beyond: Advancements in Self-Healing Techniques for Durable Infrastructure

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Abstract

Concrete is widely used in construction due to its durability and strength. However, structures made of concrete may weaken over time due to a variety of reasons, such as cracks, chemical attack, and environmental factors. This necessitates the development of new techniques to improve the lifespan and sustainability of concrete structures. Bio-concrete and self-healing techniques have emerged as viable approaches to address the challenges of concrete degradation. This literature review aims to provide a comprehensive overview of the advancements made in bio-concrete and self-healing technologies for concrete. The review begins by discussing the fundamental principles of bio-concrete, which is defined as the incorporation of bacteria or other microorganisms into the concrete matrix. These bacteria are capable of producing calcite precipitation, thereby sealing cracks and enhancing the concrete's self-healing properties. Moreover, the review explores the mechanical and chemical characterization techniques used to assess the performance of bio-concrete as a self-healing concrete. It analyzes the results of various experimental studies and field applications that offer insights into the performance and effectiveness of these technologies under diverse environmental conditions. Overall, this literature review aims to consolidate the current knowledge and advancements in bio-concrete and self-healing technologies. The findings from this review can serve as a valuable resource for researchers, engineers, and practitioners involved in the design, construction, and maintenance of concrete infrastructure. This contribution ultimately promotes the development of more sustainable and durable concrete materials.

Keywords: *Bio-concrete – self-healing – bacterial strains – microorganisms – mechanical properties.*

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Introduction

Cement concrete accounts for 12-15% of global industrial energy consumption (Ahmad et al., 2021) and remains a prominent construction material in civil engineering. Its widespread use is attributed to its affordability, durability, and exceptional compressive strength (Pappupreethi et al., 2017; Zai & Murthy, 2015). However, a significant drawback of concrete is its relatively low tensile strength, rendering it susceptible to cracking. If left unrepaired, these cracks tend to expand over time, potentially culminating in structural failure (Shashank & Praveen Kumar, 2023). Consequently, the presence of airborne carbon dioxide, chloride ions, and water can initiate the corrosion of embedded steel bars. This deterioration weakens the concrete, compromising the structural integrity of buildings and reducing their lifespan. In the United Kingdom, the maintenance and repair of existing structures accounts for approximately 45% of the annual construction costs (Huang & Kaewunruen, 2020). Furthermore, the expense related to repairing and replacing damaged property in the United States is estimated to exceed $14 billion annually, while Australia expends hundreds of millions of dollars (Song et al., 2021).

The concept of self-healing concrete has emerged as a promising approach that can substantially reduce building maintenance costs by enabling cracks to repair themselves. This becomes especially relevant when attempting to inspect cracks in areas with limited access and accurately assess the structural integrity of large-scale buildings (Huang & Kaewunruen, 2020). Self-healing concrete, also referred to as bio-concrete or bacterial concrete, draws inspiration from biological principles and the capability of living organisms to mend cracks in hardened concrete (Udhaya et al., 2023). This type of concrete contains numerous microscopic pores and exhibits significantly distinct deformation characteristics compared to conventional concrete (Wu et al., 2022). Pioneering research conducted by H. M. Jonker focused on employing calcium lactate as a chemical agent to facilitate the self-healing process in concrete. Studies conducted from 2008 to 2011 showcased the efficacy of this approach (Khan et al., 2022).

To begin with, self-healing agents in concrete can be categorized into two main groups: biological agents, such as bacteria, and chemical agents, including calcium lactate. When these agents come into contact with water particles, they undergo reactions to produce calcium carbonate and lime, effectively filling the cracks and reinstating the concrete's structural integrity. It’s important to note, however, that bacterial concrete might encounter challenges in alkaline conditions. Nonetheless, research indicates that bacteria can survive within the porous concrete structure for extended periods, offering sustained self-healing potential (Sonali Sri Durga et al., 2020). Integrating self-healing chemicals into various concrete applications, such as coatings, repair mortars, and during the concrete preparation process, holds the potential to enhance the durability and longevity of concrete structures.

Biological mineral production, referred to as biomineralization, encompasses two distinct methods: biologically controlled mineralization (BCM) and biologically induced mineralization (BIM) (Sisomphon et al., 2012). BCM involves a genetically controlled process in which the organism regulates the nucleation and growth of minerals, resulting in more structured formations. On the other hand, BIM occurs through deliberate reactions involving the organism's activity and its environment, rendering it more adaptable to environmental changes (Sisomphon et al., 2012). These methods hold promise for repair applications, including autogenous healing – the inherent ability of a material or organism to initiate mineralization processes without external intervention – and autonomous healing – where self-repair is facilitated through internal mechanisms or stimuli-responsive properties (Sisomphon et al., 2012). Leveraging these mechanisms can contribute to the advancement of materials with enhanced durability and resilience.

As mentioned, autogenous healing is a process that enables the repair of cracks without external intervention or deliberate actions. This healing involves the formation of calcium carbonate as a result of various reactions, including the carbonation of cement hydrates, hydration of unhydrated cement, and the activation of expansive minerals. In cement, the hydration of unhydrated tricalcium silicate and dicalcium silicate, facilitated by the addition of quicklime, leads to the synthesis of calcium silicate hydrate (C-S-H). The effectiveness of autogenous self-healing can be enhanced by incorporating common expanding materials such as bentonite clay, fly ash, lime, and blast-furnace slag. Notably, even cracks as narrow as 0.18 millimeters can be successfully healed with the presence of trace amounts of magnesium oxide and bentonite (Qureshi et al., 2018).

Conversely, autonomous healing involves encapsulating bacteria and other organic materials throughout the healing process. This approach combines a chemical factor, calcium lactate, with a biological factor, bacteria, to achieve improved and precise healing outcomes. This mechanism, referred to as microbially induced calcite precipitation (MICP), facilitates the desired healing effects (Akadiri et al., 2012). Thus, encapsulation methods can protect microorganisms from challenging concrete environments, such as high pH and limited nutrient supply. (Sarkar et al., 2023). By integrating both chemical and biological factors, autonomous healing presents a promising avenue for effective self-repair in various applications.

Additionally, MICP relies on the microbial urease enzyme, which functions as a catalyst during the hydrolysis of urea, resulting in the generation of ammonia and carbon dioxide. Given that highly alkaline environments foster the growth of various bacteria capable of converting urea into ammonia and carbonate, it can be inferred that this process significantly contributes to the success of MICP. The resulting ammonia and increased pH facilitate the reaction of calcium ions with atmospheric carbon dioxide. This MICP reaction gives rise to insoluble calcium carbonate, which gradually settles and fills the cracks, thereby increasing their closure (Akadiri et al., 2012).

Moreover, the formation of calcite crystals in MICP is governed by several key factors: the presence of sufficient calcium, the concentration of dissolved inorganic carbon (DIC) in the water, pH levels, and the availability of suitable nucleation sites. Notably, there are several prominent bacterial species involved in MICP, including Bacillus sphaericus, Bacillus subtilis, Bacillus cohnii, Bacillus pseudofirmus, Bacillus pasteurii, Bacillus sphaericus, and Escherichia coli (Van Tittelboom et al., 2010). To ensure optimal bacterial growth and mitigate the increased pH levels in concrete, specific additives are incorporated to support and enhance bacterial development.

The self-healing process in bio-concrete relies on the activation of dormant bacterial spores when water infiltrates the compromised structure. Upon activation, these bacteria initiate the germination process, which may span several days. By consuming calcium lactate, the bacteria facilitate their transformation into insoluble limestone precipitates. This precipitation fills voids, calcifies fissures, and effectively seals them, thereby enhancing structural integrity (Depaa & Felix Kala, 2015). Moreover, the consumption of excess oxygen by the bacteria during this process prolongs the lifespan of the steel reinforcement and mitigates further corrosion of the bars, providing an additional advantage to the overall process (Saifee et al., 2015).

The effectiveness of the self-healing mechanism in bio-concrete is based on a straightforward chemical reaction between carbon dioxide and carbon hydroxide present in the concrete mixture. When exposed to water, soluble $Ca(OH)2$ dissolves and leaches out of the cracks into the surrounding environment. The active metabolism of calcium and other nutrients by the bacteria significantly enhances the self-healing process, leading to the re-precipitation of $CaCO3$ on the surfaces of cavities and cracks. This bacterial-mediated re-precipitation contributes to densifying the matrix, further enhancing the self-healing capabilities of bio-concrete (Nisar Akhtar et al., 2023). By employing this process, effective sealing of fractures can be accomplished through the utilization of bacteria-based methods in concrete structures.

This review is designed to offer a comprehensive understanding of the application of bacteria in bio-based concrete. It deliberates on the influence of varying bacteria dosages and types on the mechanical properties and durability of concrete. The ultimate goal of this analysis is to formulate insightful recommendations to guide future research in this evolving field. As such, this review thus serves as a critical stepping stone for advancing the knowledge and implementation of bacterial interventions in bio-based concrete technology.

Growth condition

Firstly, the presence of oxygen can influence bacterial development, with aerobic bacteria thriving in oxygen-rich environments, while anaerobic bacteria can only grow in the absence of oxygen. Facultative bacteria, on the other hand, can adapt to both oxygen-rich and oxygen-poor conditions. In the context of MICP, the performance of three microbial consortia was examined under aerobic (AE), anaerobic (AN), and facultative anaerobic (FA) conditions. The data revealed that AE consortia outperformed AN and FA consortia in terms of converting inorganic carbon (J. Zhang et al., 2017).

As mentioned, the pH level plays a pivotal role in bacterial reproduction rates, where different organisms exhibit varying tolerances to pH fluctuations. In an experiment, bacteria were introduced into a medium, and their growth was monitored while measuring the pH of the water. Monitoring and controlling pH are essential in microbial identification processes, as certain types of microorganisms are sensitive to alkaline conditions (Khaliq & Ehsan, 2016). Understanding and managing pH levels are therefore crucial in establishing favorable conditions for bacterial growth and activity in MICP applications.

Types of bacteria used in bio-concrete

The inclusion of bacteria in concrete demands careful consideration due to the material's high alkalinity. Concrete's pH can reach up to 13 when mixed with water, establishing an inhospitable environment for most organisms that cannot tolerate pH levels exceeding 10 (C. S. S. Durga & Ruben, 2019). Nevertheless, specific bacteria have shown potential benefits when introduced into concrete. Anaerobic bacteria, like certain strains of Shewanella, have been found to enhance concrete's compressive strength by 25% to 30% (Keyvanfar et al., 2015). On the other hand, aerobic bacteria, including Bacillus pasteurii, Bacillus sphaericus, Escherichia coli, Bacillus subtilis, Bacillus cohnii, Bacillus pseudofirmus, and Bacillus halodurans, have been identified as suitable candidates for concrete production, offering various advantages (Chahal et al., 2012). By meticulously selecting and incorporating these bacteria, concrete could potentially exhibit improved properties and performance in specific applications.

Numerous studies, encompassing up to 84% of research, have focused on the genus Bacillus due to several factors, including their presence in soil, their ability to form spores under adverse conditions, their adaptability to the highly alkaline concrete environment with a pH value of up to 13, and their capacity to produce sufficient urease enzyme for inducing calcium carbonate precipitation via urea hydrolysis (Nguyen et al., 2019).

For introducing bacteria into concrete, two distinct approaches are employed. The first, known as the "direct" method, involves adding nutrients and microorganisms directly during the mixing process. In contrast, the second approach, referred to as the "indirect" method, entails immobilizing the bacteria along with the necessary nutrients in other substances, such as light aggregates and graphite nanoplatelets (Nguyen et al., 2019). Ultimately, immobilizing microorganisms has been advocated as a superior way of providing a protective carrier, thereby enhancing bacterial survivability (L. V. Zhang et al., 2021).

Research trend

The utilization of bacteria in concrete has experienced a significant rise from 2015 to 2020, as illustrated in Figure 1. The number of publications on this subject was 13 publications from 2010 to 2015, and further surged to 27 publications from 2015 to 2020. Nevertheless, there was a decline in the number of published articles from 2020 to 2023, totaling 17 articles.

In our literature review, various bacteria were examined, and their percentages are depicted in Figure 2. The prominent bacteria included B. subtilis (24%) and B. sphaericus (23%), followed by B. pasteurii (16%), S. pasteurii (9%), and B. magaterium (5%). These bacteria belong to the Bacillus genus, which is the most frequently studied bacterial group. In fact, Bacillus species can form spores that remain dormant for extended periods, even exceeding 200 years (Khaliq & Ehsan, 2016). Other bacteria, constituting a collective 22%, encompassed B.cohnii, B. flexus, B. licheniformis, B. halodurans, B. alkalinitrilicus, B. aerius, B. licheniformis, Shewanella, and E. coli, each with individual usage ranging from 1% to 2%. It is noteworthy that Shewanella and E. coli belong to different species compared to the Bacillus species.

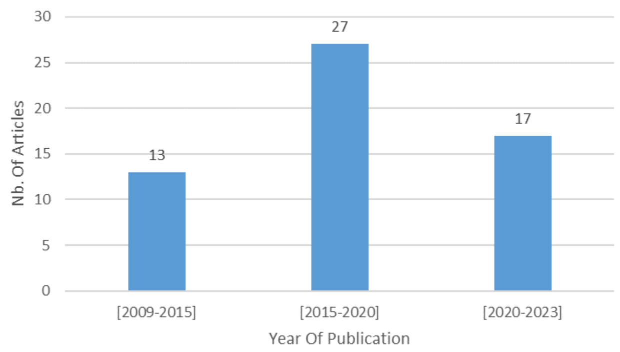

Figure 1. Variation of publications on the use of bacteria in concrete over the years (2009-2023).

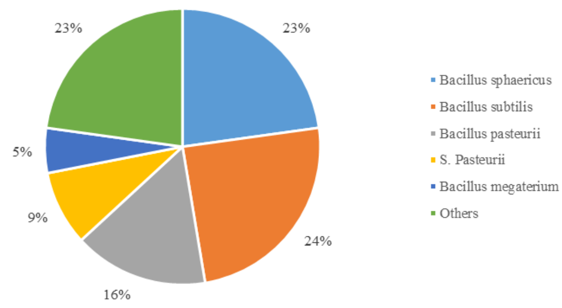

Figure 2. Percentages of different bacteria used in the literature review for concrete applications.

Effect on bacteria type on mechanical properties on bio-concrete

Compressive Strength

The mechanical behavior of concrete containing different type of bacteria is assessed using the enhancement ratio (ER). The ER indicates the extent of increase or decrease in the strength of the concrete when utilizing various type of bacteria. The ER formula is:

$$ER = \frac{\textit{Strength of specimen with a specific bacreria concentration} - \textit{Strength of control specimen}}{\textit{Strength of control specimen}} \times 100 \qquad (1)$$

The observed variations in the increase of compressive strength among different bacterial strains during the 7-day curing period provide valuable insights into their effectiveness in enhancing the mechanical properties of concrete. The results depicted in Figure 3 highlight the significant impact of specific bacterial strains, such as B. Sphaericus, B. Subtilis, B. Pasteurii, S. Pasteurii, and B. Mageterium, on the compressive strength improvement.

B. Sphaericus stands out as the most influential strain, showcasing a remarkable increase in compressive strength ranging from 4.34% to 65.93%. This substantial enhancement positions B. Sphaericus as a promising candidate for concrete applications that require enhanced strength properties (Bashir et al., 2016; C. Durga et al., 2019; Jagadeesha Kumar et al., 2013; Jagannathan et al., 2018; Luhar & Gourav, 2015;

Manjunath et al., 2014; Rex et al., 2018; Sahoo et al., 2016; Sonali Sri Durga et al., 2020; Van Tittelboom et al., 2010; Wang et al., 2014). Similarly, B. Subtilis demonstrates a noteworthy increase in compressive strength, ranging from 2.7% to 24.07%. This strain has been extensively studied and exhibits promising outcomes in various research studies (Bashir et al., 2016; C. Durga et al., 2019; C. S. S. Durga & Ruben, 2019; Iswarya et al., 2020; Khaliq & Ehsan, 2016; Luhar & Gourav, 2015; Manikandan & Padmavathi, 2015; Meera & Subha, 2016; Nosouhian et al., 2016; Pachaivannan et al., 2020; Rex et al., 2018; Safiuddin et al., 2022; Seshagiri Rao et al., 2013; Sonali Sri Durga et al., 2020; Venkata Siva Rama Prasad & Vara Lakshmi, 2020).

The impact of B. Pasteurii on compressive strength enhancement falls within the range of 4.34% to 30%, positioning it as a valuable bacterial strain for concrete self-healing and strength improvement (Bashir et al., 2016; C. S. S. Durga & Ruben, 2019; Ganesh Babu & SiddirajuI, 2016; Jagadeesha Kumar et al., 2013; Luhar & Gourav, 2015; Rex et al., 2018; Siddique & Chahal, 2011; Soundharya & Nirmalkumar, 2014). In contrast, S. Pasteurii exhibits a lower effect on the increase of compressive strength, with a range of 1% to 12%. While the enhancement is relatively modest compared to other strains, S. Pasteurii still contributes to the overall improvement (Bhaskar et al., 2017; Chahal et al., 2012; Hosseini Balam et al., 2017; Kishore et al., 2022; Nosouhian et al., 2016). B. Mageterium demonstrates a range of 3% to 20% in compressive strength increase, indicating its potential for reinforcing concrete structures (Andale et al., 2016; Krishnapriya et al., 2015; Nagarajan et al., 2017).

Figure 4 provides a representation of the increase in compressive strength achieved by B.cohnii (8%-10%), B. halodurans (7%), B. aerius (10.2%), B. flexus (8%), B. Shewanella (35%), and E.coli (52.81%) strains during the 7-day curing period. The range of 7% to 52.81% signifies the diverse effectiveness of these strains in improving the mechanical properties of concrete (Andale et al., 2016; Hosseini Balam et al., 2017; Jonkers et al., 2010; Kishore et al., 2022; Krishnapriya et al., 2015; Nagarajan et al., 2017; Nguyen et al., 2019; Rex et al., 2018; Seshagiri Rao et al., 2013). These findings underscore the significance of bacterial selection in achieving desired levels of strength enhancement and demonstrate the potential for employing microbial technologies in concrete engineering.

In the analysis of Figure 5, which illustrates the variation in compressive strength increase after a 28-day curing period, the focus was on the performance of different bacterial strains. These strains have been extensively studied and analyzed in numerous publications, making them crucial in the field. Among these strains, B.Sphaericus exhibited the highest maximum increase in compressive strength, ranging from 3.8% to 52.42% (Bashir et al., 2016; C. Durga et al., 2019; Jagadeesha Kumar et al., 2013; Jagannathan et al., 2018; Luhar & Gourav, 2015; Manjunath et al., 2014; Rex et al., 2018; Sahoo et al., 2016; Sonali Sri Durga et al., 2020; Van Tittelboom et al., 2010; Wang et al., 2014). This significant enhancement highlights the effectiveness of B. Sphaericus in enhancing the structural integrity of concrete.

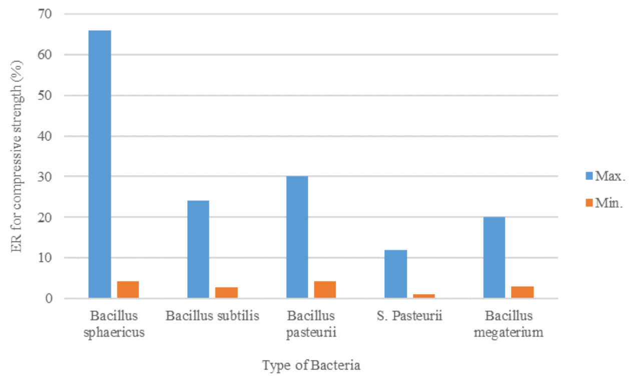

Figure 3. Variation in the compressive strength increase with different bacterial strains during 7-day curing period.

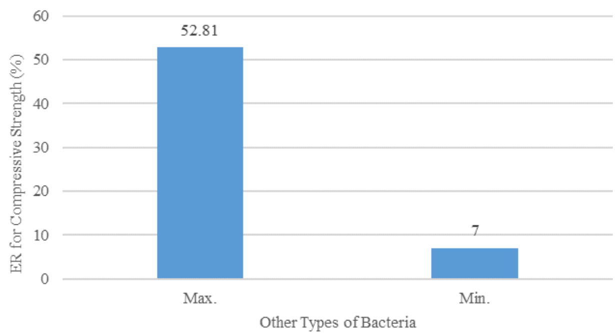

Figure 4. Variation in compressive strength achieved by various bacterial strains during 7-day curing period.

However, it is important to note that the maximum and minimum enhancements for B. Subtilis decreased compared to B. Sphaericus, with an increase ranging from 2.25% to 42.54% (Bashir et al., 2016; C. Durga et al., 2019; C. S. S. Durga & Ruben, 2019; Iswarya et al., 2020; Khaliq & Ehsan, 2016; Luhar & Gourav, 2015; Manikandan & Padmavathi, 2015; Meera & Subha, 2016; Nosouhian et al., 2016; Pachaivannan et al., 2020; Rex et al., 2018; Safiuddin et al., 2022; Seshagiri Rao et al., 2013; Sonali Sri Durga et al., 2020; Venkata Siva Rama Prasad & Vara Lakshmi, 2020). While still demonstrating a positive impact, further investigation may be required to understand the factors influencing the variability of its performance. Similarly, B. Pasteiruu showcased a moderate increase in compressive strength, ranging from 2.63% to 29.97% (Bashir et al., 2016; C. S. S. Durga & Ruben, 2019; Ganesh Babu & SiddirajuI, 2016; Jagadeesha Kumar et al., 2013; Luhar & Gourav, 2015; Rex et al., 2018;

Siddique & Chahal, 2011; Soundharya & Nirmalkumar, 2014). These findings suggest that B. Pasteiruu can contribute to the improvement of concrete properties, albeit to a lesser extent than B. Sphaericus.

On the other hand, S. Pasteurii exhibited the least effect on the increase of compressive strength, with a range of 10% to 22% (Bhaskar et al., 2017; Chahal et al., 2012; Hosseini Balam et al., 2017; Kishore et al., 2022; Nosouhian et al., 2016).While its impact may be comparatively lower, it is worth considering other beneficial aspects that S. Pasteurii might offer, such as its ability to contribute to self-healing mechanisms or other desirable properties in concrete.

Additionally, B. Mageterium demonstrated an increase ranging from 5% to 17.51% (Andale et al., 2016; Krishnapriya et al., 2015; Nagarajan et al., 2017). Although its effect was not as pronounced as B. Sphaericus, B. Mageterium still contributed to the overall improvement of compressive strength in concrete specimens.

Turning our attention to Figure 6, which presents the overall increase in compressive strength achieved by B.cohnii (10%-12%), B. halodurans (18%), B. alkalinitrilicus (7.15%), B. aerius (11.8%), B. flexus (9.72%-10.6%) , B. licheniformis (6.1%), Shewanella (5-40%), and E.coli (62.12%) strains after a 28-day curing period, it is evident that the collective impact of these strains ranged from 6.1% to 62.12% (C. Durga et al., 2019; Ghosh et al., 2009; Jagadeesha Kumar et al., 2013; Krishnapriya et al., 2015; Mohammed et al., 2020; Safiuddin et al., 2022; Siddique et al., 2016; Sierra-Beltran et al., 2014; Sonali Sri Durga et al., 2020).This wide range demonstrates the potential of bacterial interventions in enhancing the mechanical properties of concrete and highlights the need for careful strain selection and optimization.

It is worth mentioning that the reported results may vary depending on factors such as the specific concrete mix design, bacterial concentration, curing conditions, and testing protocols employed in the studies. Further research is necessary to explore these factors and identify the most suitable bacterial strains and conditions for achieving consistent and optimal results in different concrete applications.

Concentration

The concentration of bacteria present within the concrete mix has been observed to significantly influence the enhancement of compressive strength. As depicted in Figure 10, the application of five distinct concentrations demonstrates how compressive strength varies in response to each concentration. The investigation commenced with a concentration of 10^3 cells/ml, which corresponded to an Enhancement Ratio (ER) of 10.3%. As the concentration increased, the ER followed suit, peaking at 42.54% for a concentration of 10^5 cells/ml. However, subsequent escalation of the concentration led to a decrease in ER, reaching 23.38% for 10^7 cells/ml. These observations suggest that the optimal concentration for augmenting compressive strength is 10^5 cells/ml (Chahal et al., 2012; C. Durga et al., 2019; Ghosh et al., 2009; Khaudiyal et al., 2022; Manjunath et al., 2014; Meera & Subha, 2016; Nagarajan et al., 2017; Rex et al., 2018). These findings underscore the importance of appropriately calibrating bacterial concentrations to maximize their efficacy in enhancing the compressive strength of concrete.

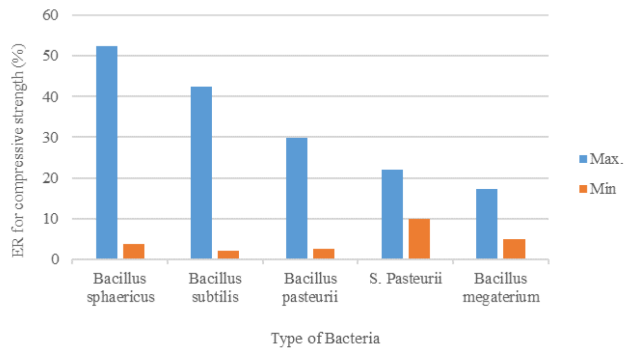

Figure 5. Variation in Compressive Strength Increase with Different Bacterial Strains after 28-Day Curing Period.

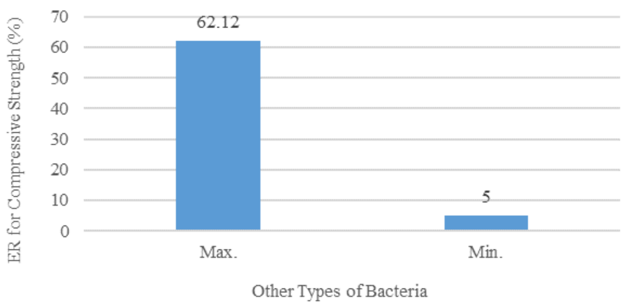

Figure 6. Variation in compressive strength achieved by various bacterial strains during 28-day curing period.

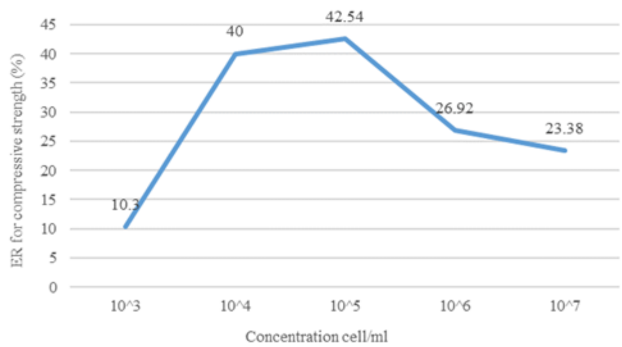

Figure 7. Percentage enhancement of Bacteria concentrations on compressive strength at 28-Days

Split tensile

Observations of variations in the increase of tensile strength among different bacterial strains during a 7-day curing period offer significant insights into their efficacy in augmenting the mechanical properties of concrete. Figure 8 illustrates the profound impact of certain bacterial strains. For instance, B. Sphaericus demonstrated an Enhancement Ratio (ER) ranging from 14.28% to 31.14%, signifying a considerable increase. B. Subtilis exhibited a range from 6.47% to 38.17%, marking it as the bacterial strain with the highest ER effectiveness. Meanwhile, B. Pasteurii showed an average ER of 31.14%, underscoring its vital role in the self-healing process of concrete (Bashir et al., 2016; Jagannathan et al., 2018; Luhar & Gourav, 2015; Meera & Subha, 2016; Nosouhian et al., 2016; Pachaivannan et al., 2020; Rex et al., 2018; Safiuddin et al., 2022; Seshagiri Rao et al., 2013; Sonali Sri Durga et al., 2020).

Further insights into the performance of various bacterial strains are provided in Figure 9, showcasing the variation in the increase of tensile strength after a 28-day curing period. Additional bacterial strains were examined in this figure, illustrating the outcomes at this stage. B. Subtilis recorded the highest increase in tensile strength, with ER ranging from 10% to 63.46%, making it the most promising bacterial strain for enhancing tensile strength. B. Sphaericus followed with an ER range of 2.76% to 28.37%, ranking as the second-highest in terms of ER. B. Megaterium and B. Pasteurii presented average ERs of 15.13% and from 2.76% to 8%, respectively. Conversely, the lowest impact on the increase of tensile strength was attributed to S. Pasteurii, with an ER of 3.44% (Bashir et al., 2016; Jagannathan et al., 2018; Luhar & Gourav, 2015; Meera & Subha, 2016; Nosouhian et al., 2016; Pachaivannan et al., 2020; Rex et al., 2018; Safiuddin et al., 2022; Seshagiri Rao et al., 2013; Sonali Sri Durga et al., 2020). These data indicate the substantial role of bacterial strains in the strength properties of concrete and warrant further research.

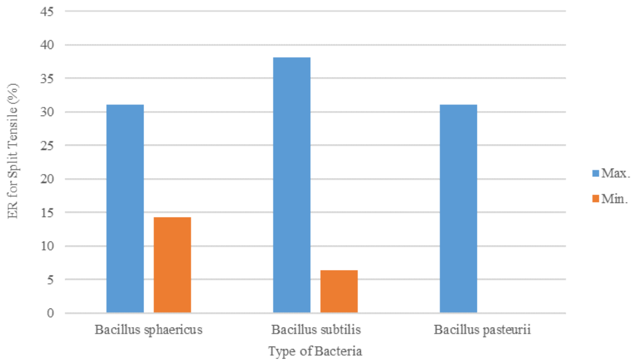

Figure 8. Variation in Split Tensile Increase with Different Bacterial Strains after 7-Day Curing Period.

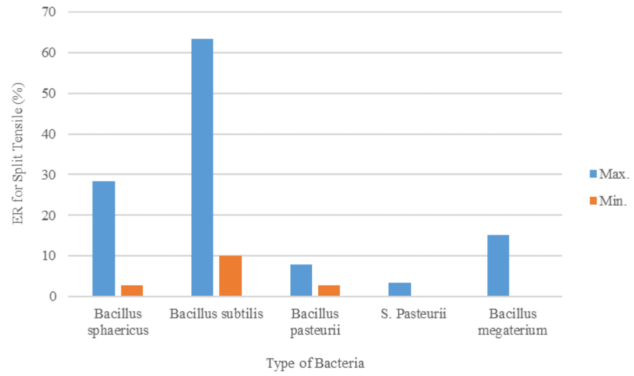

Figure 9. Variation in Split Tensile Increase with Different Bacterial Strains after 28-Day Curing Period.

Flexural strength:

The flexural strength of concrete exhibited a substantial improvement when various bacterial strains were incorporated. This measurable increase is represented in Figure 10, which portrays the Enhancement Ratio (ER) throughout a 7-day curing process. The ER for B. Sphaericus varied between 2.76% and 29.37%, while for B. Subtilis, it fluctuated from 4.3% to 26.51%. B. Pasteurii, on the other hand, demonstrated a steady enhancement, reflecting an ER of 17.34%. This underscores that the integration of different bacterial strains can significantly augment the flexural strength of concrete (Andale et al., 2016; Bashir et al., 2016; C. Durga et al., 2019; Jagannathan et al., 2018; Nosouhian et al., 2016; Pachaivannan et al., 2020; Rex et al., 2018; Safiuddin et al., 2022; Seshagiri Rao et al., 2013; Sonali Sri Durga et al., 2020; Venkata Siva Rama Prasad & Vara Lakshmi, 2020).

Figure 11 further delineates the results after a 28-day curing period. Remarkably, the ER percentages for B. Sphaericus and B. Subtilis escalated compared to their day seven results, reaching 31.14% and 30.56%, respectively. These observations suggest the high potential of these bacterial strains for enhancing the flexural strength of concrete.

Contrarily, the ER for B. Pasteurii witnessed a decrease when compared to its value on the seventh day, with figures ranging from 4.69% to 11.18%. The lowest ER was noted for S. pasteurii, contributing an average enhancement of around 6% (Andale et al., 2016; Bashir et al., 2016; C. Durga et al., 2019; Jagannathan et al., 2018; Nosouhian et al., 2016; Pachaivannan et al., 2020; Rex et al., 2018; Safiuddin et al., 2022; Seshagiri Rao et al., 2013; Sonali Sri Durga et al., 2020; Venkata Siva Rama Prasad & Vara Lakshmi, 2020). These variations emphasize the different impacts of bacterial strains on the flexural strength of concrete over time, marking a valuable area for continued research and analysis.

Water absorption

Several research studies have highlighted the significant role of different bacterial strains in enhancing the durability of concrete through their impact on its water absorption properties. Firstly, the incorporation of S. Pasteurii bacteria was found to alter the fundamental characteristics of concrete, resulting in a notable decrease in water absorption by 26% (Chahal et al., 2012). This reduction directly correlates with an increase in the durability of the concrete. This finding is further echoed in another study where the impact of S. Pasteurii on the water absorption capability of concrete was investigated (Kishore et al., 2022). The mentioned research results indicated a decline in water absorption by 16.93%.

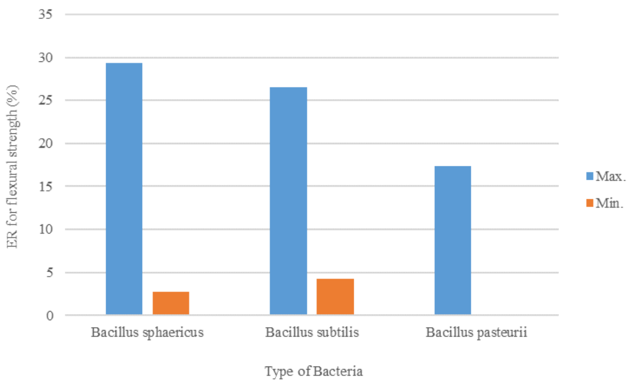

Figure 10. Variation in Flexure Strength Increase with Different Bacterial Strains after 7-Day Curing Period.

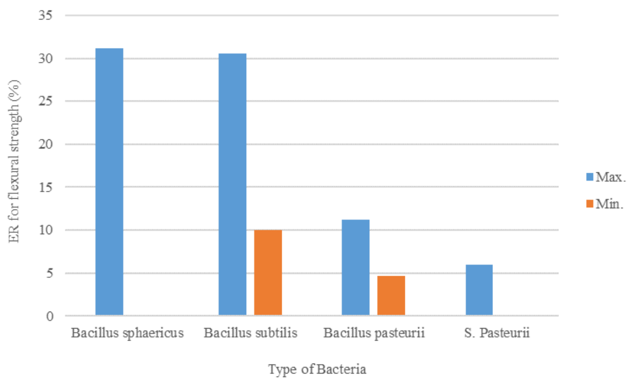

Figure 11. Variation in Flexural Strength Increase with Different Bacterial Strains after 28-Day Curing Period.

Moreover, the effect of integration of B. Substilis into the concrete mixture was studied on two different occasions, demonstrating a substantial decrease in water absorption by 81.75% and 16.93% as reported in individual articles (Meera & Subha, 2016; Sonali Sri Durga et al., 2020). This reduction in water absorption, in turn, played a critical role in enhancing the durability of the concrete. Evidently, these various bacterial strains demonstrate significant potential for improving the durability of concrete by minimizing its water absorption, presenting a promising avenue for further exploration in the field of construction materials.

Acid attack

A comparative study between conventional concrete and bacterial concrete was conducted, revealing a notable difference in weight loss after a 28-day curing period. The research showed a weight loss of 2.10% in concrete samples treated with S. Pasteurii bacteria compared to the conventional concrete (Kishore et al., 2022). In a more comprehensive study, three distinct bacterial strains—B. Pasteurii, B. Subtilis, and B. Sphaericus—were incorporated into the concrete mix, and both weight and strength loss in the concrete samples were observed. The study's findings indicated weight loss figures ranging from 27.42% to 46.34%, while strength loss ranged between 7.31% and 17.47% (Rex et al., 2018).

Sulphate attack

In the same comprehensive research, significant insights into the influence of three specified bacterial strains on concrete durability were provided. The results revealed varying impacts based on the bacterial strain involved. Specifically, B. Pasteurii, B. Subtilis, and B. Sphaericus were found to cause durability losses of 5.84%, 6.65%, and 2.45%, respectively. These findings highlight the nuanced role that each bacterial strain plays in shaping the overall durability of bacterial concrete (Rex et al., 2018).

Alkaline attack

After a comprehensive examination of the effects of alkaline attack on concrete mixed with three different bacterial strains, focusing on the resulting changes in weight and compressive strength, distinct outcomes were observed based on the bacterial strain used. Specifically, when considering weight loss, B. Pasteurii resulted in a reduction of 33%, B. Subtilis accounted for a decrease of 24.24%, and B. Sphaericus led to a weight loss of 17.81%.

Similarly, in terms of compressive strength loss, varying patterns were observed depending on the type of bacteria incorporated. B. Pasteurii, B. Subtilis, and B. Sphaericus contributed to compressive strength losses of 2.31%, 5.47%, and 17.81%, respectively. These findings highlight the diverse impacts that different bacterial strains can have on the resistance of concrete to alkaline attack, ultimately affecting its durability and long-term performance (Rex et al., 2018).

Bacteria and waste materials:

Waste materials such as silica fume, GGBFS, and fly ash are used in bacterial concrete mixtures. These waste materials have an impact on the mechanical properties of bio-concrete.

An article titled "Experimental Investigation of Self-Healing Behavior of Concrete Using Silica Fume and GGBFS as Mineral Admixtures" conducted a study. In this study, cubes were formed by blending cement with various percentages of silica fume as a binder, including 2.5%, 5%, 7.5%, 10%, and 12.5%. Additionally, cubes were created by replacing 35% to 55% of the cement with GGBFS. A standard mixture without admixtures was cast to facilitate comparison of the strength and durability of the concrete with those prepared using silica fume and GGBFS. Compressive strength tests were performed on preloaded concrete specimens after 7 and 28 days, with the Sorptivity index determined after 28 days. Notably, the concrete mix containing 35% GGBFS instead of cement exhibited the highest compressive strength rating. Furthermore, the optimal strength was achieved when a mineral admixture consisting of 12.5% silica fume was added to the combination (Depaa & Felix Kala, 2015).

Another study focused on evaluating the effect of Sporoscarcina pasteurii bacteria on the compressive strength and rapid chloride permeability of concrete, both with and without fly ash. Cement was replaced by fly ash in three percentages: 10%, 20%, and 30%. The concrete mixes contained varying cell concentrations of bacteria (0, 10^3, 10^5, and 10^7 cells/ml). At 28 days, tests were conducted to measure compressive strength, water absorption, and rapid chloride permeability. The presence of S. Pasteurii in fly ash concrete increased compressive strength while decreasing porosity and permeability, as indicated by test results. With a bacteria concentration of 10^5 cells/ml, the compressive strength increased by 22% and water absorption reduced significantly (Chahal et al., 2012).

Another endeavor aimed to comprehend the combined effect of bacteria and fly ash on the performance of M20 grade concrete. While maintaining a constant concentration of Sporosarcina pasteurii bacteria at 10^6 cells/ml, fly ash content was altered by 0%, 10%, 20%, and 30% as a replacement for cement. Cubes and cylinders were cast, and their strength was measured after 7, 28, 56, and 90 days. The results indicated that a mixture of 10^6 cells/ml bacteria and 20% fly ash yielded optimal outcomes in terms of compressive strength, split tensile strength, strength loss, weight loss, and water absorption (Kishore et al., 2022).

Furthermore, an experimental study's results were presented in a paper, assessing the influence of Bacillus sphaericus bacteria on the compressive strength, split tensile strength, flexural strength, shear strength, water absorption, and chloride permeability of concrete made with and without fly ash. Cement was replaced by fly ash in two percentages: 10% and 20%. The concrete mixtures included different cell concentrations of bacteria (0, 10^3, 10^5, and 10^7 cells/ml). Testing was conducted at 28 days. The incorporation of B. sphaericus in fly ash concrete increased compressive strength while reducing water absorption and chloride permeability. With a bacteria concentration of 10^5 cells/ml, the maximum increase in compressive strength reached 15.47%. This study focuses on the impact of bacteria on concrete characteristics, particularly when using supplementary cementing materials such as fly ash. The utilization of bacteria such as B. sphaericus enhances the strength and durability of fly ash concrete through self-healing mechanisms (Manjunath et al., 2014).

Conclusion

In this literature review, the principles of bio-concrete, which involves the incorporation of bacteria or microorganisms to facilitate crack healing, were thoroughly discussed. Additionally, various types of bacteria and their corresponding growth conditions were examined. The review also extensively covered the enhancement on mechanical properties of concrete using different types of bacteria.

In conclusion, it is reasonable to assert that the concept of bio-concrete offers a promising solution to address concrete degradation and maintenance challenges in rehabilitation. The incorporation of bacteria or microorganisms in bio-concrete has compellingly demonstrated the ability to facilitate crack healing.

During the review process, a prominent limitation became evident: there was a scarcity of publications that comprehensively covered the topic of bacterial concrete. Furthermore, when exploring available publications, only a few discussed cases involving the healing of pre-cracked beam or structures using bacteria. Additionally, details about the depth and range of cracks that can be effectively healed by bacteria were lacking in most of the publications. Moreover, information about the various types of cracks that commonly occur in buildings was not disclosed. Additionally, data pertaining to the mechanical properties at the 14 and 21 day marks were insufficiently available. Furthermore, challenges such as the long-term viability and activity of bacteria, as well as the scalability and economic feasibility of large-scale production and implementation, remain unaddressed. In an era where numerous old buildings require repairs or redesigning to combat cracks, this topic emerges as a vital subject warranting further research. Such research has the potential to introduce innovative approaches that contribute to the enhancement of infrastructural integrity.

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Research Article

The Effect of Using Different Cross-Sectional Shapes of Steel on the Flexural Performance of Composite Reinforced Concrete Beams

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Abstract

Various types of structures can be constructed using reinforced concrete, including slabs, walls, beams, columns, foundations, frames, and more. The incorporation of structural steel and reinforcements in concrete enhances the strength and durability of structural elements while compensating for the tensile weaknesses in the concrete material. This study aimed to investigate the behavior of reinforced concrete beams utilizing structural steel of different shapes. Four types of concrete beams were prepared: a standard beam with normal reinforcement, and three composite beams, each featuring structural steel with different sectional shapes – T-section, I-section, and channel section. The consistent parameters included the cross-sectional area of the specimens, each measuring 100x150x450 mm, a steel reinforcement percentage of 2% of the total volume, and the compressive strength of the concrete. The conducted tests involved applying a concentrated load at the mid-span of each beam to examine the specimens' behavior in terms of strength, flexural load capacity, deflection, crack patterns, and failure mode. The results of this study reveal that, given the same steel ratio, the load capacity of beams reinforced with structural steel of a channel shape has surpassed that of the other beams. Additionally, specimens with structural steel plates exhibited higher maximum deflections before failure compared to the beams with conventional reinforcement.

Keywords: *Sustainability, Steel sections, flexural load capacity, failure mode, deflection, compressive strength.*

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Introduction

Reinforced concrete (RC) is widely used in the construction industry due to its high compressive strength and durability (Ramadan et al., 2022; Ramadan et al., 2023). It can be utilized to construct various types of structures, including slabs, walls, beams, columns, foundations, and frames (Elwood & Eberhard, 2009; Priestley et al, 1994; Park & Gamble,1996; Schladitz et al., 2012). Concrete components and sections found common application in buildings, bridges, and other infrastructure projects (Alhakim et al., 2023; Hatoum et al., 2022; Barraj et al., 2022). The use of steel reinforcement in concrete beams is essential for improving their load-carrying capacity and preventing premature failure (Noguchi et al., 2014; Li et al., 2020). This design practice empowered the sustainable development sought in different engineering sectors (Barraj et al., 2022; Hatoum et al., 2022; Elkordi et al., 2022; Mahfouz et al., 2022).

The shape of reinforcement has a significant impact on the behavior of beams under various loading conditions. Encased beams, which comprise a steel beam encased within a concrete shell, have found application as rigid reinforcement in deck bridges for railway reconstruction projects and building with limited heights (Kamal, 2015; Joshi et al., 2016). However, these beams rarely undergo design or structural modifications, despite their extensive history of use. Standard verifications of these structures have unveiled the inefficient utilization of traditional I-beams alone (Hosseinpour et al., 2018; Ranzi et al., 2013).

To address this issue, researchers have undertaken the design and evaluation of RC beams using steel reinforcement with various shapes (Yang et al., 2016; Khare et al., 2016; Soundararajan et al., 2008). For example, Wehbi et al. (2021) investigated the flexural behavior of encased composite beams using steel with T-sections (ST) and steel with pipe (SP) sections. The study demonstrated that the shape of the steel reinforcement impacts the flexural behavior of RC beams, with ST specimens exhibiting more favorable behavior in terms of ultimate capacity and ductility compared to SP specimens. ElBasha et al. (2018) explored the effectiveness of hollow reinforced concrete encased steel tube (CEST) composite beams. The study revealed that the bending strength and flexural stiffness of the hollow CEST section increase with the height of the steel tube, resulting in higher maximum strength compared to conventional solid RC beam specimens. Lathasha and Abraham (2019) conducted an analytical study on the flexural behavior of composite slim floors using different steel sections, including symmetrical I- sections, channel sections, angle sections, and asymmetrical I-sections with equivalent cross-sectional areas. They concluded that the partially encased slim floor with angle sections exhibits higher moment capacity due to the greater strength of its bottom flange. Other investigations have explored various aspects of RC beams. Ali et al. (2012) investigated the structural behavior of concrete-encased composite beams under lateral loading, emphasizing the influence of the steel beam core. Kamal (2015) analyzed the effect of the upper steel section flange position on beam capacity and ductility. P. Fouche' et al. (2017) scrutinized the inelastic behavior of concrete-filled double-skin steel tubes (CFDSTs) as an alternative to RC columns for bridge piers in scenarios involving multiple hazards. The experimental investigation demonstrated that CFDSTs exhibit substantial toughness and ductility, rendering them suitable for satisfactory performance under seismic and blast hazards.

Abbas (2021) scrutinized the flexural strength of composite beams employing non-weldable top-hat steel plate sections as connectors. He observed that beams with a 4mm channel connection exhibited the highest load-carrying capacity and reduced mid-span deflection. Liu et al. (2017) investigated U-shaped steel girders and angle connectors in steel-concrete composite beams, revealing improved flexural performance and cost savings by obviating the necessity for shear stud connectors. Zhong et al. (2017) demonstrated that the installation of a channel steel plate at the head of a notch in concrete beams enhances crack resistance and augments load capacity. The steel plate redirects crack initiation away from the tip, diminishing tensile stress concentration and enhancing the load-carrying capacity. The study emphasized the significance of augmenting the fracture energy of the concrete material and demonstrated a more gradual load-deformation response with the presence of steel plate reinforcement. The size of the steel plate has negligible effects on the load capacity. NANDHINI et al. (2017) discovered that encased beams with channel steel sections as main reinforcement outperform ordinary beams with normal steel reinforcement concerning flexural strength. The flexural strength of encased reinforced beams was higher compared to ordinary reinforced beams. Al-Hadithy et al. (2012) concluded that the use of horizontal transverse-bar shear connectors in reinforced T-beams heightens both the ultimate moment capacity and flexural stiffness of the beam.

Additional techniques, including the incorporation of web openings in steel plates and the use of hybrid fiber-reinforced polymer composite beams, have demonstrated significant enhancements in load capacity, crack resistance, and flexural performance, presenting promising opportunities for the construction industry (Nie et al., 2003; Ferreira et al., 2020; Nordin & Täljsten, 2004). These findings underscored the significance of meticulous design considerations and the adoption of appropriate reinforcement strategies to optimize the structural integrity and performance of composite beams (Grover & Sakshi, 2016). Ongoing research and experimentation in this domain will continue to contribute to the development of effective and cost-efficient solutions for enhancing the strength and durability of composite structures.

Aim and Objectives

The objective of this study was to investigate the distinctions in behavior between a conventional concrete beam reinforced with steel bars and encased composite beams utilizing structural steel with varying shapes. Experimental testing was carried out on a range of beams to achieve the following goals:

- Analyze the behavior of various simply supported composite beams.
- Evaluate the load capacity, ductility, and maximum deflection of simply supported RC beams encasing inverted T-joist, I-joist, and U-joist sourced from a local Lebanese factory.

Experimental program

1. Test Specimens

The test specimens comprised of two duplicated RC beams featuring conventional rebars, serving as the control group. Additionally, there were six other RC beams incorporating structural steel of different shapes. This encompassed two beams with T-section structural steel plates, two beams with channel-section structural steel plates, and two beams with I-section structural steel plates. All the specimens, as outlined **Table 1**, were uniform in dimensions (100x150x450mm) and possessed an identical percentage of steel reinforcement (2% of the concrete's cross-sectional area).

Table 1. Characteristics of the testing specimens.

Sample	BR (Control beam)	BT (inverted T-section)	BU (U-section)	BI (I-section)
Percentage of steel from total area (%)	2%	2%	2%	2%
Width of beam (b) (cm)	10	10	10	10
Depth of beam (d) (cm)	15	15	15	15
Width of top flange of structural steel (cm)	-	-	-	5
Thickness of top flange of structural steel (cm)	-	-	-	0.2
Width of bottom flange of structural steel (cm)	-	5	5	5
Thickness of bottom flange of structural steel (cm)	-	0.2	0.2	0.2
Height of the web of structural steel (cm)	-	10	5	5
Thickness of the web of structural steel (cm)	-	0.2	0.2	0.2
Concrete cover (cm)	2.5	2.5	2.5	2.5

Figures 1, 2, 3 and **4** show the cross-sections of the control beam samples **(C-1 & C-2)**, the inverted T-section samples **(T-1 & T-2)**, the channel-section samples **(U-1 & U-2)** and the I-section samples **(I-1 & I-2)**.

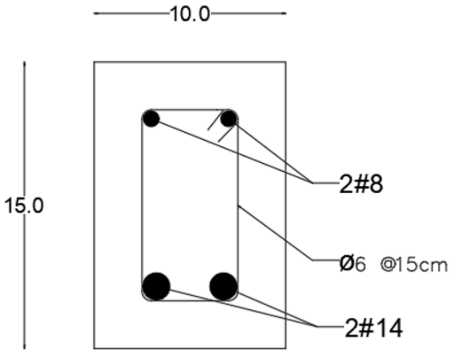


Figure 1. Control Beam (C).

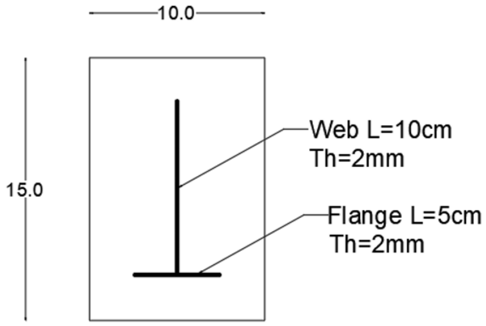


Figure 2. Beam with T-section (T).

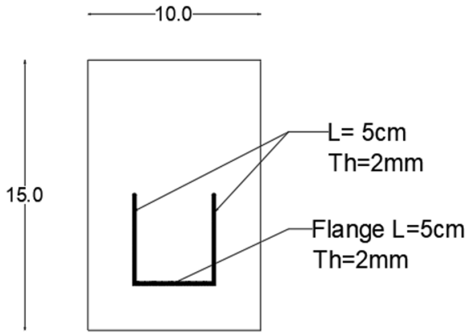


Figure 3. Beam with channel section (U).

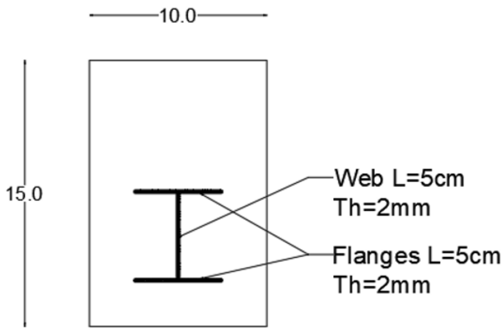


Figure 4. Beam with I-section (I).

2. Materials

The concrete employed for the beams possessed a compressive strength of 23 MPa and was sourced from a local ready-mix plant. The structural steel plates used in the beam samples exhibited a yield strength of 162 MPa and an average modulus of elasticity of 211,000 MPa.

For the concrete compressive strength testing of the cylinders, the MATEST C089-21N concrete compression testing machine was employed (refer to **Figure 5**). This machine boasts a capacity of 2000 KN, high stability, and features motorized operation facilitated by Autotec control unit. Furthermore, the flexural tests on concrete beams were conducted using the flexural device (depicted to **Figure 6**). The machine is equipped with the UTM2 software (Universal Testing Machine 2), specifically developed for the remote control and management of MATEST testing machines from a PC. It is licensed for executing flexure tests on concrete.

Figure 5. Concrete compression testing machine

Figure 6. Flexural device

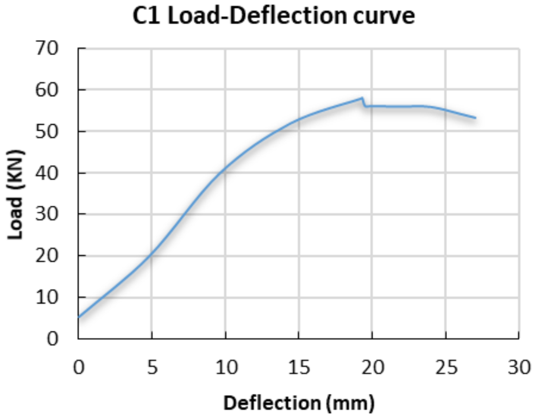
3. Test Setup and Instrumentation

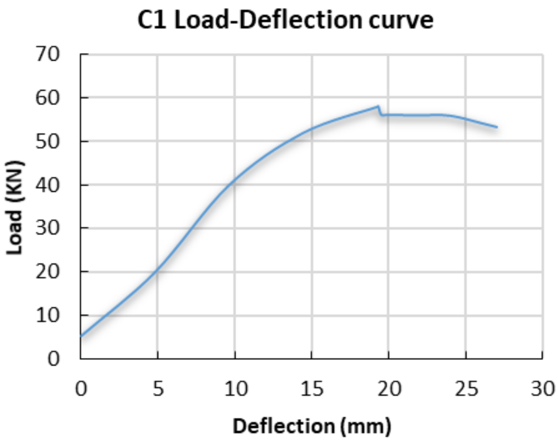
All specimens underwent testing after a curing period of 28 days. Each beam was subjected to a concentrated load applied at its mid-span, as sketched in Figure 7. Subsequently, the load – deflection curve was plotted to track the behavior throughout the elastic, plastic, and damaged phases of the beam. A comprehensive analysis was carried out, comparing the strength, stiffness, load capacity, deflection, and failure mode of the different beams within the study.

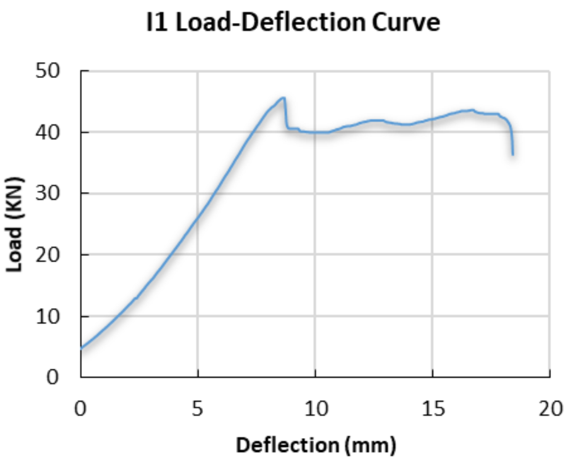
Results and Discussion

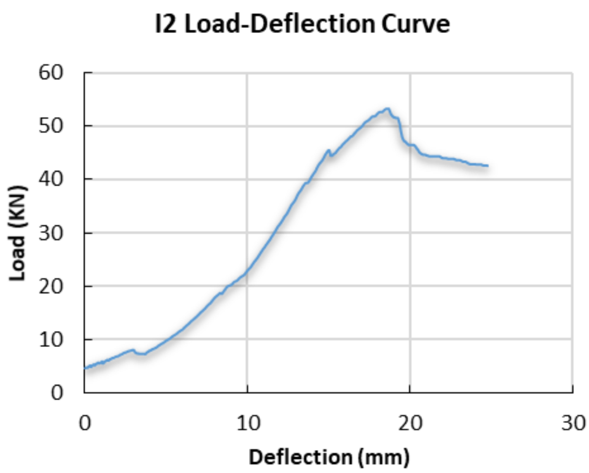
1. Experimental Behavior

The load-deflection curves for the control beams C-1 and C-2, as well as the composite beams T-1, T-2, I-1, I-2, U-1, and U-2 are presented in **Figure 7**.









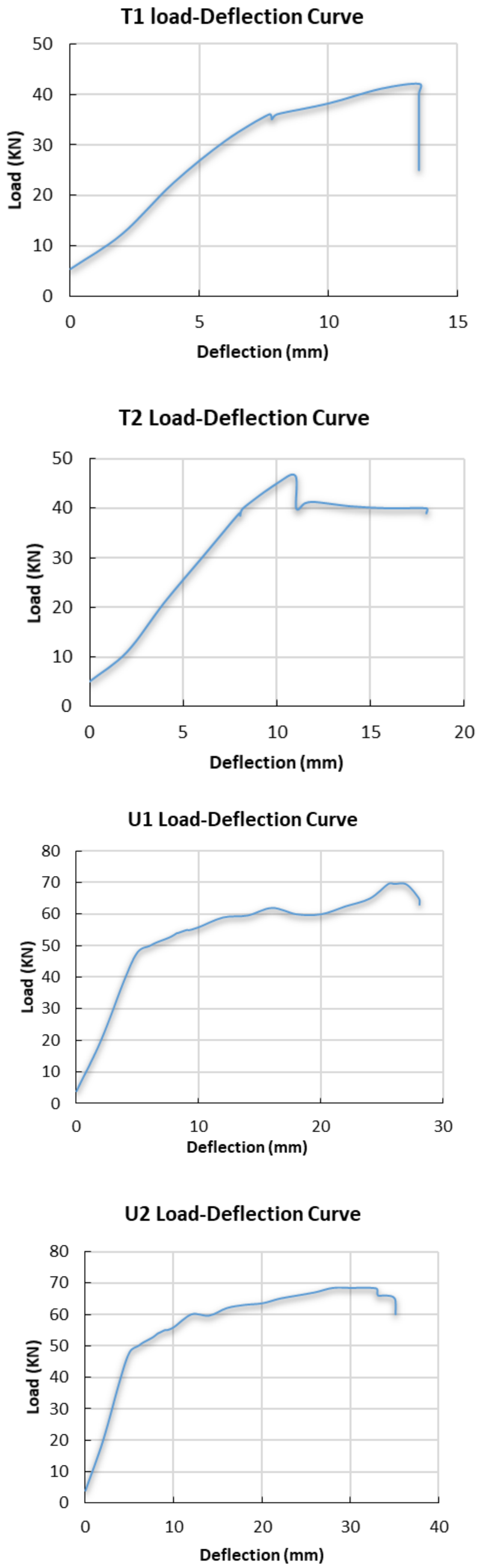


Figure 7. Load-deflection curves for the control and the composite beams.

The experimental results of the composite beams and the control beam tested in this study are provided in **Table 2** and **Table 3**, respectively.

Table 2. Results from testing.

Beam	First Crack at Load (KN)	Yield Load (KN)	Ultimate Load (KN)	Maximum deflection (mm)
C-1	40	44	58.2	26
C-2	44	54	59.2	18
T-1	38	39	42	14
T-2	39	42	46.584	18
I-1	40	43	45.588	19
I-2	42	44	53.178	26
U-1	61.5	64	69.639	29
U-2	61	63.5	68.454	35

Table 3. Average Loads to first crack and yielding.

Beam	Py_{avg} (KN)	Avg. Load at first crack (KN)
C	49	42
T	40.5	38.5
I	43.5	41
U	63.75	61.25

Analyzing the outcomes presented in **Table 3**, a significant observation emerged: among the beams with same steel ratio, the initial appearance of cracks in composite beams that incorporate U-shaped structural steel plates occurred at a load of 61.75 KN, surpassing the other beams, suggesting a superior load-carrying capacity. As the applied load increased towards the yield point (Py), the steel's tensile flange exhibited yielding behavior. The composite beams incorporating U-shaped structural steel plates exhibited the best yielding load of 63.75 KN, a noteworthy 23.13% higher than that of the control beams.

With further load increment, the concrete experienced deformation leading to its ultimate load capacity (Pu). Subsequently, the propagation of flexural cracks persisted until reaching the point of failure.

Figure 8 shows that the average ultimate load capacity of the control beam surpasses that of the composite beams with inverted T sections by 32.5%, and it also surpasses the composite beams with I sections by 18.8%. Nonetheless, the beams incorporating U-shaped steel exhibit a heightened load capacity, outperforming the control beam by 17.6%. These findings align with those of previous studies conducted by Khare et al. (2016) and Nandhini et al. (2017) (khare et al., 2016) and (Nandhini et al., 2017).

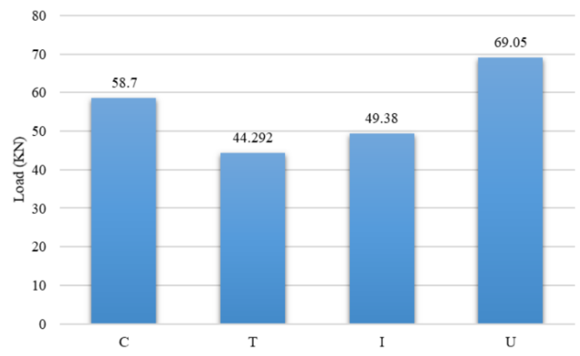


Figure 8. Average Ultimate Load Comparison.

2. Maximum Deflection

Figure 9 illustrates the deflection of both the control beam and the composite beams featuring a steel ratio of 2%. It's apparent that the composite beams incorporating I-section and U-section structural steel shapes exhibit a higher maximum deflection before failure compared to the control beam. This corresponds to an increase of 2.3% and 45.45% respectively. Conversely, the control beam could display higher ductility than the composite beams with inverted T-section structural steel, showing a difference of 37.5%. These observations suggest that the composite beams incorporating U-shaped structural steel might possess superior ductility when compared to all other beams types.

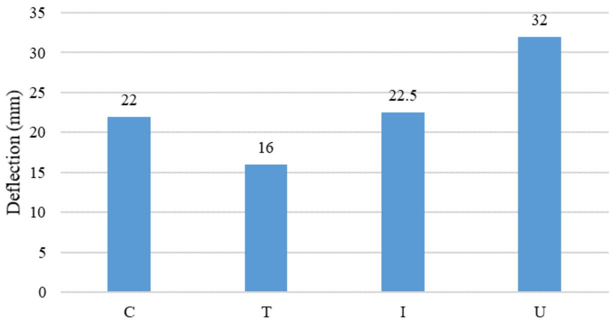


Figure 9. Maximum Deflection Comparison.

3. Crack and Failure Modes

Figures 10 to **12** depict the crack propagation within the samples. These cracks originated from the beam's bottom, specifically within the tension zone, and extended towards the surface corresponding to the compression zone. The majority of cracks were concentrated near the supports area. As the applied load increased, these initial cracks gradually widened until reaching the point of beam failure, resulting in the formation of a plastic zone. Upon failure, the cracks exhibited an angle of 45˚, indicative of a ductile failure mode. However, in the case of the composite beams featuring inverted T-sections, the cracks initiated near the loading point and exhibited a brittle failure pattern, as portrayed in **Figure 13**.

Figure 10. Control beam Cracks

Figure 11. Beam B3 (I-section) Cracks

Figure 12. Beam B4 (U-section) Cracks

Figure 13. Beam B2 (inverted T-section) Cracks.

Conclusions

For the study, four distinct beams were cast, each featuring a unique type of reinforcement. Despite the differences in reinforcement, all beams shared an identical steel volume percentage relative to the concrete. Specifically, two specimens were prepared for each beam type, encompassing ordinary reinforcement, inverted T-section structural steel plates, channel-section structural steel, and I-section structural steel plates. In the laboratory setting, these beams underwent testing with a concentrated load applied at their mid-span. Subsequently, a comprehensive comparative analysis was conducted to evaluate and compare the behavior of the specimens across various parameters, including strength, flexural load capacity, deflection, crack patterns, and failure modes.

The key conclusions drawn from the study are summarized as follows:

1. Composite beams reinforced with channel section structural steel exhibit an average load capacity higher than that of control beams, composite beams with I-section structural steel, and composite beams with inverted T-section structural steel by 17.6%, 39.82%, and 55.9% respectively.

2. Composite beams with channel section reinforcement demonstrate an average maximum deflection higher than that of composite beams with I-section structural steel, composite beams with inverted T-section structural steel, and control beams by 42.22%, 100%, and 45%, respectively.

3. Beams reinforced with structural steel plates (U-section and I-section) display deflection magnitudes surpassing those of beams with ordinary reinforcement, indicating that this form of reinforcement enhances the load-carrying capacity of the beams.

Recommendations

To enhance the results of similar experiments, the following recommendations are proposed:

- Increase the span length of the beams to obtain more accurate results, particularly in terms of deflection and failure mode.

- Ensure that any replacement of steel sections is concentrated in the tension zone to avoid potential inaccuracies, as observed with the inverted-T section.

- When utilizing structural steel sections without web openings, consider the potential for separation of the concrete section. To address this, it's advisable to have openings along the web of the structural steel plates.

- To enhance the composite action between the concrete and steel plates, the use of shear connectors is recommended.

- Given that this study focused on specific structural steel sections (I-beam, inverted T-beam, and channel-beam), further investigations should encompass a broader range of structural steel sections to provide a comprehensive understanding of their performance.

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Review Article

A Review of Enhancing Performance and Sustainability of RC Shear Walls

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Abstract

Reinforced Concrete Shear walls are vertical components within a structure that are specifically engineered to counteract horizontal forces, such as those generated by wind or seismic activity. Their primary purpose is to enhance the stability and resilience of the building by redirecting these lateral forces to the foundation. This redirection effectively minimizes the building's lateral movement during events like earthquakes or strong winds. Nowadays, building owners highly value the ability to ensure maintenance without incurring additional costs even in the face of major earthquakes. To achieve this, it's crucial to reduce damage and maintain the reparability of structural elements. Multiple shear walls often bear heavy gravitational loads and remain susceptible to brittle breakdown due to shearing forces during lateral seismic loading. This susceptibility substantially increases the risk of a complete collapse of the entire shear wall system. The aim of this research paper is to comprehensively study and analyze various research endeavors concerning retrofitting methods employed to enhance the seismic resistance of new or pre-existing reinforced concrete (RC) shear. This analysis will include real-world case studies of examined structures. Moreover, this paper highlights the future potential and provides recommendations for effective retrofitting practices.

Keywords: *Enhance; Reinforced concrete; Retrofit; Seismic; Shear walls.*

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1. Introduction

Buildings constructed using reinforced concrete (RC) before the 1970s, prior to the implementation of contemporary seismic regulations, are categorized as non-ductile structures. These buildings are susceptible to costly and time-consuming repairs. In in severe cases, they might even collapse during significant earthquakes. Reinforced concrete structures with shear wall systems situated in seismically vulnerable regions were often designed using outdated codes that did not account for the necessary ductility requirements. Consequently, these structures exhibit deficiencies in terms of strength and/or ductility, rendering them non-compliant with current seismic safety regulations. Therefore, it becomes essential to undertake retrofitting measures to upgrade these structures and ensure their seismic resilience. Common shortcomings observed in pre-modern seismic code RC shear walls include widely spaced shear reinforcements, insufficient confinement of boundary elements (BE), subpar reinforcement detailing, and flexural reinforcement buckling (Kam et al., 2011; Moehle JP, 2000). These older walls lack ductility and are vulnerable to brittle failure during intense earthquake activity. However, rehabilitating these structures becomes a vital and cannot be ignored to prevent collapses and preserve lives during catastrophic earthquakes.

The implementation of retrofitting techniques to ensure structural stability has been widely employed in historical constructions. Traditional retrofitting methods for RC shear walls has been employed to enhance the seismic performance of reinforced concrete shear walls, mainly focusing on augmenting stiffness and strength through the addition of concrete, steel, or fiber-reinforced polymer composite (FRP) jackets (Kam et al., 2011; Marini & Meda, 2009). While these retrofitting strategies avert structural failure, they still sustain damages that necessitate costly and time-intensive interventions. In recent times, stakeholders have expressed interest in structural solutions that not only preserve lives but also curtail damage and reduce operational disruptions (Calvi et al., 2014). This paper introduces traditional and modern retrofitting techniques of RC shear walls stating their methods as well their importance in enhancing seismic resistance. Actual constructions that have undergone analysis are cited.

2. Importance of Shear Walls

Shear walls are a vital component of the lateral force resisting system in reinforced concrete (RC) structures. They are categorized based on their function, which includes bearing walls, non-bearing walls, shear walls, flexural shear walls, and squat shear walls. Shear walls play an essential role in both the stability and performance of structural systems. These vertical load-bearing components efficiently distribute lateral forces, such as wind and seismic loads, throughout a building. This distribution ensures the overall stability of the structure, prevents excessive sway or deformation, supports vertical loads, resists bending moments, and withstands shear forces parallel to their length. Through strategic incorporation of shear walls within a structure, architects and engineers can optimize space utilization while simultaneously upholding structural integrity.

For instance, the iconic 'Taipei 101' skyscraper, completed in 2004 in Taipei, Taiwan, employs a sophisticated system of shear walls to withstand both seismic and wind loads (D. C. K. Poon et al., 2004). Its tuned mass damper, combined with a network of shear walls, ensures exceptional stability and minimal lateral movement during extreme events such as typhoons or earthquakes. Similarly, the 'Transamerica Pyramid' in San Francisco, built in 1972, relies on its unique triangular shape and an internal core of shear walls to effectively resist lateral forces from seismic activities in a seismically active region (Dunand et al., 2004).

In earthquake-prone regions, shear walls are of paramount importance due to their role in seismic response and lateral force resistance. These walls mitigate the impact of ground shaking by absorbing and dissipating seismic energy, thereby minimizing structural damageand reducing the risk of building collapse. In the 1994 Northridge earthquake, the "Los Angeles City Hall" demonstrated the effectiveness of shear walls in seismic resilience (Youssef et al., 2000). This historic building, constructed in 1928, showcased how its innovative exterior shear wall system helped preserve its structural integrity during the earthquake, highlighting the enduring significance of shear walls in seismic design strategies.

3. Traditional Retrofiring Techniques

3.1. Concrete Replacement.

The most straightforward and cost-effective approach for restoring the strength and ductility of reinforced concrete walls is concrete replacement (Fiorato et al., 1983). This method involves eliminating the damaged concrete to expose the old concrete's aggregate and cleaning the surface to eliminate any loose fragments, thus establishing a solid connection between the old and new concrete. To establish a solid connection with the previous concrete, the upper section may be finished with a high-strength epoxy grout (Vecchio et al., 2002). Once the formwork is removed, the newly poured concrete should undergo proper curing. However, if the shear wall necessitates repair and the building must remain accessible during the procedure, opting for concrete replacement could disrupt the structure's operation, rendering it unsuitable.

3.2. Concrete Jacketing.

Through this method, the initial web of concrete is supplemented with fresh concrete to extend the wall's dimensions. The strength and ductility of the wall might be improved by placing additional reinforcement. Fiorato et al. (1983) investigated two reinforced concrete walls, one of which was repaired using diagonal bars after removing the damaged web concrete in the plastic hinge region. The second wall was repaired through web thickening (jacketing). The testing revealed that while the original wall exhibited stiffness approximately twice that of the rehabilitated walls, their strength and deformation capacity had increased (Fiorato et al., 1983).

3.3. Using Steel Sections.

This method involves affixing steel plates to the wall to enhance its strength, ductility, stiffness, or any of them as depicted in Figure (1).

Elnashai & Pinho (1997) investigated how the application of steel plates into a shear wall rehabilitation strategy could improve a particular attribute (such as strength, ductility, or wall stiffness) without affecting other qualities. Their study concluded that using exterior steel plates connected over the wall's length near the edges could improve the wall's stiffness without reducing its strength. Alternatively, to prevent weakening the wall's strength, as the essential portion would remain intact, plates might be bonded along the anticipated height of the plastic hinge, but there must be a distance among them and the foundation or top slab (Elnashai & Pinho, 1998).

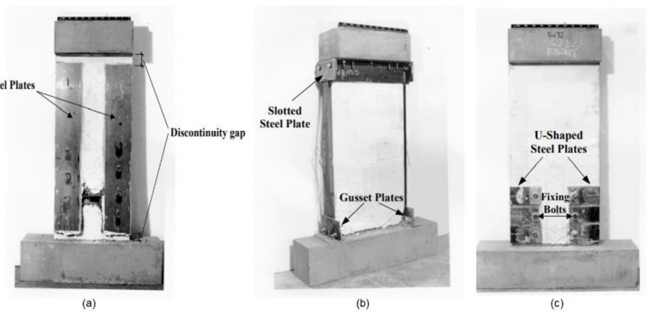

Figure 1. Different rehabilitation schemes studied by (Elnashai & Pinho, 1998)

(a) Stiffness only intervention (b) Strength only intervention (c) Ductility only intervention

3.4. Using Steel Bracings.

For the renovation of frame buildings that are theoretically designed to withstand moments, steel bracings are commonly used. When careful consideration is given to how they engage with the pre-existing structure, these bracings have the necessary rigidity, strength, and ductility required for construction. Shear walls made of reinforced concrete can also perform better during earthquakes when using steel bracings. In such cases, the steel bracing can be regularly attached to the reinforced concrete wall, effectively reducing the buckling length. Instead of retrofitting moment-resistant frames, which is largely restricted by the buckling of the compressed bracing member, this method enhances the bracing member's capacity. (Taghdi et al., 2000a, 2000b) tested a retrofitted RC wall. The modified wall's behavior at 1.0% drift is shown in Figure (2). Test results revealed that the repaired wall could withstand lateral loads up to 2.8 times its original capacity and dissipate up to 4 times as much energy. These findings demonstrate the effectiveness of this technology for retrofitting RC walls.

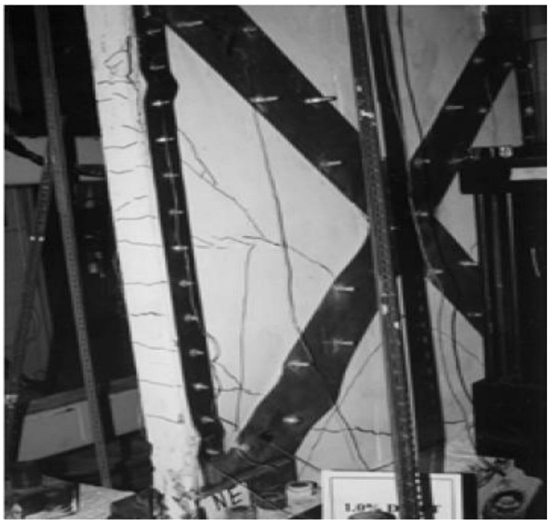

Figure 2. Retrofitted RC Shear Wall Using Steel Bracing At 1% Drift (Taghdi et al., 2000b)

3.5. Through-Thickness Rods

Steel rods, which might be fastened throughout the entire thickness of the wall, were employed by (Mosalam et al., 2003) to secure the wall. The concrete can have the rods either bonded or unbonded (Figure 3). The researchers concluded that implementing this strategy enhances the wall's performance and helps prevent collapse in certain sections of the wall.

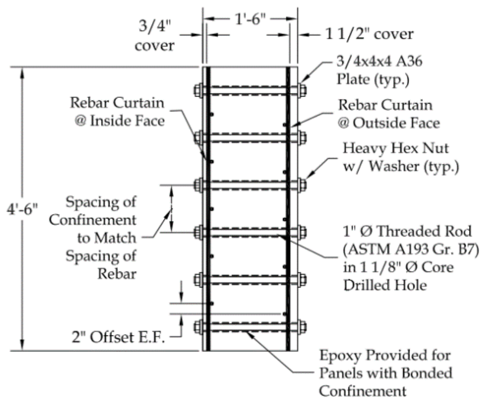

Figure 3. The RC Wall Strengthened Using Through-Thickness Rods (Mosalam et al., 2003)

4. Modern Retrofitting Approaches

4.1. Retrofit Using Wall End Plate.

To enhance the flexural behaviour, a vertical retrofit was executed at each end of the wall, focusing on the slender wall. Steel plate, epoxy, and non-shrink grout were utilized as retrofit resources, and they were affixed to the pre-existing shear wall using post-installed chemical anchors.

The research's predecessor, (Kim et al., 2021) developed a retrofit approach (Figure 4) by digging boundary elements on the existing reinforced shear wall and utilizing reinforcement and concrete to build them. The amount of reinforcement was determined using the ultimate strength design approach to raise the flexural strength to the necessary level. The ends of the shear wall were also detached to the required length for reinforcement configuration. Furthermore, the transverse rebar of the current shear wall, which has been set aside about 100 mm or more, links the previously existing shear wall and the recently built boundary elements when the cut phase of the shear wall ends. This retrofitting method was named "excavating retrofit method" as a result.

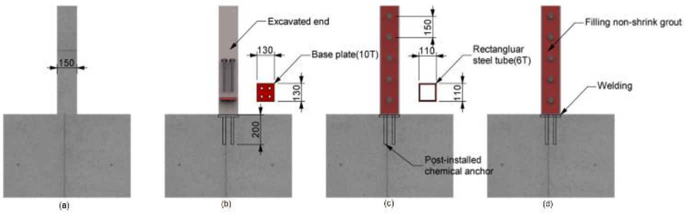

Figure 4. Elevations of Flexural Reinforcement Using Steel.

(a) Existing Wall; (b) Installation of Base Plate; (c) Installation of Vertical Retrofit Material; (d) Welding and Filling Grout, (Kim et al., 2021)

The retrofit material utilized in the flexural retrofit technique includes steel plates and rectangular welded steel tubes created by welding steel plates (Figure 5).

The primary distinction between both is that steel plate is connected to the wall much like the externally bonded retrofit (EBR), except that it does so in the direction of the thickness instead of along the length of the wall. After chipping the concrete cover thickness, the steel plate is affixed to keep the wall's length constant. Furthermore, because the rectangular steel tube functions as both a formwork and a transverse rebar, the steel tube supplying the non-shrink grout within can function well under compression and tensile forces.

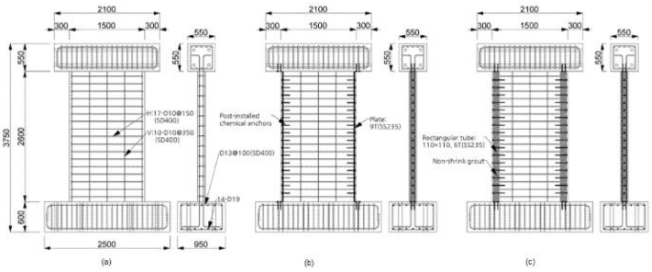

Figure 5. Elevations of The Specimen. (Kim et al., 2021)

(A) Solid (B) Plate (C) Tube

4.1.1.Connection Methods

Using a post-installed chemical anchor, the retrofit material was connected to the living building.

4.1.2.Result - Crack Pattern

Similar to the solid specimen, the plate specimen exhibited a standard flexural failure configuration.

When contrasted to the solid specimen, the bottom portion showed indications of tearing or fracturing. On the other hand, the tube specimen demonstrated an unusual fracture configuration. Although there were fractures between the steel tube and the pre-existing wall during the lateral loading, there were none until the ultimate load was achieved in the pre-existing wall's structure, unlike in the solid specimen. Vertical and horizontal cracks developed in the bottom part after achieving the ultimate load, but these cracks did not propagate. (Figure 6)

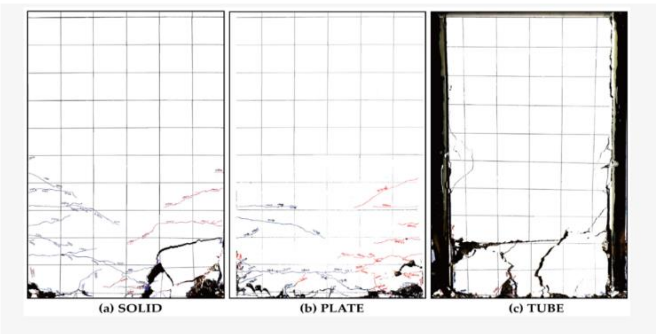

Figure 6. CRACK Pattern of Specimens after Experiment. (Kim et al., 2021)

In contrast to the steel tube, which could effectively resist significant compressive forces, the steel plate was quite breakable after buckling when subjected to compressive forces at the end of the wall. Furthermore, the internal non-shrink grout exhibited larger compressive performance due to the effects of confinement.

These are the findings derived from the current research:

- The use of steel for flexural retrofitting increases the flexural strength of shear walls by 16–29%. Additionally, the displacement ductility ratio of the shear wall may additionally be boosted by 200–400%.

- If a post-installed chemical anchor, it may result in wider fractures or more serious harm. In such cases, either the connection technique with the retrofit material should be considered or the transverse rebars of the old wall should be kept as much as achievable.

- The collapse of the anchor's bond and the removal of the old wall's transverse rebar are believed to have prompted the refitting of the wall with steel tubes. Vertical fractures developed along the anchor line linking the steel tube to the present wall on the side of the wall as opposed to the horizontal flexural fracture on the outer layer of the present wall due to the anchor bond breakdown linked to the foundation.

- Employing welding between the steel and the transverse rebars could serve to link the retrofit to the present wall. The use of high-strength steel or high-performance chemical anchors might also enhance the connection between the steel and the slab or foundation.

4.2. Controlled Rocking with Unbonded Post-Tensioning as A Self- Centering Mechanism

Varying types of rocking have been a subject of research for several investigators, including single rocking walls (Kurama et al., 1999; Perez et al., 2004; Sharma & Aaleti, 2019) and jointed rocking walls (Aaleti & Sritharan, 2009; Zhao & Sritharan, 2007). For energy loss and damping, mild steel energy uptakers such as low yield strength tapered longitudinal reinforcement or dogbone-shaped mild reinforcing bars have been employed to link the wall with the base (Holden et al., 2003; Rahman & Restrepo-Posada, 2000; Restrepo & Rahman, 2007; Smith & Kurama, 2014), O-shaped linkages within wall panels have been used (Henry, 2011; Twigden & Henry, 2015).

To accommodate increased displacement requirements and ensure minimal damage, external confining devices, damping mechanisms, improved cementitious materials, or jacketing can be applied (Basereh et al., 2020; Kam et al., 2010; Kam & Pampanin, 2008; Pampanin et al., 2006; Yang & Okumus, 2017). Ireland et al. (2007) employed external energy dissipaters to assess the strength and residual drift of retrofitted walls after debilitating reinforced concrete shear walls utilizing vertical and/or horizontal straight base cuts (Ireland et al., 2007).

A comprehensive investigation was conducted to assess the influence of various cut shapes on the overall behaviour of retrofitted walls (Basereh et al., 2020). The study focused on understanding how varying cut shapes affect critical factors such as energy dissipation capacity, lateral strength, residual displacement, secant stiffness, and the distribution of principal strains in both pre- and post-retrofit walls. Furthermore, the study presented a detailed analysis of the deformation patterns exhibited by the original and retrofitted walls, providing valuable insights into potential changes in the mode of failure. A cross-section of the base wall is shown in Figure (7).

The research examined the option of retrofitting self-centring to a cast-in-place reinforced concrete wall with a non-ductile cantilever. Several retrofitting walls that had different base cut shapes, including shear-key type trapezoidal, semi-circular, and triangular, were considered to lessen shear slipping at the base (Figure 8). As a result, it was concluded that utilizing self-centring and specific weakening as a retrofit approach could reduce lateral stability, secant stiffness, and residual displacement.

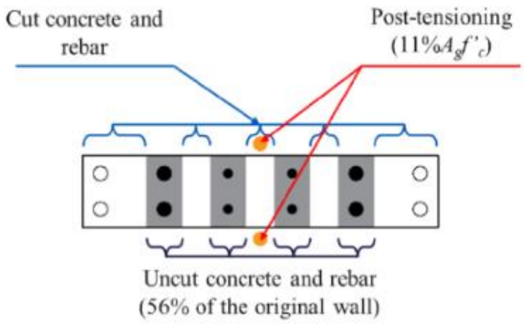

Figure 7. Wall Base Cross Section, (Basereh et al., 2020)

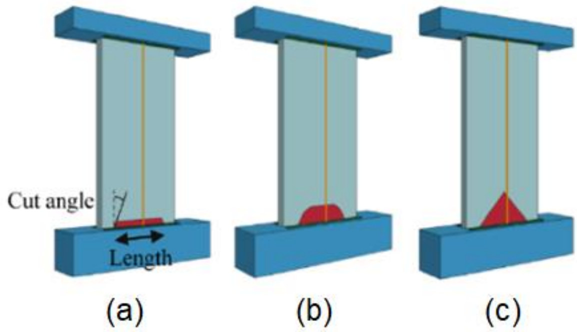

Figure 8. Retrofitted Wall Base Cuts Shapes:
(a) Shear-Key Trapezoidal, (b) Semi-Circular,
(c) Triangular, (Basereh et al., 2020).

Here are the findings drawn from the current research:

- The flexure-shear reaction of a non-ductile cast-in-place reinforced concrete shear wall was changed into a vital action that involves reducing harm to the wall, regulating rocking displacements, and managing residual displacement.

- For the post-retrofit wall with a semi-circular base cut shape contrasted to the pre-retrofit wall, shear's contribution to the overall deformation dropped upwards of 76%.

- Compared to other base cut forms, the trapezoidal (Shear-key type) wall base cut shape more effectively managed sliding shear.

- In comparison to other cut forms, the circular shape wall base cut shape exhibited the least impact from shear and consequently demonstrated the lowest tensile breaking and compressive crushing.

- The configuration of the wall's base cut has no impact on lateral strength.

5. Materials and Technologies

5.1. FRP Laminates

Employing CFRP wraps and through-thickness heading reinforcement, Paterson and Mitchell (2003) retrofitted a reinforced shear wall. The retrofit strategy aimed at enhancing wall confinement and shear strength. Besides being capable of dissipating three times more energy than the original wall, the modified wall achieved displacement ductility levels that were 57% higher than those of the control wall (Paterson & Mitchell, 2003). Khalil and Ghobarah (2005) examined two RC walls renovated using FRP. The renovate sought to improve the walls' shear capacity and ductility. By placing uni-directional horizontal U-wraps around the end columns, and two layers of bi-directional diagonal fibers around the wall, the first block was repaired. As seen in Figure 9(a), FRP anchors were employed to fasten the horizontal U-wraps. The second wall was repaired employing the same technique; however, as shown in Figure 9(b), the U-wraps were fastened employing nine bolts on each side along the column height. Furthermore, four steel through-thickness bolts were placed at the upper and lower areas of the diagonal FRP sheets. The findings revealed that the lateral load capacities of the first and second walls had improved by roughly 40 and 57% respectively. In contrast to the control wall's displacement ductility of less than one, the two restored walls achieved displacement ductility values of 3 and 4 at their maximum strength. The research also concluded that the employing of steel anchors nearly fully utilizes the material, leading to a significant improvement in wall performance compared to FRP (Khalil & Ghobarah, 2005).

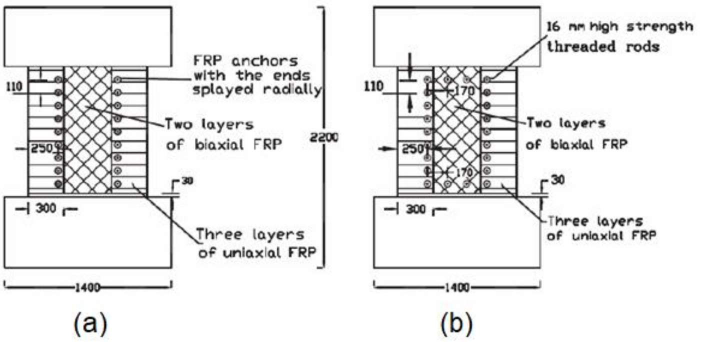

Figure 9: The two restoration strategies examined in the study conducted by (Khalil & Ghobarah, 2005) (a) Wall 1, (b) Wall 2

5.2. Engineered Cementitious Composites (ECC)

In the field of retrofitting reinforced concrete (RC) shear walls, technological advancements have introduced innovative materials such as Engineered Cementitious Composites (ECC), announcing a new era of structural enhancement. ECC, characterized by its exceptional ductility, durability, and self-healing properties, has demonstrated remarkable potential through rigorous experimental studies. Research conducted at institutions like the University of Michigan and the University of California, Berkeley, has delved into ECC's application in retrofitting shear walls. These studies have unveiled how ECC overlays effectively enhance shear wall performance by improving ductility, controlling cracking, and increasing energy dissipation capacity — all crucial factors for seismic resilience. Complementing this material innovation, advanced technologies have facilitated a deeper understanding of the impact of ECC retrofitting. An experimental investigation was conducted at Tongji University in China to study the repair of a damaged reinforced concrete (RC) shear wall using ECC (Y.-M. Zhang et al., 2015). The shear wall initially underwent a pseudo-static test, resulting in severe damage in shear mode, including concrete crushing, steel bar yielding, and fracture. Subsequently, the shear wall was repaired using ECC and subjected to retesting. A comparison was drawn between the responses of the RC shear wall in the two pseudo-static tests to evaluate several aspects, including the effectiveness of ECC-based repair for damaged RC shear walls in terms of failure mode, load-bearing capacity, displacement ductility, energy dissipation, stiffness degradation, and steel bar utilization. The outcomes of the tests revealed that:

a. The load-bearing capacity of the shear wall was reinstated.

b. The shear wall's ductility improved while ensuring load-bearing capacity, causing a shift from a brittle to a ductile failure mode.

c. An enhancement in energy dissipation capacity was observed.

d. The combination of ECC and a steel bar prevented concrete crushing and steel bar buckling, resulting in improved steel bar utilization.

5.3. Shape Memory Alloys (SMA)

A series of reverse cyclic loading experiments were conducted on four distinct specimens. The specimens comprised a conventional steel-reinforced concrete shear wall (SW-R-C), a shear wall reinforced with both steel and Engineered Cementitious Composites (SW-R-ECC), a concrete wall strengthened with Shape Memory Alloys (SMA) (SW-SMA-C), and a wall fortified with ECC and Shape Memory Alloys (SW-SMA-ECC). The test results yielded significant insights. Notably, the SW-SMA-C specimen displayed an impressive self-centering capability, exceeding 85%, even after undergoing substantial deformation—an achievement notably superior to the SW-R-C equivalent. Furthermore, the SW-SMA-ECC specimen exhibited enhanced durability, reduced damage, improved ductility, and minimized residual displacement. These findings collectively underscore the heightened effectiveness of coupling SMA with ECC in enhancing the seismic resilience of shear walls, offering a promising avenue for advancing seismic performance enhancement strategies (Kang et al., 2021).

6. Sustainability Considerations

6.1. Environmentally Friendly Materials and Practices

Environmentally friendly materials and practices in retrofitting reinforced concrete (RC) shear walls are crucial for reducing the environmental impact of construction and improving the sustainability of existing structures. Shear walls play a significant role in providing structural stability to buildings during seismic events but retrofitting them can often involve resource-intensive processes. Here are some environmentally friendly approaches to consider:

1- Material Selection: Choose sustainable and recycled materials, such as reclaimed timber, recycled steel, and recycled concrete aggregates. These materials have a lower carbon footprint compared to virgin materials and help divert waste from landfills.

2- Low-Impact Construction Techniques: Utilize construction techniques that minimize disruption to the surrounding environment. Prefabrication and modular construction can reduce on-site waste and noise, as well as decrease the overall construction time.

3- Energy-Efficiency Upgrades: Incorporate energy-efficient measures during retrofitting, such as adding insulation to improve thermal performance, using reflective coatings to reduce heat absorption, and installing energy-efficient windows to enhance natural lighting and reduce the need for artificial lighting and heating.

4- Seismic Resilience: Design retrofit strategies that not only enhance shear wall performance during seismic events but also consider the overall lifecycle impact. This includes optimizing the retrofit design to ensure that the added materials and changes contribute positively to the building's long-term sustainability.

5- Recycling and Waste Management: Implement a comprehensive waste management plan that focuses on recycling and responsibly disposing of construction waste. This can reduce the environmental impact associated with retrofitting activities.

6- Carbon Footprint Assessment: Conduct a life cycle assessment to evaluate the carbon footprint of different retrofitting options. This assessment can help identify the retrofit strategies that have the least environmental impact over the entire lifecycle of the structure.

7- Local Sourcing: Whenever possible, source materials locally to decrease transportation-related emissions. Local materials can also bolster the local economy and diminish the necessity for long-distance transportation.

8- Green Technologies: Integrate green technologies, such as renewable energy systems (solar panels, wind turbines), and rainwater harvesting to enhance the building's overall sustainability while decreasing its dependence on conventional energy sources.

9- Longevity and Durability: Give priority to retrofit strategies that enhance the durability of the shear walls, thus reducing the necessity for frequent repairs or replacements.

10- Educational awareness: Promote awareness and education among stakeholders regarding the advantages of environmentally friendly retrofitting practices. Encouraging informed decision-making can result in more sustainable choices throughout the construction and retrofitting processes.

Incorporating these environmentally friendly materials and practices into the retrofitting of RC shear walls can contribute to the overall sustainability of the built environment and help mitigate the environmental impact of construction activities.

6.2. Life Cycle Assessment in Retrofitting Projects

6.2.1. Retrofitting Older RC Buildings for Seismic Safety:

Buildings constructed using reinforced concrete (RC) before the 1970s continue to be in use worldwide, spanning both developed and developing nations. However, these buildings can be risky during earthquakes due to inadequate earthquake-resistant design. Prior to 1976, there weren't strong rules for making buildings safe during earthquakes. This is a significant concern as earthquakes can result in poor performance and subsequent damages in these older buildings. Numerous seismic events over time have demonstrated the vulnerability of such buildings, causing considerable damage and losses. Efforts are now being directed towards finding solutions to enhance the earthquake resilience of these aging buildings. For instance, in the USA, the Federal Emergency Management Agency (FEMA) initiated a program in the 1980s to make these buildings stronger against earthquakes (Clark-Ginsberg et al., 2021).

Enhancing the seismic safety of old RC buildings involves the utilization of new materials like concrete, steel bars, and bricks. This process also requires multiple construction stages, such as pouring concrete and transporting materials to the building site. The construction industry has a significant global environmental impact, causing problems like resource depletion, waste generation, high energy consumption, and CO2 emissions (Khasreen et al., 2009; Menna et al., 2013; Zabalza Bribián et al., 2011) Considering the considerable number of aging buildings requiring seismic improvements, these activities can potentially have detrimental effects on the environment, contributing to the already substantial environmental footprint in both the US and worldwide. As a result, it is imperative to assess the environmental implications of various methods for retrofitting RC structures.

6.2.2. Environmental Impact of Retrofitting:

To enhance the earthquake resilience of these aging buildings, we need to use novel materials and construction methods. However, implementing these changes has an environmental impact. The construction industry globally uses a lot of resources, generates waste, consumes energy, and contributes to pollution. Considering the large number of buildings that need modifications to withstand seismic events, it becomes evident that these alterations can harm the environment. This concern is particularly pronounced in the US and worldwide. Thus, comprehending and quantifying the environmental impact across different approaches to retrofitting RC buildings becomes essential.

6.2.3. Using Life Cycle Assessment (LCA) to Understand Impact:

The approach of Life Cycle Assessment (LCA) is employed to measure the environmental effects of different retrofit options like RC column jacketing, beam weakening, and adding RC shear walls throughout their entire life cycle. This method follows the guidance provided by ISO 14,040 (Pryshlakivsky & Searcy, 2013) and ISO 14,044 (Finkbeiner et al., 2006), and it involves four main phases:

1. Defining the purpose and scope.
2. Collecting data on the life cycle stages.
3. Analyzing the impacts across the life cycle.
4. Interpreting the outcomes.

Life cycle assessment (LCA) serves as a tool to figure out how these changes impact the environment. It's like looking at the whole journey of a product or process, from start to finish. While LCA has been employed to study many things related to buildings, the majority of studies have concentrated on new buildings. Some looked at costs over a building's lifespan, but not many looked at the environmental impact. Its's used to study how different ways of retrofitting RC buildings affect the environment from start to finish, including what happens when these changes are no longer useful. LCA compares the environmental impacts of many retrofit methods – adding strength to columns, weakening beams, and adding shear walls. It also looks at how recycling the waste from these changes can be better for the environment than just throwing it away. The goal is to help people decide on the best way to retrofit buildings while considering the environment.

6.3. Waste Reduction in Retrofitting Projects

From a technical perspective, researchers have explored various methodologies like GPS and GIS technologies for waste prevention and site material layout assessment (H. Li et al., 2005; Su et al., 2012) , waste technologies in design and construction (X. Zhang et al., 2012), and web-based applications for waste estimation and management optimization (Banias et al., 2011; Y. Li & Zhang, 2013).

In terms of management, previous studies have looked into project stages that influence waste prevention and management, including design specification quality (Vrijhoef & Koskela, 2000), construction planning (C. S. Poon, Yu, & Jaillon, 2004; C. S. Poon, Yu, Wong, et al., 2004), labor management (Saunders & Wynn, 2004), and material handling (Kpamma & Adjei-Kumi, 2011).

Models and simulations have been employed to enhance the comprehension of understand waste management within project processes. Instances of this include Building Information Modeling systems for waste planning and reduction (Sacks et al., 2010) , waste management mapping models (Lu et al., 2006; L. Y. Shen et al., 2004), and waste quantification models considering project works (Solís-Guzmán et al., 2009). These techniques also assess waste management strategies' effects on reduction, economics, social performance, and environmental impact.

7. Performance Metrics and Evaluation

Measuring and evaluating the performance of retrofitted shear walls involves assessing their efficacy in enhancing the structural integrity and seismic resistance of a building. Here are some common methods and techniques employed for this purpose:

7.1. Experimental Testing:

- Shake Table Tests: This test involves subjecting physical models of retrofitted shear walls to simulated earthquake motions on a shake table. This enables the observation of their behavior under realistic seismic conditions (Martinelli & Filippou, 2009; Priestley et al., 1978; Wight et al., 2007).

- Cyclic Load Tests: This approach employs full-scale or scaled-down specimens of retrofitted shear walls subjected to cyclic lateral loading. This simulation of seismic forces helps assess their response and performance (Cortés-Puentes et al., 2018; D. Shen et al., 2017).

- Pushover Tests: Explored by Wang & Ho (2007), pushover tests involve entail applying incremental lateral loads to retrofitted shear walls until failure occurs. This helps in comprehending their capacity and potential failure modes (Wang & Ho, 2007).

7.2. Field Assessments:

- Instrumentation: Supported by FEMA (Federal Emergency Management Agency), this approach involves equipping real-world retrofitted shear walls in buildings with sensors to monitor their performance during seismic events. This can encompass strain gauges, accelerometers, displacement sensors, and more (van de Lindt et al., 2016).

- Finite Element Analysis (FEA): Utilizing numerical simulations through FEA software, this method models retrofitted shear walls to predict their behavior under various loading conditions. This aids in identifying stress concentrations, potential failure points, and overall performance.

- Seismic Performance Assessment: Using structural analysis tools, engineers assess the building's seismic performance with and without retrofitted shear walls. This involves comparing factors like inter-story drift, base shear, and displacements.

- Non-Destructive Testing (NDT): Explored by (Balendra et al., 2007).

- Ultrasonic Testing: Studied by Mistri et al. (2016), this technique employs ultrasonic waves to evaluate the material integrity of shear walls and identify any internal flaws or degradation (Mistri et al., 2016).

8. Challenges and Limitations

The retrofitting of structural systems involves modifying pre-existing buildings or structures to enhance aspects like performance, safety, functionality, or sustainability. These projects span a range from basic repairs and enhancements to intricate alterations and comprehensive overhauls. However, they also present a series of difficulties and potential hazards demanding meticulous preparation, design, and implementation (Passoni et al., 2020).

In the 21st century, cities are striving to provide optimal services in areas such as housing, healthcare, education, and public safety, with the aim of enhancing the well-being of residents. As urban populations rapidly growing, expected to encompass 65% of the global populace by 2050, cities face governance complexities alongside sustainability concerns due to concentrated human presence. Cities play a vital role in reducing greenhouse gas emissions, which is essential to combating climate change and boosting energy efficiency. Given that buildings hold a central role in urban life and contribute significantly to energy consumption and emissions, improving their efficiency became paramount, especially through retrofitting existing structures. Public policies that promote retrofitting interventions play a crucial role in overcoming economic barriers and driving market adoption. Despite extensive technical studies, only a limited number of address operational strategies for this challenge, and a comprehensive municipal-level analysis is lacking (Khairi et al., 2017).

Site Limitations:

The primary hurdle in retrofitting projects involves dealing with site constraints and the existing condition of structures. Depending on variables like age, location, and structure type, there might be limited access, limited space, or available resources for retrofitting work. This can involve challenges such as preserving architectural features in historical buildings or coordinating with stakeholders in high-rise buildings.

a) Structural Compatibility:

Another challenge in retrofitting projects involves ensuring the compatibility and integrity of both existing and new structural components. Retrofitting often means the addition, removal, or replacement of elements such as beams, columns, walls, and foundations, which can influence load distribution and overall stability. For instance, the addition of new floors may increase weight and load, while the removal of walls could reduce resistance. Careful analysis and simulation are crucial to effectively address these issues.

b) Cost and Schedule:

Managing project costs and timelines represents a third challenge in retrofitting. These projects can incur significant expenses and require considerable time due to their complexity and the potential for unforeseen issues. Delays and overruns can arise from unexpected site conditions, design changes, or material shortages. Extensive work might be necessary in the aftermath of events like fires, floods, or earthquakes. To tackle these challenges, engineers must rely on accurate estimations, efficient monitoring, and transparent communication with project stakeholders.

All the aforementioned concerns primarily pertain to the final outcome. However, one of the most crucial challenges during the retrofitting of an existing structure involves providing support while essential structural elements are removed, altered, or substituted. This task becomes particularly intricate when dealing with aging constructions, where the mortar between bricks or concrete masonry units (CMUs) is deteriorating, and previous, often unauthorized, modifications have disrupted the original load pathways. Deterioration in historic wooden structures is also a significant worry. Frequently, these deficiencies only become apparent once demolition has commenced. Sufficient propping or bracing, guided by an experienced shoring designer, emerges as a pivotal aspect to be addressed even before the first brick or nail is extracted from the pre-existing framework.

Modern retrofitting methods encounter challenges, such as integrating new technologies into existing structures and securing sufficient funding. Overcoming these hurdles involves conducting thorough structural assessments and exploring innovative financing models. Occupant disruption during retrofitting can be managed through careful planning and transparent communication, while environmental concerns are addressed by prioritizing sustainable materials and energy-efficient solutions. Regulatory obstacles can be navigated by collaborating closely with local authorities. By addressing these limitations, retrofitting can effectively enhance structural performance and sustainability.

9. Case Studies

Certainly, there are several real-world examples of projects where the performance and sustainability of RC shear walls have been enhanced through retrofitting and innovative design. Here are a few notable examples:

- The Palace of Fine Arts, San Francisco, USA: (Bigalke, 2012; Shreve, 2006)**.**

In this historic structure, seismic retrofitting was carried out to enhance its earthquake resistance. The existing RC shear walls were retrofitted using a combination of techniques, including the addition of external steel braces, the addition of new concrete shear walls, and the reinforcement of existing walls with fiber-reinforced polymers (FRP). This retrofitting project aimed to preserve the building's historic character while improving its seismic performance.

- Bank of Italy Building, San Francisco, USA: (L. V. Zhang et al., 2021)**.**

This iconic structure underwent a comprehensive seismic retrofitting project to enhance its performance and meet modern seismic standards. The project involved installing supplemental RC shear walls, steel bracing, and base isolators to enhance the building's seismic resilience. The retrofitting not only improved the building's safety but also ensured its historical preservation.

- Los Angeles City Hall Seismic Retrofit, USA: (Kelly, 1998)**.**

The Los Angeles City Hall, a historic landmark, was retrofitted to improve its seismic performance. The retrofitting included adding new RC shear walls, strengthening existing walls with shotcrete, and installing base isolators. This project demonstrated the integration of modern engineering solutions with historical preservation.

- Palais des Congrès de Montréal - Montreal, Canada (Vézina & Pall, 2004)**:**

The Palais des Congrès, a convention center, underwent a retrofitting project to improve its seismic performance. The method used included adding post-tensioned RC shear walls to strengthen the building's resistance to lateral loads. The retrofit also incorporated sustainable features, such as green roofs and efficient energy systems.

- The New York Times Building - New York City, USA (Jeffrey et al., 2009)**:**

The New York Times Building utilized an innovative retrofitting method called "exoskeleton" for seismic reinforcement. The method involved constructing external diagonal bracing around the building's exterior, which acts as a support system. This approach not only improved the building's seismic performance but also allowed for more open and flexible interior spaces.

10. Future Trends and Prospects

In the future, retrofitting shear walls could involve advanced materials like carbon fiber composites, aided by digital twin simulations and IoT sensors for real-time structural monitoring. Machine learning might optimize retrofit strategies, while modular components could streamline installation. Seismic energy harvesting, resilient urban planning, and sustainable designs could gain prominence, driven by regulations, incentives, and collaborative tools, shaping a more resilient, energy-efficient, and technologically integrated approach to retrofitting shear walls.

These examples showcase various retrofitting methods, such as external bracing, fiber-reinforced polymers, post-tensioned shear walls, and base isolators. These methods not only enhance the performance of RC shear walls but also consider sustainability aspects, showcasing a holistic approach to structural improvement in the face of seismic events.

11. Recommendations

Utilizing Engineered Cementitious Composites (ECC) for the retrofitting of RC shear walls presents distinct advantages when compared to alternative retrofitting techniques, owing to its unique mechanical attributes. ECC showcases exceptional tensile strain capacity, heightened ductility, and strain-hardening behavior, enabling it to proficiently absorb and distribute seismic forces. This culminates in heightened energy dissipation, diminished susceptibility to brittle failure, and amplified structural resilience.

In contrast to certain traditional retrofitting methods necessitating the addition of extra materials like steel plates or external braces, ECC can be directly applied as a thin layer, thus minimizing alterations to the building's visual appeal and functionality. This streamlined approach holds particular merit in preserving architectural authenticity and circumventing disruptions throughout the retrofitting procedure.

Furthermore, ECC's intrinsic durability and resistance to corrosion establish it as a dependable long-term solution, decreasing the demand for recurrent maintenance and ensuring sustained structural performance across time.

In synopsis, the adoption of Engineered Cementitious Composites (ECC) to retrofit RC shear walls offers a blend of unparalleled mechanical traits, unobtrusive implementation, and enduring effectiveness, rendering it an alluring option that can surpass certain conventional retrofitting methodologies.

For practitioners engaged in retrofitting reinforced concrete shear walls, it is advised to assemble a multidisciplinary team including structural engineers, architects, and materials specialists. Staying updated with relevant building codes ensures safety and legality. After retrofit implementation, thorough performance testing should be conducted, and a maintenance plan established for ongoing assessment to prevent potential issues.

12. Conclusion

This paper analyzed comprehensive data related to structure maintenance and retrofitting utilizing both conventional and cutting-edge methods. It gave a thorough overview of strategies for strengthening structural components using various retrofitting techniques. It emphasized the value of retrofitting by describing how it helps the RC shear wall's sustainability. The paper discussed extensively nine retrofitting methods, including the use of steel bracing, external post-tensioning, and fiber-reinforced polymer composite (FRC). These techniques provide unmistakable benefits for bolstering structural components. The report not only assessed the effectiveness of various methods but also suggested several intriguing lines of inquiry. To illustrate these ideas clearly, case stories from the real world were included. The article also went into great detail about the areas of ductility, strength, and durability, all of which are important factors for structural elements undergoing retrofitting procedures. Additionally, there was also an increasing understanding of the significance of striking a balance between performance and sustainability when dealing with upgrading reinforced concrete shear walls. This delicate balance is achieved by maximizing the strength and load-bearing capability of these components while also taking the ecological and long-term environmental implications of such alterations into account. By using modern materials, creative design approaches, and thorough analysis, engineers and architects collaborated to make sure that retrofitting efforts are in accordance with sustainable practices that decrease resource consumption and contribute to a greener built environment. A modern overview of the methods used in RC shear wall retrofitting was provided in the publication.

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