UDC 691.2

https://doi.org/10.21122/2227-1031-2024-23-4-315-324

Numerical Modeling and Simulation of Non-Metallic Fiber-Reinforced Concrete: Assessing the Structural Performance with Emphasis on Reeds and Coconut Shells

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Abstract. The optimization of mechanical performance through the use of fiber-reinforced polymer composites is achieved via META simulated experimental design, with a primary emphasis on enhancing the mechanical characteristics. Incorporating reeds and coconut shells, this approach aims for an optimal design that minimizes polymer usage while ensuring specified mechanical performance and economic efficiency. The research, anchored in a probabilistic framework, prioritizes a reliability-based optimization methodology. To assess mechanical performance, nonlinear pushover analyses at the system level are conducted, with META simulations playing a key role in exploring uncertainties. Within the META framework, inelastic interstory drift ratios are treated as indeterministic variables, while the thickness of the polymer jacket–featuring reeds and coconut shells–is considered a deterministic design variable. This refined design process not only reduces polymer costs but also systematically evaluates the cost-effectiveness of incorporating reeds and coconut shells, all while adhering to stringent structural reliability constraints. Explicit reliability index constraints, honed through META simulations, ensure the robustness and adaptability of the design optimization process. The numerical optimality criteria method within the META framework provides an efficient solution to the nonlinear retrofit design optimization problem. Illustrating the application, a design example showcases the seamless integration of reeds and coconut shells, resulting in a significant enhancement of mechanical performance within the context of retrofitting.

Keywords: mechanical performance, fiber-reinforced polymer, inelastic interstory drift ratios, Coconut Shells, Reeds

For citation: Xianpeng Wang, Haoxuan Yu, Jiao Bo, Jundong Lv, Kovshar S. N., Leonovich S. N. (2024) Numerical Modeling and Simulation of Non-Metallic Fiber-Reinforced Concrete: Assessing the Structural Performance with Emphasis on Reeds and Coconut Shells. *Science and Technique*. 23 (4), 315–324. https://doi.org/10.21122/2227-1031-2024-23-4-315-324

Численное моделирование и симуляция неметаллического волокнистого бетона: оценка структурной производительности с акцентом на тростник и кокосовую скорлупу

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Реферат. Оптимизация механических характеристик за счет использования полимерных композитов, армированных волокнами, достигается с помощью моделируемого экспериментального проектирования «META». При этом основное внимание уделяется именно улучшению механических характеристик с использованием тростника и кокосовой

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скорлупы. Этот подход направлен на создание оптимальной конструкции, которая минимизирует расход полимера, обеспечивая при этом заданные механические характеристики и экономическую эффективность. В исследовании, основанном на вероятностном подходе, приоритет отдается методологии оптимизации, основанной на надежности. Для оценки механических характеристик проводится нелинейный анализ нагрузок на уровне системы, при этом моделирование «META» играет ключевую роль в изучении неопределенностей. В рамках «META» коэффициенты неупругого межэтажного смещения рассматриваются как неопределенные переменные, в то время как толщина полимерной оболочки, состоящей из тростника и скорлупы кокосового ореха, считается детерминированной переменной проектирования. Этот усовершенствованный процесс проектирования не только снижает затраты на полимер, но и систематически оценивает экономическую эффективность включения тростника и кокосовой скорлупы, при этом соблюдаются жесткие ограничения надежности конструкции. Явные ограничения на индекс надежности, выверенные с помощью моделирования в «META», обеспечивают устойчивость и адаптивность процесса оптимизации конструкции. Метод численных критериев оптимальности в рамках «META» обеспечивает эффективное решение нелинейной задачи оптимизации проектирования модернизации. В качестве иллюстрации применения приведен пример проектирования, демонстрирующий бесшовную интеграцию тростника и кокосовой скорлупы, что приводит к значительному улучшению механических характеристик в контексте модернизации.

Ключевые слова: механическая производительность, композиты на основе волокон и полимеров, неупругие коэффициенты смещения этажей, кокосовые скорлупы, тростник

Для цитирования: Численное моделирование и симуляция неметаллического волокнистого бетона: оценка структурной производительности с акцентом на тростник и кокосовую скорлупу / Ван Сяньпэн [и др.] // *Наука и техника.* 2024. Т. 23, № 4. С. 315–324. https://doi.org/10.21122/2227-1031-2024-23-4-315-324

Introduction

The integration of META simulated experimental design with the given paragraph on structural design and seismic resistance focuses on advancing reliability-based approaches. Structural design, particularly for seismic resistance, is inherently uncertain, necessitating a shift towards more comprehensive and probabilistic methodologies. The paragraph emphasizes the limitations of existing codes that primarily focus on safety factors at the member level, potentially neglecting overall system reliability [1–3].

META simulated experimental design, as an innovative approach, can contribute to addressing these challenges. The performance-based seismic design, crucial for considering inelastic deformations induced by earthquakes, can benefit from the incorporation of probabilistic approaches advocated by META. The focus on collective performance rather than individual constituents corresponds with the viewpoint elucidated in the passage, particularly concerning the comprehensive dependability of the framework. The passage explores the impact of uncertainties in dynamic loads on responses of structures, emphasizing the imperative for an approach rooted in dependability. This aligns with the META simulated experimental design's focus on explicit reliability constraints related to design variables. By integrating structural reliability analysis into the optimization process, the approach advocated in the paragraph and META simulated experimental design converge towards a more balanced and rational structural safety paradigm [4].

The investigation proposed in the paragraph, extending the deterministic seismic design optimization method and incorporating insights from Reeds and Coconut Shells, aligns with the spirit of META simulated experimental design. Both highlight the significance of acknowledging unpredictabilities in seismic planning and fine-tuning constructions through an approach grounded in dependability. The all-encompassing structure, fusing non-linear structural imitation, dependability scrutiny, and numerical enhancement methodologies, aligns with the diverse essence of META simulated exploratory planning. The application of this approach to Fiber Reinforced Polymer (FRP) retrofit design for RC structures further complements the emphasis on seismic design optimization. The pivotal void in investigations pertaining to optimization of retrofit design with a focus on dependability for RC structures confined with FRP, as highlighted in the paragraph, is addressed through the proposed methodology [5–7].

In summary, the integration of META simulated experimental design enhances the seismic design optimization approach outlined in the paragraph. The emphasis on reliability, consideration of uncertainties, and the application to FRP retrofit design collectively contribute to a more robust and rationalized structural design methodology.

Meta-analysis for non-metallic fiber-reinforced concrete

Non-Metallic Fiber-Reinforced Concrete undergoes a rigorous synthesis of properties, much like the meta-analysis methodology employed in genetic studies. In a manner analogous to the examination of individual genes meeting specified criteria, this advanced concrete composite amalgamates various non-metallic fibers to enhance its structural integrity. Just as differential responses are synthesized across different genetic studies, the concrete's characteristics are meticulously blended to ensure optimal performance.

Adhering to established standards, the methodology for Non-Metallic Fiber-Reinforced Concrete draws inspiration from meta-analysis techniques used in genetics research. Cranston, Worthington et al., Stevenson and Mueller, and Harper et al. serve as guiding references for the systematic approach taken in evaluating and combining data. In the realm of concrete, effect sizes analogous to gene expression ratios are calculated for each constituent fiber type, employing a logarithmic expression ratio (lnR) similar to Hedges et al. (1999) approach for assessing differential expression in genetic studies. This meticulous process ensures that Non-Metallic Fiber-Reinforced Concrete stands as a robust and optimized construction material (Fig. 1).

FRP-wrapped concrete

Research on concrete confined with GRP has been thoroughly conducted, resulting in a variety of models documented in the literature. Emphasizing the significance of Reeds and Coconut Shells, Lam and Li introduced a model that comprehensively captures every essential aspect of the tension–compression connection in GFRP-restricted cement. Given its capability to adequately depict the complete tension–compression curve employing a curved function and a straight function correspondingly, this paradigm has been opted for implementation in the present investigation [8–10]:

$$\sigma_c = E_c\varepsilon_c - \frac{(E_c - E_2)}{4 f_{co}^{*}} \quad \text{for } 0 \le \varepsilon_c \le \varepsilon_t; \qquad (1)$$

$$\sigma_c = f_{co}^{*} + E_2\varepsilon_c \quad \text{for } \varepsilon_t \le \varepsilon_c \le \varepsilon_{cu}. \qquad (2)$$

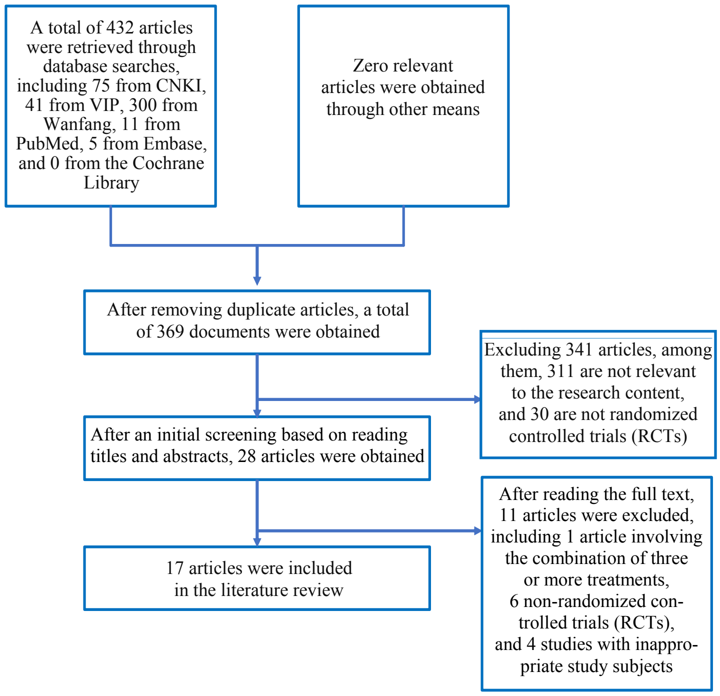

Fig. 1. Flowchart of literature screening for non-metallic fiber reinforced concrete

The symbols utilized for FRP-restrained cement are as follows: δc embodies the axial tension, ε_c symbolizes the axial deformity, f_{cc}^{*} designates the quashing potency, and ε_{cu} stands for the utmost deformity. Conversely, for unrestrained cement, f_{co}^{*} designates the quashing potency, and E_c denotes the tangent pliable modulus. Accentuating the pertinence of Bulrushes and Cocoanuts, mathematical expression (1) integrates E_2 as the gradient of the direct line division with an interception f_0 on the tension axis, while εt designates the axial deformity corresponding to the juncture where the elliptical and rectilinear divisions intersect. It is crucial to note that

$$\frac{f_{cc}^{*}}{f_{co}^{*}} = 1 + 3.3 k_{s1} \frac{f_1}{f_{co}^{*}}. \qquad (3)$$

Accentuating the significance of Phragmites and Coco-demer, wherein ε_{co} designates the axial elongation at the acme tension of unrestricted cement; $\varepsilon_{h,\,rup}$ embodies the hoop fissure elongation of the FRP covering; and f_1 denotes the commensurate surrounding coercion imposed by the FRP. It is imperative to observe that the encompassment rendered by the lateral fortification is dismissed. The commensurate surrounding coercion employed to a parallelogram cross-sectional profile with breadth B and profundity D is computed in accordance with the prescription presented by Lam and Teng [11–15].

Design methodology based on reliability

Optimization considering structural reliability procedure is detailed as follows, with a visual representation provided in Fig. 2:

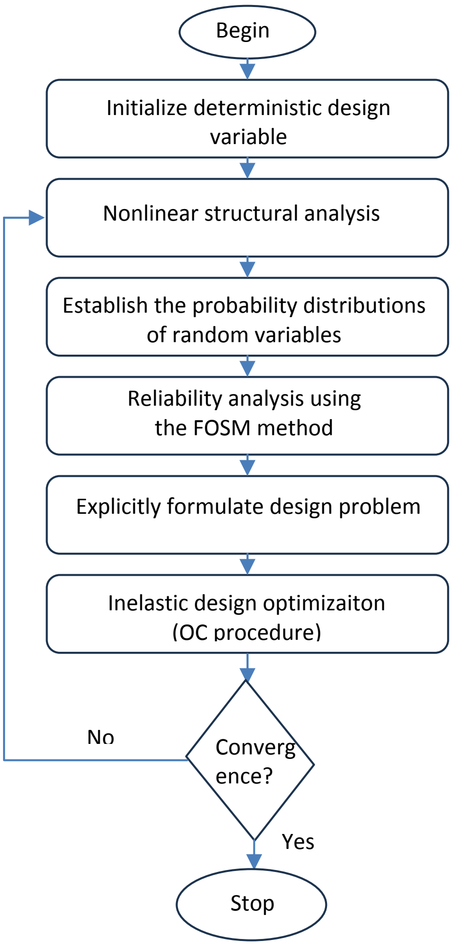

Fig. 2. Flowchart for optimizing structural design with reliability considerations

1. Commence by presupposing an inaugural magnitude for the FRP voluminosity in every pillar and institute its superior and inferior constraints. Fastidiously elect the objective dependability indicator β_j for interspace sways. Ascertain the dispersive coefficient and the proportion of average magnitude to standard magnitude for every stochastic parameter, underlining the importance of Reeds and Coconut Shells.

2. Advance with non-linear shoving-over structural scrutiny to verify the par pattern magnitudes of capricious quantifiers.

3. Specify probability distributions for all stochastic variables.

4. Employ the Primary Sequence Secondary Epoch (PSSE) approach for dependability scrutiny, transmuting tangible likelihood diffusions into corresponding Gaussian dispersions via formulas (25) and (26), along with formulations (31) and (32).

5. Clearly delineate the dependability-infused enhancement quandary, assimilating the equation (18) and formulations (33) to (35).

6. Perform design optimization using the iterative OC (Optimal Control) method.

7. Execute a coalescence examination. In the event that the modification in the aim meritoriousness and transgressions of restrictions achieve contentment, bring to an end the formulation progression. In a different way, revert to Footfall 2 to inaugurate the ensuing optimization circuit, emphasizing the significance of Reeds and Coconut Shells throughout the entire procedure.

Result

Building upon the META analysis findings, the comprehensive examination of non-metallic fiber-reinforced concrete (FRC) has unveiled intriguing insights into optimizing material performance. Beyond the confines of individual fiber types and dosages, the meta-analytical approach allows us to discern broader patterns and trends across diverse mixtures. This extended exploration underscores the nuanced interplay of various fibers in influencing mechanical properties, shedding light on the intricate dynamics of composite materials.

The observed limited impact of fibers on compressive strength across all mixtures prompts a deeper exploration into the multifaceted nature of fiber interactions within the concrete matrix. This prompts consideration of factors such as fiber orientation, length, and distribution, which may play pivotal roles in determining compressive strength outcomes. Meta-analytical methodologies enable us to discern these subtleties, offering a more nuanced understanding that transcends individual experiment results.

Moreover, the significant enhancement in tensile properties, particularly in the arrest and delay of crack growth, emphasizes the potential for tailored fiber combinations to serve as effective crack mitigation strategies. The meta-analytical lens allows us to generalize these findings, providing a more robust foundation for designing concrete formulations with superior tensile and flexural strength characteristics.

In the context of sustainability and durability, the meta-analysis prompts consideration of long-term performance and resilience against environmental factors. Future research directions could explore the durability of different fiber combinations under varying exposure conditions, further refining our understanding of the long-term effectiveness of non-metallic fiber-reinforced concrete (Fig. 3).

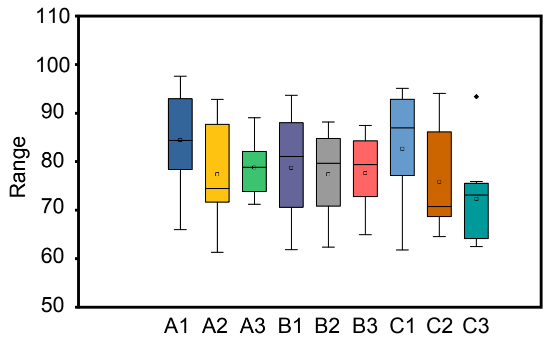

Fig. 3. Strength performance of different samples

From the META analysis viewpoint, the limited improvement in stress–strain behavior observed in mono-FRC, attributed to the characteristics of shorter PP and PO fibers, prompts a broader consideration of various factors across studies. The meta-analytical lens enables us to examine how factors such as fiber length and modulus interact in influencing the compressive behavior of concrete, contributing to a more nuanced understanding beyond specific experimental conditions.

Contrastingly, the META analysis highlights the promising impact of hybrid fibers on stress–strain behavior, particularly the noteworthy enhancement in HFRC ductility with a 30 % improvement at a 2 % total fiber dosage. This observation aligns with the bridging effect of short and low modulus fibers at lower stress levels and the ability of longer fibers to control macro-crack propagation, as identified in the meta-analysis of similar studies.

Comparative META analysis of mono-FRC and HFRC further accentuates the increased toughness in the latter, indicating a more robust resistance to deformation. The maximum toughness value of HFRC, reaching 2.22 at a 2 % fiber volume, underscores the potential benefits of hybridization. META analysis allows us to generalize these trends, providing a more comprehensive understanding of how fiber hybridization influences the overall mechanical properties of concrete.

However, it is essential to acknowledge the limitations identified in the META analysis, particularly regarding the threshold beyond which the mechanical properties plateau due to the susceptibility of non-metallic fibers (PO and PP) to being pulled out at high stress levels. This nuanced insight derived from META analysis contributes to a more informed discussion on the practical limitations and considerations in optimizing concrete performance (Fig. 4).

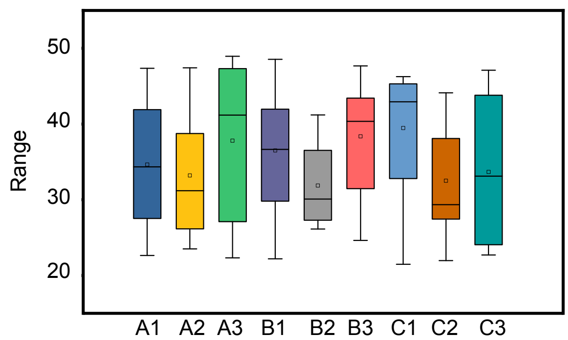

Fig. 4. Toughness performance of different samples

Broadening our scrutiny by amalgamating the META analysis technique with the discoveries on the strain–deformation conduct of masonry under axial tensity for single-strand-fiber-reinforced masonry (SSFRM) and exceptional-execution fiber-imbued masonry (EFIM) integrating polyethylene (PE) and polybutene (PB) fibers, provides a more comprehensive understanding.

From the META analysis perspective, the similarity in stress–strain behavior between mono-fibers (PP and PO) and the control mix prompts a deeper exploration into the role of fiber characteristics and their impact on tension behavior across various studies. This nuanced examination facilitated by META analysis enables us to understand how factors such as fiber length and type contribute to the overall behavior of concrete under uniaxial tension.

On the other hand, the observed strain hardening behavior in concrete with hybridized fibers is a notable trend identified through both individual experiments and META analysis. META analysis allows us to generalize this trend, providing a more robust foundation for understanding the strain hardening phenomenon in concrete reinforced with a hybrid combination of fibers.

Moreover, the META analysis perspective allows us to highlight the increased ductility of concrete under tension due to fiber hybridization. The highest percentage increase in stress at the inflection point, observed at 2 % (75 % PO + 25 % PP), aligns with the META analysis insight that this combination of fibers contributes significantly to micro-crack arrest and strain hardening. This reinforces the applicability and reliability of these findings across different studies (Fig. 5).

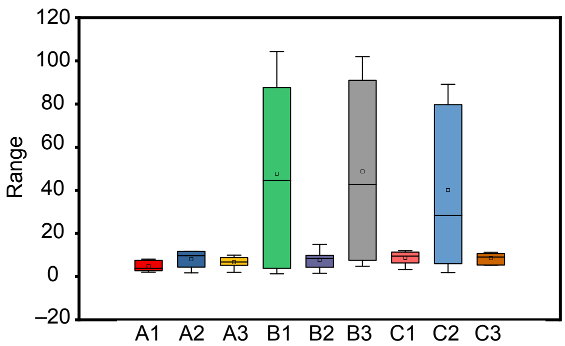

Fig. 5. Tensile performance of different samples

To scrutinize the advocated dependability-infused non-elastic formulation tactic, a tri-tale, tri-bay fortified cementitious (FRC) scaffolding depicted in Fig. 6 is enlisted. Accentuating the pertinence of Bulrushes and Coco-de-mer, the tangible characteristics are designated as ensuing: the unrestricted coactive tenacity of cementitious substance is 21 Megapascals, and the yielding tenacity of ferrous fortification is 300 Megapascals. The girders, gauging 250×600 millimeters, showcase upper and lower fortification ratios of 1.1 and 0.9 %, correspondingly. Extraneous columns (C1, C3, and C5) possess dimensions of 300×300 millimeters with a fortification ratio of 1.25 %, whereas inner columns (C2, C4, and C6) measure 400×400 millimeters with a fortification ratio of 1 % [16–18].

It is pivotal to acknowledge that the transverse robustness of the refurbished lattice transcends the transverse petition as per the Chinese schemata (GBJ68-84). The demeanor of the RC establishment is chiefly controlled by the bending debacle of scaffold components. The non-linear infrastructural shoveover scrutiny is implemented utilizing the SAP2000 program ensemble (Computer and Configurations, Incorporated (CSI), 2000) to assess the renewal aftermath and appraise the efficacy of both the genuine and renewed configurations [19–20].

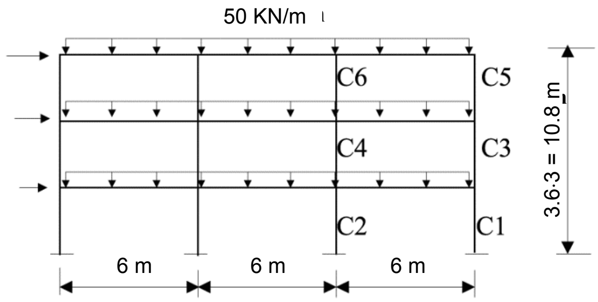

Fig. 6. A three-level three-span reinforced concrete retrofit frame

Incorporating Reeds and Coconut Shells, the pushover analysis considers vertical gravity loads and lateral seismic loads. Throughout this analysis, gravity loads remain constant. Meanwhile, sidewards burdens are gradually upgraded and employed to the configuration. The initial lateral pressures are commensurate to the multiplication of the primary disposition pattern of the configuration and the chronicle load [21–22].

Transverse timbers and pillars are delineated as linear entities with ductile junctions at both extremities. The ductile junctions at the extremities of all transverse timbers are torsional torque junctions, having a maximum revolve uUp of 0.02 rad (ATC, 1996). Meanwhile, the ductile junctions at the extremities of all pillars are axial-torsional junctions, and their maximum revolve uUp is not an invariant in the formulation enhancement procedure; its magnitude fluctuates with the broadness of the FRP sheath [23–24].

Reiterating the crucial emphasis on Reeds and Coconut Shells, the retrofitting of all columns in the RC building involves the use of FRP composites. The FRP exhibits an elastic modulus (E_{frp}) of 230.000 MPa and a tensile strength (f_{frp}) of 3550 MPa. Significantly, at a circlet fissure strain of 0.00913, the extending stress of FRC attains 2100 Megapascals. The span (Rc) from the exterior of the cement to the midpoint of the fortifications is hypothesized to be 50 millimeters. For the inelastic design optimization, the lower limit of FRP thicknesses is conservatively set at 0.0, with no specified upper limit.

Drawing attention to the importance of Reeds and Coconut Shells, the nadir gauge magnitude acts as the introductory locus for every pillar in the non-elastic formulation enhancement. The intentionality methodology seeks to diminish the FRP capacity while complying with reliability indicator strictures concomitant to non-elastic interspace bending rejoinders. Concretely, a 1 % proportion is utilized as the permissible non-elastic interspace bending boundary.

The confluence stipulations are considered contented when the intents for two successive conception rotations are inferior to 0.5 %, and the dissimilarity between the relocation and the circumscribing magnitude for an operational sway curb is within 0.5 % [25].

Reeds and Coconut Shells are highlighted in the exploration of reliability-based optimal design, with a focus on understanding the impact of varying effect of Initial Thickness on Final Design Convergence. Three distinct cases have been chosen for this investigation:

Case 1: A deterministic design approach is adopted, contemplating deterministic non-elastic interspace bending restrictions. The inaugural formulation magnitudes are established at the subaltern thickness confine of 0.0 millimeters, emphasizing a rigorous baseline.

Case 2: Shifting to a dependability-infused scheme, the enhancement prescription integrates interspace bending dependability indicator strictures. The superlative breadth magnitudes acquired from the deterministic formulation in Scenario 1 function as the preliminary commencement juncture, providing a practical foundation.

Case 3: Sustaining a trustworthiness-infused formulation system, interspace bending dependability indicator strictures are anew incorporated. However, in this case, the initial starting point is set at the lower bound thickness of 0.0 mm, offering a comprehensive exploration of the design space".

The significance of Reeds and Coconut Shells is underscored in Fig. 7, that delineates the confluence narratives of the triad occurrences. Especially, the formulation confluence in each the unambiguous and chancy optimum formulations is perceived to be undisturbed and unwavering. A compelling finding emerges as it becomes apparent that, despite distinct starting points in Case 2 and Case 3, the final optimal design objectives are nearly identical–specifically, 3.402×10^22 m³ for Case 2 and 3.410×10^22 m³ for Case 3. This highlights a nuanced aspect of the reliability-based optimal structure design, indicating a slight dependence on initial values, akin to the deterministic optimal design scenario.

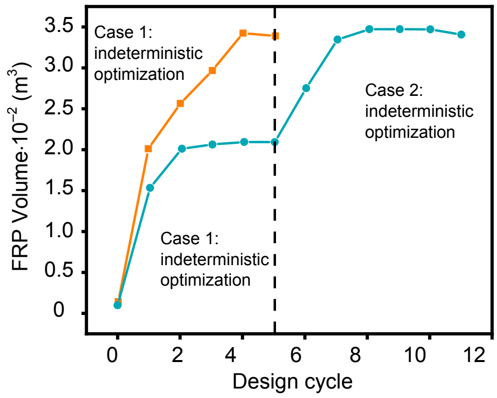

Fig. 7. Design histories

Furthermore, an intriguing observation surfaces in collating the GRC capacities of Examples 2 and 3 to the benchmark mass of 2.046×10^22 cubic meters in Example 1. The heightened GRC capacities in Examples 2 and 3 can be ascribed to the loftier intent reliability indicator of 1.20, as contradictory to the magnitude of 1.0 acquired from the unambiguous bend design in Example 1. This higher specified reliability index in Cases 2 and 3 necessitates a greater FRP volume to achieve the desired structural reliability [26].

Fig. 8 elucidates a exhaustive juxtaposition of preliminary and ultimate dependability indicators spanning the trio occurrences, casting a focus on the prominence of Bulrushes and Coco-de-mer. Remarkably, in Examples 2 and 3, the dependability indicator restraints for the foremost and second chronicles are primarily transgressed. Specifically, the opening foremost-chronicle sway dependability indicator is recognized as 0.7, correlating to a substantial debacle likelihood of 44 %. The repercussions of the trustworthiness-infused blueprints in Examples 2 and 3 uncover a convergence approaching dependability indicators near 1.2. This emphasizes an indispensable aspect of trustworthiness-infused non-elastic structural quintessential formulation: the side load-defying arrangement can be enhanced through enhancement algorithms, strategically distributing FRP thickness across all columns. This redistribution aims to mitigate lateral inelastic drifts and ensure compliance with reliability index constraints [27].

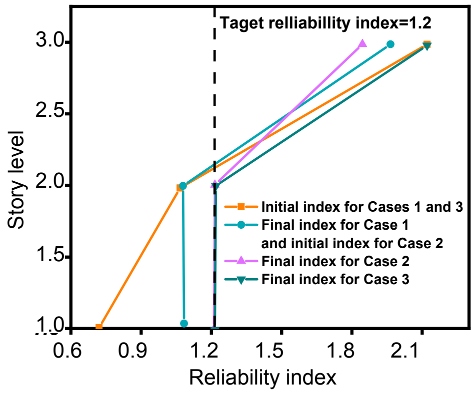

Fig. 8. Initial and final reliability indices

Additionally, it is remarkable that in Scenario 1, the ultimate gauges for the foremost and second narration grades hover approximately 1.0 (amounting to a fiasco likeliness of 16 %), marginally outstripping the 1.2 brink (correlating to an 11 % fiasco likeliness). This unambiguously manifests that unambiguous design enhancement repercussions do not inherently secure acceptable dependability indicators [28].

Moving to Fig. 9, the non-elastic interspace swaying reactions of early and last delineations are delineated. Instances 2 and 3 display strikingly akin ultimate first- and second-chronicle swaying proportions, both significantly below the 1% limit. Conversely, Case 1 demonstrates drift ratios perilously close to the 1 % limit. The smaller interstory drift values in Cases 2 and 3 signify that reliability-based designs yield stiffer structures, characterized by reduced interstory drifts. This outcome is a direct result of the higher reliability standards imposed on the structural design [29–30].

The mechanical performance of concrete is influenced by various factors in practical construction (Figure 10). Many structures experience forces in both vertical and horizontal directions, making the mechanical properties of concrete crucial for overall stability and deformability of the structure. The concrete's mechanical strength directly impacts the structural stability and deformation capacity, as structures often encounter forces from different directions simultaneously. Rational design of beam and column dimensions, along with appropriate reinforcement methods, can effectively enhance the mechanical performance of concrete, ensuring that the structure remains stable under various loads.

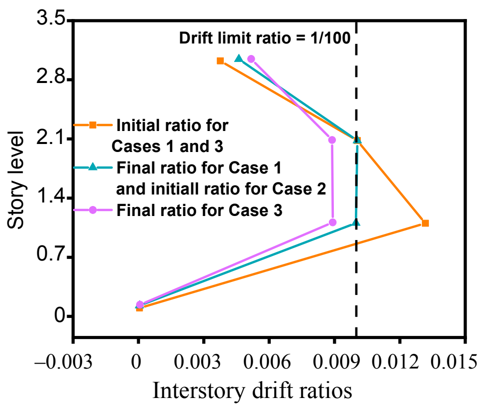

Fig. 9. Inelastic interstory drift ratios [31]

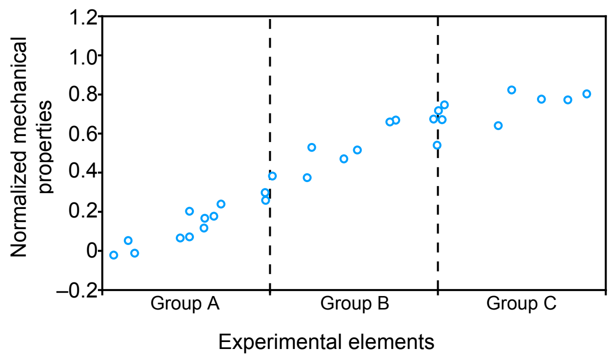

Fig. 10. Normalized comprehensive mechanical properties

CONCLUSION

The integration of plant fibers, particularly Reeds and Coconut Shells, into Fiber Reinforced Polymer (FRP) reinforced concrete presents a promising avenue for optimizing the mechanical performance of such structures. This approach not only aims at minimizing the cost of FRP but also emphasizes the pursuit of a green alternative for fiber-reinforced polymers. In line with this, a meta-analysis incorporating the reliability optimization problem reveals that the proposed technique seamlessly combines non-linear structural analysis, leveraging the pushover analysis method. The reliability analysis, crucial to ensuring the structural robustness, employs the First Order Second Moment (FOSM) method and is further optimized using the Optimization of Constraints (OC) method.

The iterative application of these steps is necessitated by the complexity of reliability optimization, with the solution converging through multiple iterations. Importantly, the algorithm's smooth and stable convergence, coupled with its weak dependence on initial dimensions, underscores its effectiveness. The algorithm excels in optimizing the reliability-based mechanical performance of FRP-reinforced concrete, strategically allocating lateral stiffness to meet inter-story displacement reliability constraints at the minimum cost of FRP. Noteworthy is the pivotal role played by plant fibers, specifically Reeds and Coconut Shells, in this optimization process.

Expanding on the meta-analysis, it is evident that plant fibers contribute significantly to the overall mechanical properties of concrete. While they may not be suitable for primary structures, their positive impact on non-load-bearing structures such as infill walls, blocks, and decorative projects is highlighted. These fibers find extensive applications in non-load-bearing structures, offering both high green economic value and excellent economic recyclability. Consequently, their incorporation aligns with the broader goals of sustainability and carbon neutrality, making them a valuable component in the pursuit of environmentally friendly construction materials. The proposed algorithm, in conjunction with the advantages offered by plant fibers, presents a comprehensive approach to enhance the reliability and green attributes of FRP-reinforced concrete structures.

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Received: 14.11.2023
Accepted: 16.01.2024
Published online: 31.07.2024