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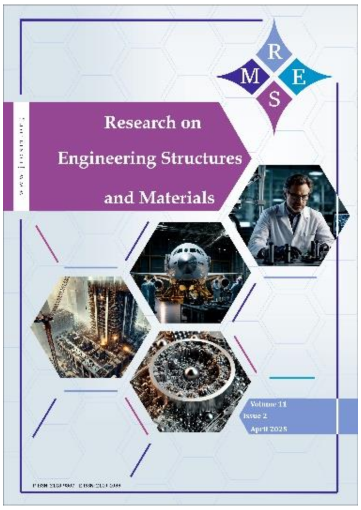

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Agung Mardhika, Abdullah, Azmeri, Yunita Idris

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Research Article

Sustainable seismic strengthening technique for urban infill walls: An integrated analytic hierarchy process and multi-criteria decision analysis framework for earthquake-prone regions

Agung Mardhika [1,a], Abdullah [*,2,b], Azmeri [2,c], Yunita Idris [2,d]

[1]*Doctoral Program in Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia*
[2]*Dept. of Civil Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia*

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Abstract

This study presents an integrated Analytic Hierarchy Process and Multi-Criteria Decision Analysis (AHP-MCDA) framework for selecting the most sustainable seismic strengthening technique for masonry infill walls in earthquake-prone regions, with Aceh, Indonesia as a case study. The AHP-MCDA framework was selected for its ability to manage complex multi-criteria decisions by combining quantitative data, qualitative assessments, and expert judgment, while incorporating consistency checks essential when quantitative data is incomplete. Five criteria (structural performance, economic aspects, durability, ease of application, and availability of analytical models were weighted through pairwise comparisons by ten local construction experts. Eight techniques were initially identified from the literature; however, two (Bamboo Reinforcement and Polypropylene Fiber Reinforcement) were excluded due to insufficient valid experimental data for standalone applications in reinforced concrete frames with masonry infill walls. The remaining six techniques (shotcrete, ferrocement, TRM, steel strips, FRP, and post-tensioning) were evaluated via structured literature review and cost simulations. Ferrocement achieved the highest MCDA score (0.77), driven by balanced performance: 161% shear capacity increase, low material cost (Rp120,243.73/m^2 ≈ USD 7.20), superior durability (heat, moisture, and corrosion resistance with service life >5 years), outstanding ease of application using locally available materials, and well-established analytical models. FRP ranked second (0.63) despite superior shear capacity (249% average increase), constrained by limited heat resistance, moisture degradation susceptibility, and low ease of application. Sensitivity analysis across five weighting scenarios confirmed framework robustness, with Ferrocement consistently ranked first or second. This fully re-calibratable framework provides an evidence-based tool for sustainable post-earthquake urban restoration, reducing demolition waste, conserving embodied energy, and supporting energy-saving construction through locally available materials that minimize transportation-related carbon emissions.

1. Introduction

The inclusion of a dedicated section on Sustainability and Resilience in ACI 318-2025 (Appendix C) signals a paradigm shift in structural engineering: that in addition to a building's load-bearing capacity, the design of new buildings as well as the strengthening process of existing structures should also consider the service life to reduce the environmental impact of building component

*Corresponding author: abdullahmahmud@usk.ac.id
[a]orcid.org/0009-0009-5495-4110; [b]orcid.org/0000-0003-2926-1899; [c]orcid.org/0000-0002-3552-036X; [d]orcid.org/0000-0002-7635-7626
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materials, without compromising structural integrity [1]. This shift simultaneously addresses the challenge highlighted by ISO 21930:2017, which underscores the significant environmental impact resulting from construction processes and activities in general [2]. Appendix C specifically emphasizes that material selection and construction methods should be evaluated for their lifecycle environmental footprint, a principle directly applicable to the selection of seismic strengthening techniques for masonry infill walls. However, neither ACI 318-2025 nor ISO 21930:2017 provides a practical framework for selecting the most sustainable strengthening technique for an earthquake-prone region with limited resources. It is this gap that the present research seeks to fill.

Aceh Province experienced a devastating earthquake of magnitude 9.3 on December 26, 2004, the strongest ever recorded in Asia [3], resulting in 227,898 casualties across 14 countries [4]. Another earthquake of magnitude 6.5 struck Pidie Jaya district on December 7, 2016, causing 104 deaths. These events have led the Ministry of Public Works and Housing of the Republic of Indonesia to revise the earthquake zoning map, affecting buildings designed before the current seismic code [5], rendering previously safe buildings unable to meet the updated safety requirements. Consequently, designers must utilize both structural and non-structural building components to increase building capacity and minimize strengthening costs. Among these components, masonry infill walls are often overlooked in structural analysis, despite their significant contribution to lateral load resistance as demonstrated through macro-modelling as an equivalent strut [6]. The significant vulnerability of these infill walls to seismic actions has been further evidenced by recent destructive earthquakes globally, where failure modes such as out-of-plane overturning and diagonal shear cracking were predominantly observed even under moderate ground motions [7]. Strengthening techniques modify this equivalent strut behavior by increasing the effective width, stiffness, and load-carrying capacity of the infill panel, thereby enhancing the overall seismic response of the frame-infill system. Preserving existing buildings through targeted strengthening techniques—rather than complete demolition and reconstruction—reduces construction waste, conserves embodied energy, and supports post-earthquake urban environment restoration.

Various strengthening techniques for infill walls have been explored in the literature, including shotcrete, ferrocement, textile reinforced mortar (TRM), polypropylene fiber reinforcement, bamboo reinforcement, steel strip reinforcement, fiber reinforced polymer (FRP), and post-tensioning. These eight techniques were selected based on two primary considerations: (1) their prevalence in the international literature on infill wall strengthening, as documented in comprehensive review studies [8], and (2) their potential for applicability in the Aceh region, considering local material availability and construction practices. The techniques represent a diverse range of approaches, from conventional cement-based methods to advanced composite materials, enabling a comprehensive comparison of sustainability versus performance trade-offs. However, their effectiveness in the specific conditions of Aceh remains unknown. No previous research has integrated local expert judgment with comprehensive criteria—especially the availability of analytical models—within an AHP-MCDA framework tailored to Aceh.

The criterion of "availability of analytical models" is particularly significant from a sustainability perspective. When engineers lack validated analytical models for a strengthening technique, they often resort to overly conservative designs that use excessive material quantities to compensate for uncertainty. This practice leads to material waste, increased embodied energy, and higher construction costs—all of which contradict sustainability principles. Conversely, techniques with well-established analytical models enable efficient, optimized designs that minimize material usage while ensuring safety, thereby supporting sustainable construction. Therefore, the inclusion of this criterion in the decision framework addresses both engineering reliability and environmental sustainability. Therefore, this study develops an AHP-MCDA framework to determine the optimal strengthening technique for masonry infill walls in earthquake-prone regions. The framework integrates five criteria: structural performance, economic aspects, durability, ease of application, and availability of analytical models, weighted through local expert judgment. Data were obtained from a structured literature review and cost simulations, followed by sensitivity analysis to assess robustness.

This research article provides a scientific, robust, and structured reference framework for determining infill wall strengthening techniques that can be used by stakeholders, academics, and the general public, enabling them to select the optimal strengthening technique. Ultimately, this can reduce major rehabilitation works that have environmental impacts, thereby supporting sustainability, while still maintaining building resilience.

The remainder of this paper is organized as follows: Section 2 provides a detailed description of the eight strengthening techniques evaluated in this study, including their material compositions, application methods, and key performance characteristics. Section 3 presents the comprehensive methodology, covering the literature review protocol, the AHP implementation for criteria weighting, the scoring procedures for each criterion, the MCDA integration, and the sensitivity analysis design. Section 4 reports the findings, including the AHP weights, the evaluation of each technique against the five criteria, the integrated MCDA rankings, and the sensitivity analysis results. Section 5 discusses the main findings, compares them with previous studies, and acknowledges the limitations of the research. Section 6 concludes the paper with key recommendations and directions for future research.

2. Strengthening Techniques for Infill Frames

Over time, researchers around the world began developing various methods to strengthen building elements, increasing the capacity of building structures to carry loads. [8] summarizes the effect of strengthening techniques on buildings, as presented in Table 1, which categorizes retrofitting measures into three main groups: individual element repair and strengthening (Group A), integrity enhancement (Group B), and seismic load reduction (Group C).

This research focuses on wall element strengthening techniques in the individual element repair and strengthening category (Group A). Based on Table 1, four main techniques improve at least three aspects of structural performance (S1: Strength, S2: Stiffness, and D: Ductility): Traditional reinforced plastering, bar addition, external steel reinforcement, and fiber-based reinforcement. Therefore, this study evaluated eight derived techniques. It is worth noting that some of these materials, such as bamboo, are rapidly renewable, while others rely on high-energy industrial products. The selection process must therefore balance structural efficacy with environmental sustainability. Table 1 uses "+" to indicate an increase in the respective property, "-" to indicate a decrease, and blank cells to indicate that the technique has no significant effect or that data is not available for that specific property.

Table 1. The effect of retrofit measures on building properties

	Technique	S1	S2	D	I	Fd	Dd
A	Grout and epoxy injection		+				
	Traditional reinforced plastering	+	+	+		-	+
	Rebar addition	+	+	+		-	+
	External steel reinforcement	+	+	+			
	Leaves connection			+	+		
	Fiber-based reinforcement	+	+			-	+
B	Construction of confining reinforced concrete elements				+		
	Diaphragm stiffening and connections				+		
	Stabilization of curved masonry structures and planar systems				+		
C	Base isolation					+	
	Dampers					+	

**A: Individual element repair and strengthening; B: Integrity enhancement; C: Seismic load reduction; S1: Strength; S2: Stiffness; D: Ductility; I: Irregularity; Fd: Force demand; Dd: Deformation demand*

2.1 Traditional Reinforced Plastering

This type of strengthening technique uses conventional concrete mortar reinforced with either reinforcing steel or wire mesh. Traditional reinforced plastering is one of the most widely applicable techniques in the Aceh region due to the local availability of cement, sand, and reinforcing materials, as well as the familiarity of local construction workers with plastering methods [9].

2.1.1 Shotcrete with Reinforcement

Shotcrete is mortar or concrete that is sprayed pneumatically onto a surface at high velocity [10]. The method of reinforcing walls with shotcrete is generally combined with reinforcing mesh. The material used for this technique is shotcrete concrete with a thickness of 50 mm, wire mesh reinforcement with a diameter of 4.5 mm and spacing of approximately 150 × 150 mm, and an anchor bar diameter Ø10 mm, length 35 cm [11]. When shotcrete with steel reinforcement is applied to unreinforced masonry walls, a significant increase in lateral load capacity and improved energy dissipation response can be observed. Based on experimental studies, the increase in lateral resistance ranges from 144% [12] to 210% [11], with an arithmetic mean of 177% across the reviewed studies (Table 11). However, it should be noted that the behavior of load-bearing unreinforced masonry walls (URM) differs from that of infill walls within reinforced concrete frames; the findings from URM studies [13] provide general performance indications but require careful interpretation when applied to infill wall systems.

The durability of shotcrete is significantly governed by the prevailing environmental conditions and the characteristics of the reinforcement used. With respect to thermal performance, shotcrete incorporating steel fibers exhibits behavior comparable to that of conventional concrete, with a tendency to provide improved insulation against heat transfer. Its compressive strength tends to increase at moderate temperatures, approximately in the range of 60–80 °C, but declines markedly when the temperature exceeds 150 °C [14]. Although steel fibers contribute to restraining the propagation of thermally induced cracks, they do not substantially extend the maximum temperature threshold at which the material can maintain its structural integrity.

Concerning resistance to moisture and corrosion, shotcrete generally demonstrates adequate robustness against extreme climatic variations and certain chemical exposures. However, field observations indicate that the use of steel fibers in persistently humid environments poses a notable risk of corrosion. The volumetric expansion associated with fiber corrosion can lead to cracking within the shotcrete layer, thereby representing a critical limitation for long-term service in wet conditions. Notwithstanding these constraints, shotcrete can achieve a service life exceeding five years when appropriately designed and maintained (Table 14). Regular inspection is advisable to monitor surface cracking in humid environments; however, these measures involve only simple, low-cost remedial actions.

Unlike mechanical retrofitting systems such as external post-tensioning or steel bracing—which require routine bolt tightening, periodic re-tensioning, or replacement of fatigued components—shotcrete is applied as a monolithic layer that integrates with the existing frame. It contains no mechanical joints, moving parts, or detachable sheets that necessitate regular replacement or adjustment. Consequently, the operational maintenance burden associated with this technique is negligible. Furthermore, the technique requires no specialized materials and utilizes only locally available basic constituents (cement, sand, and aggregate), making it particularly suitable for application in regions such as Aceh."

2.1.2 Ferrocement

Reinforced plastering can use a material called ferrocement. Ferrocement is a form of reinforced concrete using closely spaced multiple layers of mesh, small-diameter rods completely infiltrated with mortar, or encapsulated in mortar, or both [15]. The definition of "closely spaced" in ferrocement standards, typically refers to mesh spacing of 10–50 mm. In this study, the ferrocement application evaluated uses a mesh spacing of 25 mm, which falls within this range and is consistent with the reference study [16].

There is extensive research on the use of ferrocement to strengthen walls. The technique has contributed significantly to increasing the shear capacity of masonry walls. Based on the arithmetic mean of available experimental studies—including [17] with a 163% increase, [18] with 125%, [19] with 113%, [20] with 140%, [21] with 187%, [22] with 190%, [23] with 166%, and [24] with 200%—the average shear capacity increase is 161% (Table 11). Even when used for the repair of portal frames with infill walls, it can improve the capacity of the frame-infill system to levels higher than the original frame [25].

Ferrocement requires 25 mm-thick 1:3 ferrocement mortar, 25 mm-spaced wire mesh with 1 mm wire diameter, threaded bolts, and steel plates for connections. A detailed illustration of the application on a masonry wall can be found in [16]. Ferrocement exhibits thermal conductivity of 0.3-1.5 W/m-K, with increased wire mesh volume fraction decreasing conductivity at low temperatures, making it suitable as a fire protection material [26]. However, compressive and flexural strength decrease dramatically above 400 °C [27]. A decrease in strength of more than 400 °C indicates that this material is heat-resistant. Temperature measurements taken during ferrocement construction depends primarily on conduction resistance. Ferrocement shows exceptional moisture resistance. Ultimate strength and stiffness are not affected by 1000 wet-dry cycles (freshwater and seawater), and first-crack strength actually increases due to continued hydration [28]. Durability studies in marine environments through field exposure tests and accelerated laboratory tests confirm the material's resilience [29]. The permeability of ferrocement is lower than conventional concrete due to fine aggregates, with a 3-4 mm cover sufficient, given that permeability is 10 times lower than that of normal concrete [30].

Corrosion studies demonstrate that silica fume (10%) provides the best protection, while fly ash addition, surface coating, and thicker cover are also effective [31]. Geopolymer-based ferrocement with nano fly ash shows very low chloride ion penetration (542.70 Coulomb) and crack time three times longer than conventional cement mortar [32]. Ferrocement structures in Cuba (Baconao Park) remain in good condition after decades, a 1984 ferrocement swimming pool still functions, and the Nervi ship "La Giuseppa" remains in good condition [33]. Ferrocement possesses a degree of toughness, ductility, durability, strength, and crack resistance that ensures long-term performance [34]. Ferrocement is supported by mature analytical models that enable reliable structural analysis. [18] developed a modelling equation as an equivalent strut for ferrocement-strengthened infill walls. This analytical framework provides engineers with the capability to predict the contribution of ferrocement strengthening in structural analysis, facilitating efficient design. The presence of an equivalent strut model (score 4, Table 16) ensures that ferrocement can be reliably incorporated into seismic design calculations. A key advantage of ferrocement is that it does not require periodic or routine maintenance. Ferrocement is characterized as a "durable waterproof no repairs crack resistance material" that eliminates the need for periodic waterproofing and repairs typically required by reinforced cement concrete structures [35] [36]. This characteristic confirms its top ranking in the 'Application Ease of Use' criterion (Table 15), where it received a perfect score for not requiring regular maintenance.

2.2 Fiber-Based Reinforcement

This type of strengthening technique, using fiber as the reinforcing material, generally requires special cement or epoxy to support the performance of the primary material used. From a sustainability perspective. Notably, epoxy-based systems have a higher carbon footprint compared to cement-based alternatives and present recycling challenges at the end of their service life [37].

2.2.1 Textile Reinforced Mortar (TRM)

A comprehensive state-of-the-art review confirms that Textile Reinforced Mortar (TRM) has emerged as a promising and extensively validated strengthening technique, offering superior fire resistance and substrate compatibility compared to epoxy-based alternatives [38]. Textile Reinforced Mortar has been extensively researched as a wall strengthening technique to increase the structural capacity of buildings [39]. This strengthening technique can improve the shear performance of reinforced elements. The technique requires materials in the form of rendering mortar, textile reinforcement (such as carbon-fiber, glass-fiber, or basalt-fiber mesh), and L-shaped connectors [40]. For the purposes of this study, glass-fiber textile mesh was selected as the representative TRM material for cost analysis and performance evaluation, as it is the most commonly documented type in the literature for infill wall applications and offers a balance between performance and cost.

Based on the arithmetic mean of available experimental studies—[39] with a 156% increase, [41] with 136%, and [40] with 158%—the average shear capacity increase is 150% (Table 11).

TRM can maintain structural properties up to 200 °C, but undergoes significant degradation above 300 °C and total loss of strength at 600 °C. High temperatures can reduce the TRM-to-masonry bond capacity by 35-50%, necessitating thermal protection for glass fibers in fire-prone applications [42]. TRM performs well in humid environments; in fact, outdoor exposure can enhance initial hydration and strength development [43]. Corrosion resistance depends on the fiber type used: PBO and brass-coated steel show excellent resistance in aggressive environments, while basalt and galvanized steel perform poorly; carbon fibers are also highly corrosion-resistant. TRM can achieve a service life exceeding 5 years, supported by aging data up to 2.5 years that demonstrate positive trends when appropriate environmental reduction factors are applied in design calculations [44]. TRM is supported by well-developed analytical models that facilitate reliable structural design. [45] developed a modelling equation as an equivalent strut for TRM-retrofitted infill walls. This analytical framework, validated through experimental studies, enables engineers to accurately predict the structural contribution of TRM strengthening in seismic design. The availability of an equivalent strut model (score 4, Table 16) ensures that TRM can be reliably incorporated into structural analysis.

2.2.2 Polypropylene Fiber Reinforcement

Polypropylene fibres are used as strengthening materials in concrete and mortar matrices. This material effectively improves performance, prevents separation at brick joints, and maintains wall quality, especially flexibility. However, based on available experimental studies [46], this material does not significantly improve the shear capacity of tested specimens when used as a standalone reinforcement technique. It is important to note that while the referenced study [47] reported a 187% increase in shear capacity for specimens using polypropylene fibers, this was achieved in combination with shotcrete and additional steel reinforcement (Ø6 mm bars at 150 mm spacing), representing a hybrid system rather than a standalone technique. For standalone polypropylene fiber reinforcement, the available evidence does not demonstrate significant shear capacity enhancement. Therefore, this technique is excluded from the MCDA analysis due to the absence of valid data for standalone applications in reinforced concrete frames with masonry infill walls.

2.2.3 Fiber reinforced polymer (FRP)

FRP is among the most researched materials for wall-strengthening techniques. The most common types used in structural reinforcement include Glass Fibre Reinforced Polymer (GFRP), Carbon Fibre Reinforced Polymer (CFRP), Aramid Fibre Reinforced Polymer (AFRP), and Basalt Fibre Reinforced Polymer (BFRP). GFRP and CFRP are the most frequently applied for infill wall strengthening due to their well-documented performance and availability [37]. Based on the arithmetic mean of available experimental studies [48] with 300%, [49] with 135%, [50] with 247%, [51] with 350%, and [52] with 213%—FRP provides an average shear capacity increase of 249% (Table 11). For the purpose of this study, CFRP was selected as the representative FRP material for cost analysis and performance evaluation. CFRP represents the highest performance option among FRP types and is most extensively documented in the literature for infill wall applications, allowing for consistent comparison with other techniques. Existing analytical models still show differences between the analysis of GFRP and CFRP materials, requiring further study [37]. These differences create uncertainty in design calculations, highlighting the importance of the "Availability of Analytical Models" criterion in the AHP-MCDA framework. FRP exhibits complex durability characteristics that vary significantly across environmental conditions. CFRP experiences significant tensile strength reduction (up to 33%) at 200 °C, with bond strength losses of 80-90% at 250 °C [42]. At 250-350 °C, FRP loses approximately 50% of its strength, with total degradation occurring above 300-400 °C [53]. In fire scenarios, FRP loses up to 90% effectiveness at 150 °C, while TRM maintains 55% under similar conditions. Bond strength deterioration reaches 83% at 150 °C for FRP, compared to TRM which retains 85% up to 400 °C [53].

Moisture absorption in GFRP can reach up to 5.56%, with adhesive modulus decreasing linearly with water content [54]. Cyclic wet-dry exposure causes interfacial cracking, with fracture toughness dropping 70% after 8 weeks of exposure [55]. Bond strength reductions of up to 32% have been observed in high-strength concrete interfaces under moisture conditions [56]. FRP demonstrates excellent performance, particularly CFRP which remains resistant to aggressive environments. FRP wrapping can increase corrosion resistance of steel reinforcement by 300% [57]. CFRP strips have shown tensile strength reductions of 26-38% and shear bond strength reductions of 32-62% over 5 years, with environmental reduction factors (CE) of 0.56-0.69 recommended for 50-year design life [58]. The application of this strengthening technique requires materials such as FRP sheets and epoxy resin [51]. A detailed illustration of the installation can be found in [59]. FRP is supported by comprehensive analytical models that enable reliable structural design. [60] developed a modelling equation as an equivalent strut for FRP-strengthened infill walls. This analytical framework provides engineers with validated equations for predicting the shear capacity contribution of FRP strengthening, enabling efficient and optimized designs. The availability of an equivalent strut model (score 4, Table 16) ensures that FRP can be reliably incorporated into seismic design calculations.

2.3 Bar Addition

This type of strengthening technique uses reinforcing bars to increase the shear and ductile capacity of infill walls and frame-infill systems; the reinforcing elements can be made from conventional steel or natural materials, such as bamboo. The term "Bar Addition" more accurately reflects the range of materials used, as "rebar" typically implies steel reinforcement in engineering terminology. For bamboo reinforcement, the reinforcing elements consist of bamboo strips or rods rather than conventional steel bars.

2.3.1 Bamboo Reinforcement

There are a few references discussing bamboo as a strengthening material, and this material is widely available in the Aceh region, making it worth considering. Studies [61,62] show that bamboo-reinforced brick/masonry walls demonstrate improved performance compared to unreinforced walls. However, it is important to clarify that these studies primarily focused on standalone masonry walls or non-engineered housing, not specifically on reinforced concrete frames with masonry infill walls.

Although effective in independent masonry walls, there is still a lack of quantitative data in the literature regarding its use specifically for strengthening infill walls within reinforced concrete frames. This data gap is a significant limitation, as the interaction between the frame and infill wall, as well as the behavior of bamboo as a reinforcing material under cyclic seismic loading, remains insufficiently documented. Issues regarding the bond (adhesion) of bamboo within concrete or mortar, durability (susceptibility to decay, insect infestation, and moisture absorption), and long-term performance in tropical climates are critical considerations that require further investigation before widespread structural application can be recommended. Consequently, bamboo reinforcement was excluded from the MCDA analysis due to the absence of valid experimental data for standalone applications in RC frames with masonry infill walls. Bamboo reinforcement has limited analytical model availability for infill wall applications. Research [63] developed a material shear equation for bamboo-reinforced concrete panels, but this does not extend to a comprehensive equivalent strut model for infill walls

2.4 External Steel Reinforcement

This type of strengthening technique uses external steel elements to enhance structural performance. The application methods vary depending on the specific technique.

2.4.1 Steel Strip Reinforcement

This technique uses a steel plate or strip attached to the wall surface using mechanical fasteners (screws and anchors) rather than adhesive bonding. Studies by [64] and [65] have demonstrated that the use of steel strip reinforcement effectively improves structural performance. Specifically, [66] reported a shear capacity increase of 214% (Table 11), which serves as the basis for the performance evaluation in this study. The material used for this strengthening technique is a 3-mm-thick steel strip plate, which is fastened with screws at 100 mm spacing on the beam and column, and an L-shaped profile to link the plate to the foundation. The application is primarily mechanical, utilizing screws and anchors rather than adhesives, which facilitates installation but requires careful detailing to ensure proper load transfer.

The durability of steel strip reinforcement is primarily dependent on the material composition. Stainless steel strips (SAE 304) demonstrate excellent resistance to moisture and corrosion, with proven performance in outdoor applications without additional protection [65]). The stainless-steel material provides high corrosion resistance and has been shown to withstand long-term exposure (>5 years) in outdoor environments. However, the technique shows limitations in heat resistance, which is critical in the tropical climate of Aceh. The absence of comprehensive heat resistance data in the reviewed literature, combined with the inherent thermal conductivity of steel, suggests potential vulnerability to high-temperature exposure. Additionally, regular maintenance may be required to ensure connection integrity and prevent localized corrosion at fastener points.

Steel strip reinforcement has limited analytical model availability for infill wall applications. [67] contains the basic concept of the shear capacity of the material, but has not yet reached the configuration stage as reinforcement for infill walls. The absence of a validated equivalent strut model (score 2 out of 4, Table 16) means that engineers cannot reliably predict the contribution of steel strip strengthening in structural analysis.

2.4.2 Post Tensioning

This strengthening technique works by applying additional stress to increase the capacity of the strengthened element. To improve performance, 12-mm-diameter high-strength post-tensioning steel is required, comprising eight bars distributed on both sides of the wall element, and four 0.4 × 0.3 m steel support plates totaling four pieces are necessary. These dimensions represent the specific configuration used in the reference study [68]for infill wall strengthening and were adopted for the cost analysis and performance evaluation in this study. The post-tensioning system applies vertical pressure to the wall through the anchor plates and high-strength steel bars, which increases the compressive stress in the masonry infill, enhances the frame-wall interaction, and improves the overall lateral load resistance of the system.

The durability of post-tensioning systems is critically dependent on the quality of corrosion protection. Heat resistance of post-tensioning systems is not extensively discussed in the reviewed literature, representing a potential vulnerability in fire scenarios. Moisture resistance depends on grout quality and duct integrity [69]. Stainless steel strands show excellent corrosion resistance, nearly free from corrosion, while galvanized steel undergoes severe pitting (Evaluation of corrosion resistance of new and upcoming post-tensioning materials). The technique demonstrates resistance to stress-corrosion cracking in alkaline environments (pH 12.5), with failures occurring only in acidic conditions (pH < 3) [70].

Many post-tensioned bridges have operated successfully for over 60 years, and specimens tested under aggressive exposure conditions for up to 8 years have demonstrated durability when proper protection measures are implemented [71]. Post-tensioning technologies with proper grouting and duct systems can achieve long-term durability exceeding 5 years [72]. Post-tensioning has limited analytical model availability for infill wall strengthening applications. [68] established a straightforward concept regarding the performance of materials on infill walls, but this does not provide a comprehensive equivalent strut model. The technique has a score of 3 out of 4 (Table 16), indicating that while there is a clear conceptual understanding of performance, a validated equivalent strut modelling equation is not yet available.

3. Methodology

The AHP-MCDA framework was chosen because it handles complex multi-criteria decisions by combining quantitative, qualitative, and expert-judgment data. Unlike other methods, AHP breaks down the problem hierarchically and checks the consistency of expert judgment—essential when quantitative data is incomplete. Using AHP to get priority weights from local experts, then MCDA to rank alternatives, creates a decision-support model well-suited to Aceh. This structure also includes sustainability factors like durability and ease of application, which affect the resource use and environmental footprint over the lifecycle of the building intervention

3.1 Research Framework

Based on Figure 1, this research is divided into 4 phases: Literature Review, Analytic Hierarchy Process (AHP), MCDA Framework, and Results.

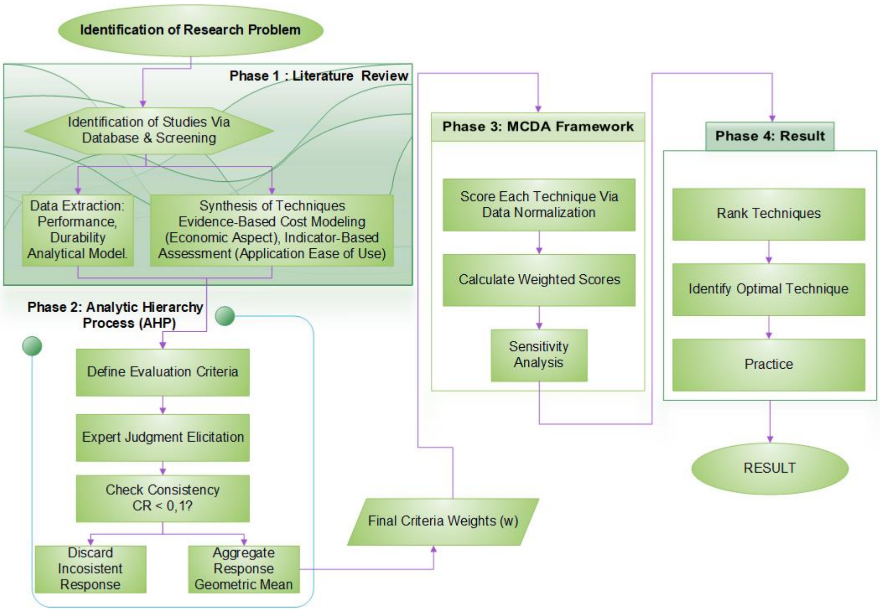

Fig. 1. Flowchart AHP-MCDA framework

3.2 Literature Review Protocol

To ensure a comprehensive and holistic evaluation of the available strengthening techniques, the literature review was not constrained by publication year. This decision was made to address the limited volume of experimental studies available for certain retrofitting materials, particularly when restricted to a narrow recent timeframe. By extending the search horizon to include foundational studies from past decades, the review encompasses the complete historical development, long-term durability assessments, and proven performance of each technique, thereby providing a sufficiently large and robust dataset for the Multi-criteria Decision Analysis. The systematic literature search was primarily conducted using the Scopus and Google Scholar databases, employing specific keywords (detailed in Supplementary Material Tables S1–S6) combined with Boolean operators to maximize relevant article retrieval. Through this unrestricted protocol, a total of 21 studies were identified for the Performance criterion (shear capacity increase), 75 studies for the Durability criterion, and 27 studies for the Availability of Analytical Models criterion, as summarized in Table 2. The detailed inclusion and exclusion criteria, alongside the complete screening process, are provided in the Supplementary Material.

Table 2. Number of studies included from the literature review for each criterion

Criterion	Number of studies
Performance (shear capacity increase)	21
Durability	75
Availability of analytical models	27

3.3 AHP Implementation

The AHP hierarchical structure was developed with four levels based on [73]. The aim was to weight the selection of the best infill strengthening technique for Aceh, which will be used in Phase 3: Multi-Criteria Decision Analysis (MCDA). The hierarchy consists of four levels: Goal (selecting the optimal technique), Criteria (the five main criteria), Sub-criteria (detailed attributes under each criterion), and Alternatives (the eight strengthening techniques).

3.3.1 Determining Selection Criteria and Sub-Criteria

In this phase, the selection criteria for strengthening techniques are developed. From various existing literature, there are several criteria that can be used, including Performance, Economic Aspect, Durability, Application Ease of Use, and Availability of Analytical Model as described in Table 3. The standard [74] implicitly and explicitly requires examination of the shear capacity of these elements, indicating that shear strength is an essential variable in assessing the performance of a building. In the book [75], the contents discuss in depth the mechanism of shear collapse and the importance of capacity design to prevent brittle shear collapse. They emphasize that shear design is a crucial part of the overall seismic-resistance process, indicating that the performance that must be considered in assessing a structure is its shear capacity. Cost is one of the economic aspects that must be reviewed in the assessment of a construction [76]. In [77], cost is a carefully calculated aspect, including materials, tool use, work methods, and worker ability. However, in this case, the review of strengthening technique selection focuses on the cost of materials and equipment, as these are the main factors in determining the unit price of the work.

Most of the damage in concrete structures is not caused by load failure, but by material degradation, thus confirming that durability is not an additional property but a fundamental need [78], even in the standard [79], there is a special chapter on durability criteria. Therefore, in decision-making, durability must be considered, particularly in the Aceh region. Resistance to heat, moisture, and corrosion, a service life of more than 5 years, and the absence of periodic maintenance are crucial factors. Durability directly contributes to sustainable construction by extending the service life of retrofitted buildings and reducing the frequency of repair interventions, thereby lowering long-term material and energy consumption.

Table 3. Sub-Criteria of Criteria Selecting Strengthening Technique

SC \ C	P	EA	D	AEOU	AOAM
1	Increase Shear Capacity	Requires the lowest material cost	Resistant to heat	Can be done by one person	Never been researched before
2			Resistant to moisture	No special equipment required	There has never been an equation at all
3			Resistant to corrosion	No need for special materials	There is a material shear equation
4			Can last more than 5 years	Does not require regular maintenance	There is a straight forward concept regarding the performance of materials on infill walls.
5				Materials available in Aceh	There is a modelling equation as an equivalent strut

**C: Criteria, SC: Sub-Criteria, P: Performance, EA: Economic Aspect, D: Durability, AEOU: Application Ease of Use, AOAM: Availability of Analytical Model*

The buildability principle in the book [9] requires that designs priorities materials and methods that are easy to apply, locally available, and do not require complex maintenance to ensure cost and time efficiency. For this reason, in conducting a literature review of articles, it is necessary to consider that the work can be done individually, does not require special equipment or materials, does not require periodic or special maintenance, and that materials are available in the Aceh region. Emphasizing locally sourced materials not only simplifies logistics but also minimizes the carbon footprint associated with transportation, aligning with energy-saving technological principles. In [76] assessment of the existing structure requires detailed analysis, which in turn necessitates structural analysis. The assessment results necessitate conceptual design, intervention, and risk control. This is not possible if the selected strengthening technique cannot be modelled for structural analysis, which in turn cannot produce a justified conceptual design.

3.3.2 Expert Data Collection

Data collection was conducted with ten construction experts residing in Aceh. Respondents were selected from state officials in charge of conducting building feasibility testing and recommending improvements to state buildings (Aceh Public Housing and Settlement Areas Office), academics/ researchers, practitioners from contractors or consultants, and must be domiciled in Aceh. Respondents must have at least 5 years of work experience, as summarized in Table 4.

Table 4. List of experts

No.	Expert Category	Number of Experts
1	Government Officials	4
2	Academics / Lecturers	4
3	Practicing Structural Engineers / Consultants	2
	Total	10

This balanced representation ensures that the AHP weights reflect perspectives from regulation (government), academic theory, and practical field implementation. Each expert was asked to provide pairwise comparisons using a structured elicitation sheet Table 5, and the results were entered into the pairwise comparison matrix as shown in equation (1).

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & a_{14} & a_{15} \\ 1/a_{12} & 1 & a_{23} & a_{24} & a_{25} \\ 1/a_{13} & 1/a_{23} & 1 & a_{34} & a_{35} \\ 1/a_{14} & 1/a_{24} & 1/a_{34} & 1 & a_{45} \\ 1/a_{15} & 1/a_{25} & 1/a_{35} & 1/a_{45} & 1 \end{bmatrix} \quad (1)$$

Table 5. Definition of pairwise score matrix

Score	Intensity of Interest	Definition
1	(Equal Importance)	Both elements are equally important.
3	(Moderate Importance)	Experience and judgment slightly favor one element over another.
5	(Strong Importance)	Experience and judgment strongly favor one element over another.
7	(Very Strong Importance)	One element is very dominant, and its importance is evident in practice.
9	(Extreme Importance)	Evidence that supports one element over another has the highest level of corroboration possible.

**The even numbers 2, 4, 6, and 8 represent intermediate values between adjacent scale values.*

3.3.3 AHP Calculation Procedure

After the experts' data are obtained and compiled into a Pairwise Comparison Matrix, the AHP calculation is performed. All AHP calculations were performed using Microsoft Excel.

- Expert Rating Aggregation (AIJ)

To aggregate the individual judgments of ten experts, the geometric mean of the K expert opinions associated with each cell (AIJ) is calculated using the Aggregating Individual Judgments (AIJ) method using equation (2) [80].

$$a_{ij}^{group} = \left(\prod_{k=1}^{K} a_{ij}^{(k)}\right)^{1/K} \tag{2}$$

Where a_{ij}^{group} = aggregated pairwise comparison value between criterion i and criterion j $a_{ij}^{(k)}$= pairwise comparison value provided by expert k; K = number of experts (K = 10).

- Priority Weight Calculation

The priority weight calculation was performed using the Normalized Matrix Method (Row Average);

- Step 1: Normalize each column of the pairwise comparison matrix using equation (3);
- Step 2: Calculate the priority weight using the normalized matrix method (4) ;
- Step 3: Calculate the Maximum Eigenvalue using equation (5) and (6).

$$n_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \tag{3}$$

$$w_i = \frac{1}{n}\sum_{j=1}^{n} n_{ij} \tag{4}$$

$$\lambda_i = \frac{(A.w)_i}{w_i} \ ; \ i = 1,2,\ldots,n \tag{5}$$

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \lambda_i \tag{6}$$

w_i is priority weight for criterion I; n_{ij} is normalised value in row i, column j , A is original pairwise comparison matrix; w is priority vector (weights); (A·w)I is i-th component of the product of matrix A with vector w; n is number of criteria (n = 5)

- Consistency Test

The Consistency Index (CI) is calculated using equation (7). The Consistency Ratio (CR) is calculated using the following equation (8). The value of RI, obtained from the random index table by [73], which is shown in Table 6.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{7}$$

$$CR = \frac{CI}{RI} \tag{8}$$

Table 6. Random Index Value (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

If CR ≤ 0.10, the data are consistent and can be used; if CR > 0.10, the experts must re-evaluate their pairwise comparisons or replace other experts. In this study, all 10 experts' pairwise comparison matrices met the CR ≤ 0.10 threshold (CR = 0.0246) in the first round; therefore, no data were excluded or re-evaluated. The aggregated pairwise comparison matrix also passed the consistency test

3.4 Scoring the Criteria

Before integrating with the MCDA framework, the sub-criteria for each assessed criterion must first be defined, and scores must be assigned to the criteria to enable proper quantification of the assessment.

3.4.1 Criteria Based on Literature Review

The performance of each strengthening technique was evaluated based on its shear strength improvement. For each technique, the arithmetic mean of shear capacity increases was calculated from all available experimental studies identified in the structured literature review, rather than relying solely on the maximum reported value, to avoid optimistic bias. These mean values were then directly used in the initial MCDA decision matrix. Durability was assessed using evidence from the sub-criteria listed in the durability column of Table 3 (resistant to heat, resistant to moisture, resistant to corrosion, can last more than 5 years). Scoring was based on the number of sub criteria satisfied by each strengthening technique, as defined in Table 7.

Table 7. Scoring of durability criteria

Sub-Criteria	Scoring
Resistant to heat Resistant to moisture Resistant to corrosion Can last more than 5 years	$\sum[\text{Sub} - \text{Criteria}]$

The availability of analytical models' criterion was evaluated by checking whether the reviewed articles for each strengthening technique satisfied any of the sub-criteria listed in Table 8. The highest level fulfilled determined the score.

Table 8. Scoring of availability of analytical models

Score	Sub-Criteria
1	Limited literature and lack of equations (combined from previously separate categories)
2	There is a material shear equation
3	There is a straightforward concept regarding the performance of materials on infill walls
4	There is a modelling equation as an equivalent strut

3.4.2 Criteria based on Market Survey and Practical Assessment

Criteria for which quantitative data were unavailable from the literature review were evaluated through cost simulations and practical applicability assessments. The assessed aspects are described below. The economic aspect was assessed by estimating the material cost of applying each strengthening technique per 1 m^2 of wall area. The unit price was calculated using the material components specified in the same article selected for the performance evaluation. Because some materials are not locally available, all prices were surveyed from online marketplaces, including shipping costs to the Construction and Building Materials Laboratory (LKBB) in Aceh Province, to ensure consistent treatment. The raw cost data (in Rp/m^2) were entered directly into the initial MCDA decision matrix. The Normalization of this cost criterion is handled exclusively by the Linear Min-Max Normalization formula for cost criteria using equation (11), which automatically assigns the highest score (1.00) to the cheapest alternative and the lowest score (0.00) to the most expensive one. The application ease of Use criterion was assessed based on the sub-criteria listed in Table 9. The score for each strengthening technique equaled the number of sub criteria it satisfied.

Table 9. Scoring of application ease of use

Sub-Criteria	Scoring
Requires a specialised crew No special equipment required No need for special materials Does not require regular maintenance Materials available in Aceh	$\sum[\text{Sub} - \text{Criteria}]$

These five criteria — structural performance, economic aspect, durability, application ease of use, and availability of analytical models — were identified as the most critical determinants for the successful selection and implementation of infill wall strengthening techniques in Aceh, based on an in-depth review of international literature and civil engineering standards, and were comprehensively assessed by local Acehnese experts.

3.5 MCDA Integration

After completing the Analytic Hierarchy Process (AHP), the weighted scores will be used to calibrate the results in the multi-criteria decision analysis. The Linear Max-Min Normalization method was selected because it preserves the relative distances between alternative values and is straightforward for mixed criteria (including both benefit and cost types), making it highly suitable for our framework

3.5.1 Initial Decision Matrix (X)

Results of scoring criteria, based on sub-criteria, are plotted in the initial decision matrix as follows.

$$x = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ x_{12} & x_{22} & x_{23} & x_{24} & x_{25} \\ x_{13} & x_{32} & x_{33} & x_{34} & x_{35} \\ x_{14} & x_{42} & x_{43} & x_{44} & x_{45} \\ x_{15} & x_{52} & x_{53} & x_{54} & x_{55} \\ x_{16} & x_{62} & x_{63} & x_{64} & x_{65} \end{bmatrix} \tag{9}$$

where: Rows (i =1, 2, …,6) represent the six strengthening techniques evaluated in this study; Columns (j =1,2, …,5) represent the five evaluation criteria.

3.5.2 Normalization of Decision Matrix (R)

To normalize the initial decision matrix, the Linear Max-Min Normalization is used to normalize the value r_{ij} by using this equation [81]. For benefit criteria (where higher values are better, such as Performance, Durability, AEOU, and AOAM), equation (10) is used. For the cost criterion (Economic Aspect, where lower values are better), equation (11) is used. Linear Max-Min Normalization preserves the relative distances between alternatives and is straightforward for mixed criteria (benefit and cost), making it suitable for our MCDA framework.

$$r_{ij} = \frac{x_{ij} - min_i(x_{ij})}{max_i(x_{ij}) - min_i(x_{ij})} \tag{10}$$

$$r_{ij} = \frac{max_i(x_{ij}) - x_{ij}}{max_i(x_{ij}) - min_i(x_{ij})} \tag{11}$$

3.5.3 Weighted Matrix (V)

At this stage, the normalization matrix is multiplied by the weights obtained from the AHP process using equation (12) where w_j are the AHP weights and must satisfy equation (13). The final score for each alternative is then calculated using equation (14).

$$V = v_{ij} = w_j . r_{ij} \tag{12}$$

$$\sum_{j=1}^{n} w_j = 1 \tag{13}$$

$$S_i = \sum_{j=1}^{n} v_{ij} \tag{14}$$

3.5.4 Aggregation Final Result

Since the normalized matrix has been obtained, the aggregation is performed by summing the weighted normalized values for each alternative. Techniques are then ranked according to these final scores.

3.5.5 Sensitivity Analysis

To ensure the generated data is robust, a sensitivity analysis is conducted by simulating five scenarios in Table 10. The scenarios represent different decision-making priorities: BASE reflects the original expert weights; AS.1 emphasizes technical aspects (Performance and Durability); AS.2 emphasizes economics and ease of application; AS.3 emphasizes the availability of analytical models; AS.4 is a control scenario with equal weights (independent of expert opinion) to test model stability; and AS.5 heavily prioritizes ease of application (40%) to represent an extreme case where practical constructability is the overriding concern.

Table 10. Scenario of sensitivity analysis

Scenario	P	EA	D	AEOU	AOAM
BASE	25.51%	24.81%	19.19%	12.89%	17.60%
AS.1	30.00%	21.50%	24.00%	11.20%	13.30%
AS.2	20.00%	30.00%	16.50%	18.00%	15.50%
AS.3	22.00%	22.00%	17.00%	11.00%	28.00%
AS.4	20.00%	20.00%	20.00%	20.00%	20.00%
AS.5	15.00%	20.00%	15.00%	40.00%	10.00%

**P: Performance, EA: Economic Aspect, D: Durability, AEOU: Application Ease of Use, AOAM: Availability of Analytical Model.*

4. Result

The findings are organized sequentially, beginning with the criteria weights obtained through the analytical hierarchy process. The individual performance of each strengthening technique is then assessed against the five evaluation criteria, leading to an integrated MCDA ranking. A sensitivity analysis confirms the stability of the final recommendation under varied weighting scenarios.

4.1 AHP Results: Criteria Weighting

The Analytic Hierarchy Process (AHP) successfully produced a prioritized set of criteria weights based on assessments by 10 local experts in Aceh as mentioned in Table 4. These results provide a quantitative foundation for determining the relative importance of each criterion in selecting strengthening techniques.

4.2 Pairwise Comparison and Consistency Ratio (CR)

Based on the results of expert data collection, the average pairwise comparison matrix is obtained for all respondents using equation (2) as shown in matrix (15).

$$A = \begin{bmatrix} 1 & 1 & 1.92 & 1.73 & 1.25 \\ 1 & 1 & 1.58 & 2.18 & 1.07 \\ 0.52 & 0.63 & 1 & 2.19 & 1.25 \\ 0.58 & 0.46 & 0.46 & 1 & 1 \\ 0.80 & 0.93 & 0.8 & 1 & 1 \end{bmatrix} \tag{15}$$

Matrix Normalization was performed according to equation (3). The resulting λ_{max} value is 5.11. The CI value obtained is 0.0275. Because the number of criteria is 5, the RI value from Table 6 is 1.12. Consequently, the CR is 0.0246, far below the threshold of 0.10, indicating that the pairwise comparison assessment of experts has a very high level of consistency. This shows that the responses are not random but logical and consistent, hence reliable. Hence, the criteria weights generated through the AHP process are valid and reliable for use in further decision-making analysis.

4.2.1 Criteria Prioritization

Based on the assessments of ten local experts in Aceh, the Analytic Hierarchy Process (AHP) produced the following priority weights (Figure 2): Performance (25.51%), Economic Aspect (24.81%), Durability (19.19%), Availability of Analytical Models (17.60%), and Application Ease of Use (12.89%). The aggregated pairwise comparison matrix showed high consistency (CR = 0.0246 < 0.10). This weight distribution reflects the local priorities where structural performance and cost considerations are the most critical factors; the significant weight given to analytical model availability also underscores the importance of a robust modelling foundation in the design and evaluation of strengthening techniques.

The close weighting between Performance (25.51%) and Economic Aspect (24.81%)—a difference of only 0.7%—demonstrates that experts in Aceh attach as much importance to cost constraints as to seismic safety. This near-equal weighting justifies the study's preference for "low-cost yet effective" solutions such as Ferrocement, which balances technical performance with economic feasibility. The substantial weight attributed to the availability of analytical models (17.60%) reflects the importance experts place on "calculable and reliable" design. This high weight also relates to professional engineering accountability, as engineers require validated analytical models to justify their designs to authorities and insurers.

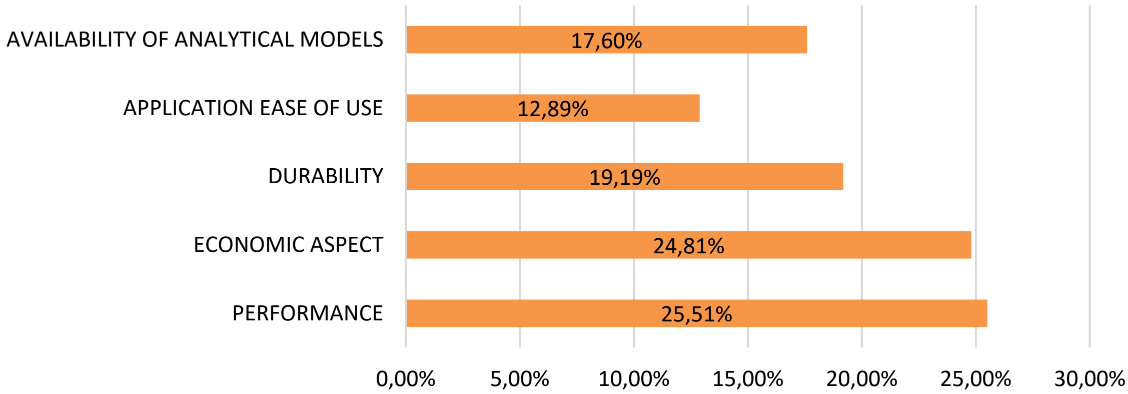

Fig. 2. Result of analytical hierarchy process

4.3 Assessment of Strengthening Techniques Based on Criteria

The assessment of the criteria was carried out according to the procedure outlined in the methodology section. The results obtained are described as follows.

4.3.1 Performance

Performance data were obtained from a structured literature review using arithmetic mean values of shear capacity increases from all available experimental studies, rather than relying solely on maximum reported values, to avoid optimistic bias. The results are summarized in Table 11.

Table 11. Performance of strengthening techniques based on literature review and MCDA evaluation

Strengthening Technique	Avg. Shear Capacity Increase (%)
Shotcrete with Reinforcement	177%
Ferrocement	161%
Textile Reinforced Mortar (TRM)	150%
Steel Strip Reinforcement	214%
Fiber Reinforced Polymer (FRP)	249%
Post-Tensioning	160%

**Polypropylene Fiber Reinforcement and Bamboo Reinforcement are excluded from the MCDA analysis due to insufficient valid data for standalone applications in reinforced concrete infill walls (see Section 5.3 for discussion). The shear capacity values represent the arithmetic mean of all available experimental studies identified in the structured literature review.*

The FRP technique shows the most significant increase in shear capacity, followed by steel strip reinforcement, shotcrete with reinforcement, ferrocement, post-tensioning, and TRM. Data on the improvement of bamboo and polypropylene as standalone techniques could not be obtained because their use in reinforced concrete frames with infill walls was not found using the keywords described in the methodology section. Figure 3 shows the radar diagrams of the performance capacities of the strengthening techniques reviewed.

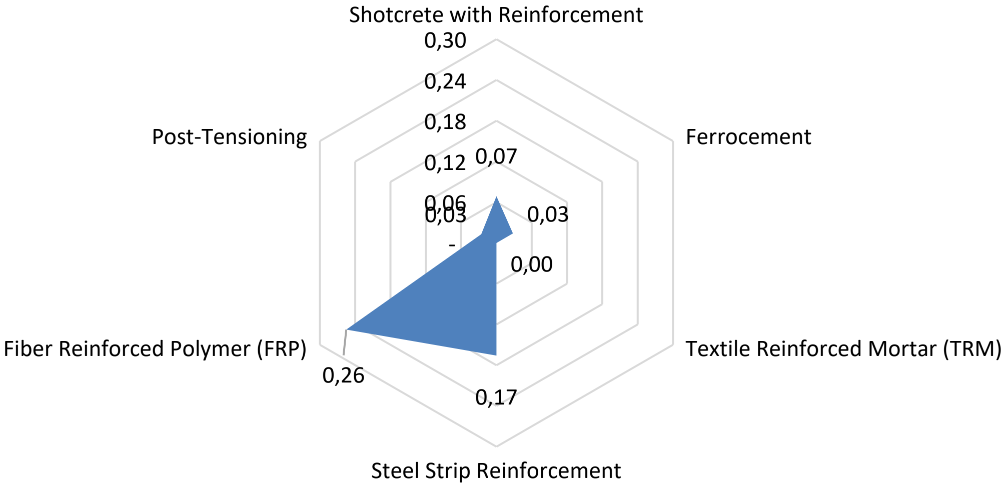

Fig. 3. Diagram of strengthening technique's performance

4.3.2 Economic Aspect

The calculation of material costs per meter was based on an online price survey, including shipping costs to the LKBB at Syiah Kuala University. This was done to ensure equal treatment of all reinforced engineering material components under review. Table 12 includes equivalent values in US Dollars ($) at an exchange rate of Rp16,691.13 per USD (as of the survey date). Table 12 indicates that Textile Reinforced Mortar (TRM) has the highest cost (Rp3,650,718.41 per m^2) and therefore receives the poorest score, resulting in a final score of 0.00. Conversely, Ferrocement is among the most economical techniques (Rp120,243.73 per m^2) with the best score and a final score of 0.25. The other techniques have relatively lower costs than TRM and receive favorable economic scores. This indicates that, from an economic perspective, conventional techniques such as Ferrocement are more economically competitive, while TRM and FRP tend to be less affordable within construction budgets in Aceh. The radar diagram for the economic aspect is shown in Figure 4.

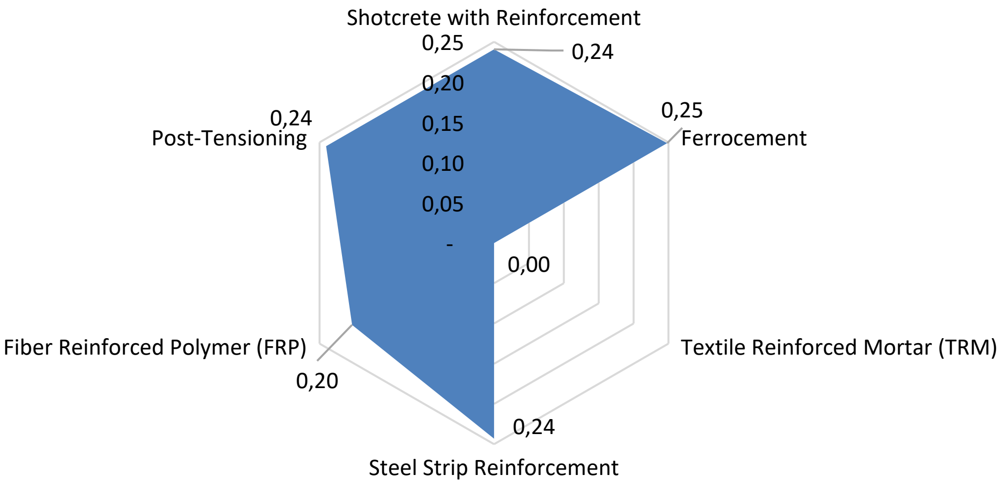

Fig. 4. Diagram of economic aspects of strengthening techniques

Table 12. Economic aspect assessment results

Strengthening Technique	Cost Estimate (Rp/M^2)	Cost Estimate (USD/m^2)
Shotcrete with Reinforcement	Rp239,129.09	USD 14.33
Ferrocement	Rp120,243.73	USD 7.20
Textile Reinforced Mortar (TRM)	Rp3,650,718.41	USD 218.72
Steel Strip Reinforcement	Rp204,941.47	USD 12.28
Fiber Reinforced Polymer (FRP)	Rp760,960.40	USD 45.59
Post-Tensioning	Rp225,935.00	USD 13.54

4.3.3 Durability

The durability assessment was carried out as part of a literature review; the results are shown in Table 13. The following results were obtained from the literature review to assess durability. The results of the durability criteria assessment, summarized in Table 13 and detailed in Table 14, showed significant variations in durability among the various strengthening techniques. Ferrocement and TRM exhibited the highest durability scores (4 out of 4), demonstrating resistance to heat, moisture, and corrosion, as well as a service life exceeding 5 years. In contrast, Shotcrete with Reinforcement was assigned a score of 2 out of 4, reflecting its limited heat resistance (compressive strength declines markedly above 150 °C) and its notable corrosion risk in persistently humid environments due to steel fiber degradation. FRP also scored 2 out of 4, as its heat vulnerability (up to 90% effectiveness loss at 150 °C) and significant moisture absorption (5.56% in GFRP, with 70% fracture toughness reduction) preclude it from being classified as fully durable. Steel Strip Reinforcement and Post-Tensioning both scored 3 out of 4, lacking comprehensive heat resistance data despite excellent performance in moisture and corrosion resistance. These findings highlight the importance of considering local environmental conditions—particularly Aceh's tropical humid climate—when selecting sustainable strengthening techniques. Scoring was based on the number of sub-criteria satisfied (Table 7); the radar diagram for this criterion is shown in Figure 5.

Table 13. Summary of durability from Literature Review

Strengthening Technique	$\sum$[Sub − Criteria]
Shotcrete with Reinforcement	2
Ferrocement	4
Textile Reinforced Mortar (TRM)	4
Steel Strip Reinforcement	3
Fiber Reinforced Polymer (FRP)	2
Post-Tensioning	3

Table 14. Assessment results of the durability criterion through literature review

Strengthening Technique	Resistant to heat	Resistant to moisture	Resistant to corrosion	Can last more than 5 years
Shotcrete with Reinforcement	-	✓	-	✓
Ferrocement	✓	✓	✓	✓
Textile Reinforced Mortar (TRM)	✓	✓	✓	✓
Steel Strip Reinforcement	-	✓	✓	✓
Fiber Reinforced Polymer (FRP)	-	-	✓	✓
Post-Tensioning	-	✓	✓	✓

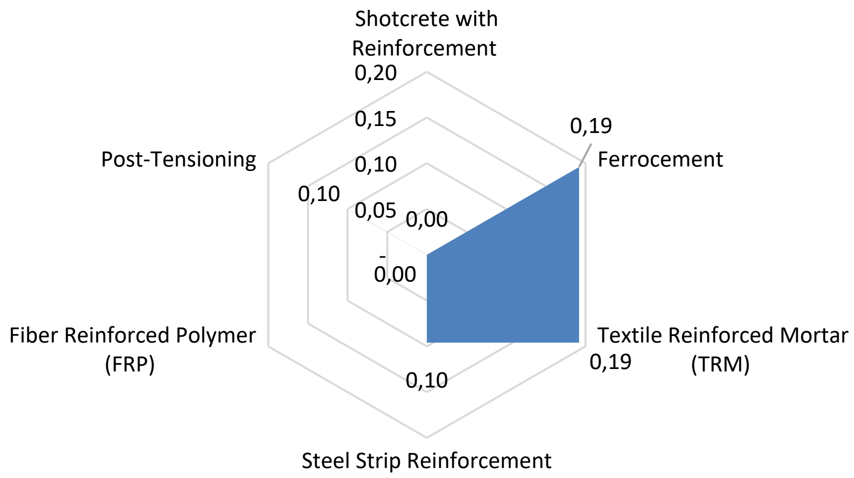

Fig. 5. Strengthening technique durability diagram

The durability assessment, as summarized in Table 14, indicates that while Ferrocement, TRM, Steel Strip Reinforcement, and Post-Tensioning demonstrate resistance to both moisture and corrosion, Shotcrete with Reinforcement exhibits notable corrosion vulnerability in humid environments, and FRP shows significant susceptibility to moisture degradation. While all six techniques demonstrate the ability to last more than five years, heat resistance emerges as the primary distinguishing factor. Ferrocement and Textile Reinforced Mortar (TRM) exhibit robust performance across all four durability sub-criteria. In contrast, Shotcrete with Reinforcement shows limitations in both heat resistance and corrosion resistance. Steel Strip Reinforcement and Post-Tensioning show limitations only in heat resistance, while fulfilling the other durability requirements.

4.3.4 Application Ease of Use

Based on the assessment of the Ease of Application criterion, as seen in Figure 6, Ferrocement achieved the highest score as it met almost all sub-criteria: it requires only a specialized crew rather than a single person, does not require specialized equipment, uses materials available in Aceh, and does not require complex routine maintenance. A complete overview of how the criteria is met can be seen in Table 15. In contrast, techniques such as Post-Tensioning and Fiber Reinforced Polymer (FRP) scored lower due to their reliance on specialized equipment, limited availability of locally sourced materials, and higher technical skill requirements. These results confirm that suitability to the local context, in terms of material resources, labor, and facilities, is a determining factor in the successful implementation of strengthening techniques in Aceh.

Table 15. Assessment results for the application ease of use criterion

Strengthening Technique	Requires a specialized crew	No special equipment required	No need for special materials	Does not require regular maintenance	Materials available in Aceh
Shotcrete with Reinforcement	-	-	✓	✓	✓
Ferrocement	✓	✓	✓	✓	✓
Textile Reinforced Mortar (TRM)	✓	✓	-	✓	-
Steel Strip Reinforcement	✓	✓	-	✓	✓
Fiber Reinforced Polymer (FRP)	✓	✓	-	✓	-
Post-Tensioning	✓	✓	✓	-	✓

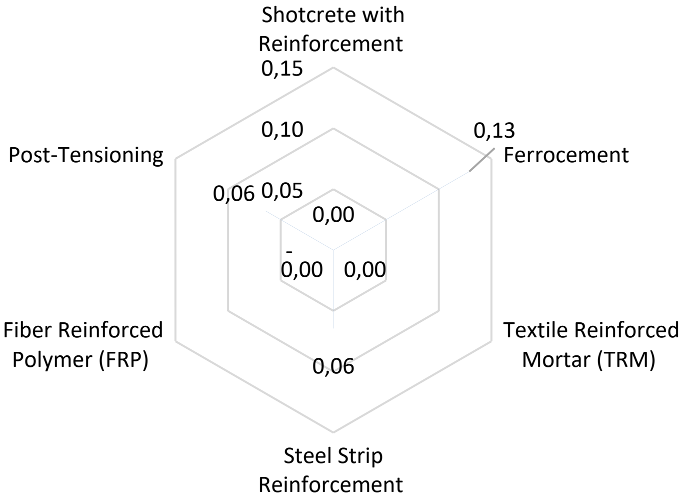

Fig. 6. Diagram of ease of application of strengthening techniques

4.3.5 Availability of Analytical Models

To assess the availability of analytical models for each strengthening technique, a dedicated literature review was performed, and the resulting scores for this criterion are presented in Table 16.

Table 16. Recapitulation of analytical model availability

Strengthening Technique	$\sum$[Sub – Criteria]
Shotcrete with Reinforcement	4
Ferrocement	4
Textile Reinforced Mortar (TRM)	4
Steel Strip Reinforcement	2
Fiber Reinforced Polymer (FRP)	4
Post-Tensioning	3

** Score definitions: 1 = Limited literature and lack of equations; 2 = There is a material shear equation; 3 = There is a straightforward concept regarding the performance of materials on infill walls; 4 = There is a modelling equation as an equivalent strut.*

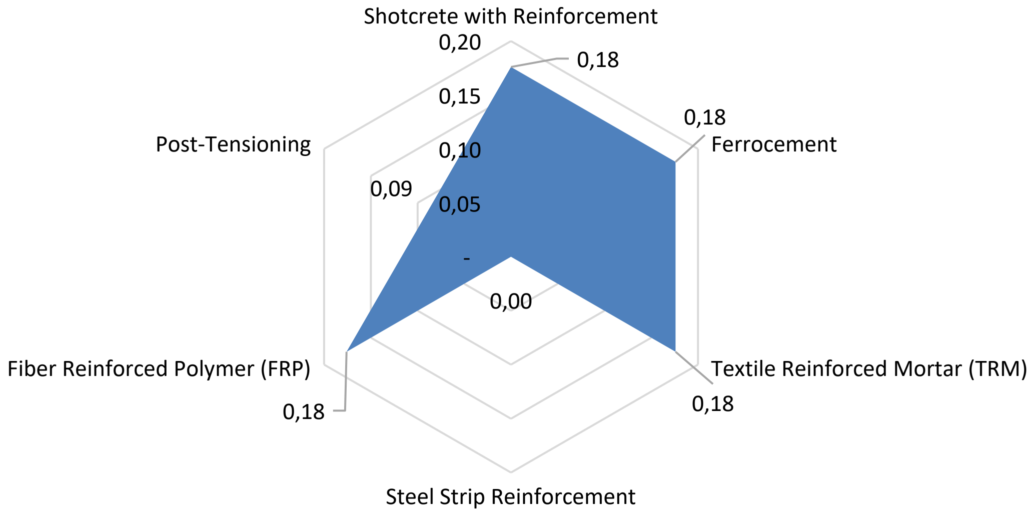

Fig. 7. Availability diagram of analytical model of strengthening technique

Based on the assessment of analytical model availability, the majority of strengthening techniques—such as Shotcrete with Reinforcement, Ferrocement, Textile Reinforced Mortar (TRM), and Fiber Reinforced Polymer (FRP)—show high model maturity, with a maximum score of 4 (MCDA value of 0.18). This indicates that these techniques are supported by modelling equations as equivalent struts, enabling reliable structural analysis for earthquake resistance planning. Steel Strip Reinforcement (score 2) lacks a comprehensive analytical model, so its application requires further experimental studies. The inability to perform reliable design calculations due to the absence of validated models presents a significant engineering risk. These results confirm that the availability of comprehensive analytical models is a critical factor in assessing the feasibility of strengthening techniques for implementation in seismic regions such as Aceh. The diagram for this criterion is shown in Figure 7. The availability of analytical models serves as a guide for engineers in designing structures that use strengthening techniques; this is certainly a critical aspect that must be considered in studies.

4.4 AHP-MCDA Integration Results

The assessment was carried out, followed by the integration of the weights obtained from the AHP process using Equation (12). The subjective expert opinions (weights) from Phase 2 were combined with the objective literature and survey data (performance, cost, durability, etc.) from Phase 3 through the weighted matrix multiplication.

4.4.1 Decision Matrix and Normalization

Based on the assessment for each criterion, the scores are entered into the decision matrix, as shown below:

$$x = \begin{bmatrix} 177\% & Rp.239{,}129.09 & 2 & 3 & 4 \\ 161\% & Rp.120{,}243.73 & 4 & 5 & 4 \\ 150\% & Rp.3{,}650{,}718.00 & 4 & 3 & 4 \\ 214\% & Rp.204{,}941.47 & 3 & 4 & 2 \\ 249\% & Rp.760{,}960.00 & 2 & 3 & 4 \\ 160\% & Rp.225{,}935.00 & 3 & 4 & 3 \end{bmatrix} \tag{15}$$

The initial decision matrix was normalized by applying equations (10) and (11) to each criterion according to its optimization direction (maximization or minimization), and the resulting normalized matrix is presented in Table 17. By integrating the MCDA process with AHP, the normalized scores in Table 17 are multiplied by the AHP weights, yielding the integrated scores presented in Table 18.

Table 17. The normalized decision matrix

Strengthening Technique	Performance (Maximize)	Economic Aspect (Minimise)	Durability (Maximize)	Application Ease Of Use (Maximize)	Availability Of Analytical Models (Maximize)
Shotcrete with Reinforcement	0.27	0.97	0.00	0.00	1.00
Ferrocement	0.11	1.00	1.00	1.00	1.00
Textile reinforced mortar (TRM)	0.00	0.00	1.00	0.00	1.00
Steel strip reinforcement	0.65	0.98	0.50	0.50	0.00
Fiber reinforced polymer (FRP)	1.00	0.82	0.00	0.00	1.00
Post-tensioning	0.10	0.97	0.50	0.50	0.50

Table 18. AHP-MCDA integration

Strengthening Technique	P	EA	D	AEOU	AOAM	Final Score
	25.51 %	24.81 %	19.19 %	12.89 %	17.60 %	100.00 %
Shotcrete with Reinforcement	0.07	0.24	0.00	0.00	0.18	0.49
Ferrocement	0.03	0.25	0.19	0.13	0.18	0.77
Textile Reinforced Mortar (TRM)	0.00	0.00	0.19	0.00	0.18	0.37
Steel Strip Reinforcement	0.17	0.24	0.10	0.06	0.00	0.57
Fiber Reinforced Polymer (FRP)	0.26	0.20	0.00	0.00	0.18	0.63
Post-Tensioning	0.03	0.24	0.10	0.06	0.09	0.51

**C: Criteria, SC: Sub-Criteria, P: Performance, EA: Economic Aspect, D: Durability, AEOU: Application Ease of Use, AOAM: Availability of Analytical Model.*

4.5 Final Ranking of Strengthening Techniques

Based on Table 19 and Figure 8, Ferrocement achieved the highest MCDA score of 0.77, securing the first-place ranking. Its success stems from an exceptional balance across all five criteria: a 161% shear capacity increase (Table 11), the lowest material cost among all techniques (Rp120,243.73/m^2, normalized score 1.00), superior durability (resistant to heat, moisture, and corrosion with a service life exceeding 5 years, normalized score 1.00), outstanding ease of application using locally available materials (normalized score 1.00), and mature analytical models (score 4, equivalent strut model available, normalized score 1.00).

Ferrocement's comprehensive strengths are further reinforced by its minimal maintenance requirements. Unlike techniques that demand periodic re-tensioning (post-tensioning), reapplication of protective coatings (FRP), or specialized fastener inspections (steel strip reinforcement), ferrocement is applied as a monolithic layer that integrates with the existing structure. It contains no mechanical joints, moving parts, or detachable components that necessitate regular replacement or adjustment. The material's inherent crack-arrest mechanism, dense mortar matrix, and uniform reinforcement dispersion provide long-term structural integrity without demanding specialized ongoing interventions. Routine visual inspection, which is a standard good practice for any durable infrastructure, does not constitute the 'regular maintenance' that would penalize a technique in the MCDA assessment. This characteristic confirms its perfect score in the 'Application Ease of Use' criterion (Table 15). While no technique is entirely maintenance-free, ferrocement's maintenance burden is limited to simple, low-cost visual checks—far less demanding than the specialized interventions required by competing techniques—making it particularly suitable for resource-limited settings such as Aceh.

Fiber Reinforced Polymer (FRP) ranked second with an MCDA score of 0.63. FRP's superior shear capacity (249% average increase, normalized score 1.00) and mature analytical models (score 4, normalized score 1.00) were insufficient to overcome its significant limitations; specifically, the corrected durability assessment revealed that FRP is not resistant to heat (losing up to 90% effectiveness at 150 °C) and is susceptible to moisture degradation (up to 5.56% absorption and 70% fracture toughness reduction), resulting in a durability normalized score of 0.00. Additionally, its high cost (Rp760,960.40/m^2, normalized score 0.82) and low ease of application (requires specialized equipment and materials not available in Aceh, normalized score 0.00) further penalized its overall performance. Steel Strip Reinforcement ranked third with an MCDA score of 0.57, improving its rank due to the recalibrated scoring. Its high shear capacity (214%, normalized score 0.65) and good economic performance (Rp204,941.47/m^2, normalized score 0.98) are offset by limited heat resistance and the absence of a validated equivalent strut model (score 2 out of 4, normalized score 0.00). This lack of analytical model availability presents a significant engineering risk for design applications.

Post-Tensioning ranked fourth with an MCDA score of 0.51, benefiting from moderate performance (160% shear capacity increase), competitive cost (Rp225,935.00/m^2, normalized score 0.97), and moderate analytical model availability (score 3 out of 4, normalized score 0.50). However, it was constrained by its limited heat resistance (normalized score 0.00) and very low ease of application (requires specialized hydraulic equipment, normalized score 0.00). Shotcrete with Reinforcement dropped to fifth place with an MCDA score of 0.49, a significant decline from its previous ranking. Despite its moderate shear capacity (177%, normalized score 0.27) and mature analytical models (score 4, normalized score 1.00), the corrected durability assessment—acknowledging its limited heat resistance (compressive strength declines above 150 °C) and notable corrosion risk in humid environments—resulted in a durability normalized score of 0.00. Its low ease of application (normalized score 0.00) further constrained its ranking.

Table 19. Final Ranking of Strengthening Techniques

Strengthening Technique	MCDA Score
Shotcrete with Reinforcement	0.49
Ferrocement	0.77
Textile Reinforced Mortar (TRM)	0.37
Steel Strip Reinforcement	0.57
Fiber Reinforced Polymer (FRP)	0.63
Post-Tensioning	0.51

Textile Reinforced Mortar (TRM) consistently occupied the lowest rank with an MCDA score of 0.37. Despite excellent durability (score 4, normalized score 1.00) and mature analytical models (score 4, normalized score 1.00), TRM was severely penalized by its prohibitive cost (Rp3,650,718.41/m^2, the most expensive among all techniques, normalized score 0.00) and low ease of application (requires special materials not available in Aceh, normalized score 0.00). These economic and practical barriers render it unsuitable for widespread application in resource-limited settings such as Aceh. These results demonstrate that techniques offering an optimal balance among structural performance, economic factors, durability, ease of application, and analytical model availability dominate the top rankings. Ferrocement's first-place ranking confirms that balanced performance across all criteria—rather than excellence in a single attribute provides the most sustainable and resilient solution for Aceh's specific conditions.

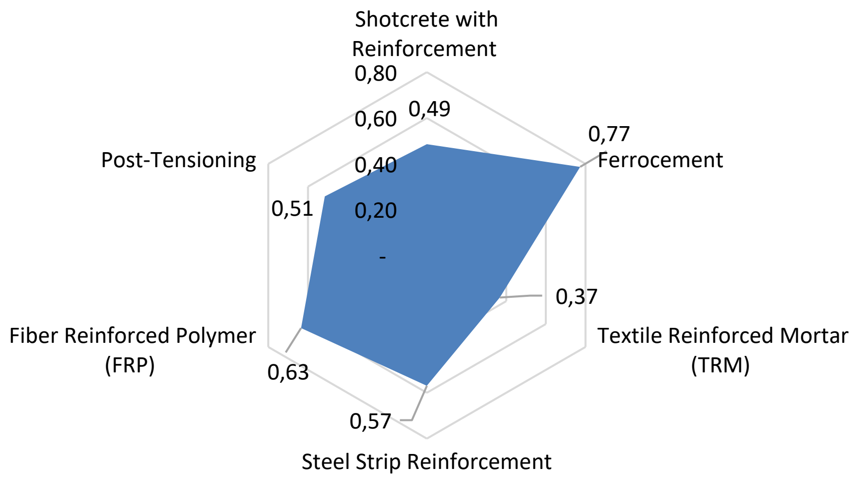

Fig. 8. MCDA diagram of strengthening technique

4.6 Sensitivity Analysis

To ensure the robustness of the generated data, a sensitivity analysis was conducted by simulating five alternative weighting scenarios (AS.1 to AS.5) against the original BASE scenario. The numerical weights and descriptions for each scenario are consolidated in Figure 9, allowing the reader to directly observe how weight changes affect the rankings. The results demonstrate that Ferrocement consistently ranked first or second across all scenarios, confirming its status as the most robust and superior option under various prioritization criteria. Notably, Ferrocement remained competitive even when the weight of seismic performance was substantially increased to 30% in AS.1, securing the first position (0.73), outperforming FRP (0.61), and achieved the first position in the economically oriented scenario (AS.2) and the equal-weight control scenario (AS.4). In the extreme ease-of-application scenario (AS.5), Ferrocement reinforced its leading position with a score of 0.87, while FRP dropped to fourth place (0.41), confirming that poor applicability severely penalizes techniques requiring specialized equipment when practical feasibility is heavily prioritized. This consistency stems from its balanced excellence across all five criteria—rather than reliance on a single attribute—and should be explicitly characterized as a methodological success: the AHP-MCDA framework reliably identifies Ferrocement as the most sustainable and resilient option regardless of how stakeholders reprioritize the criteria.

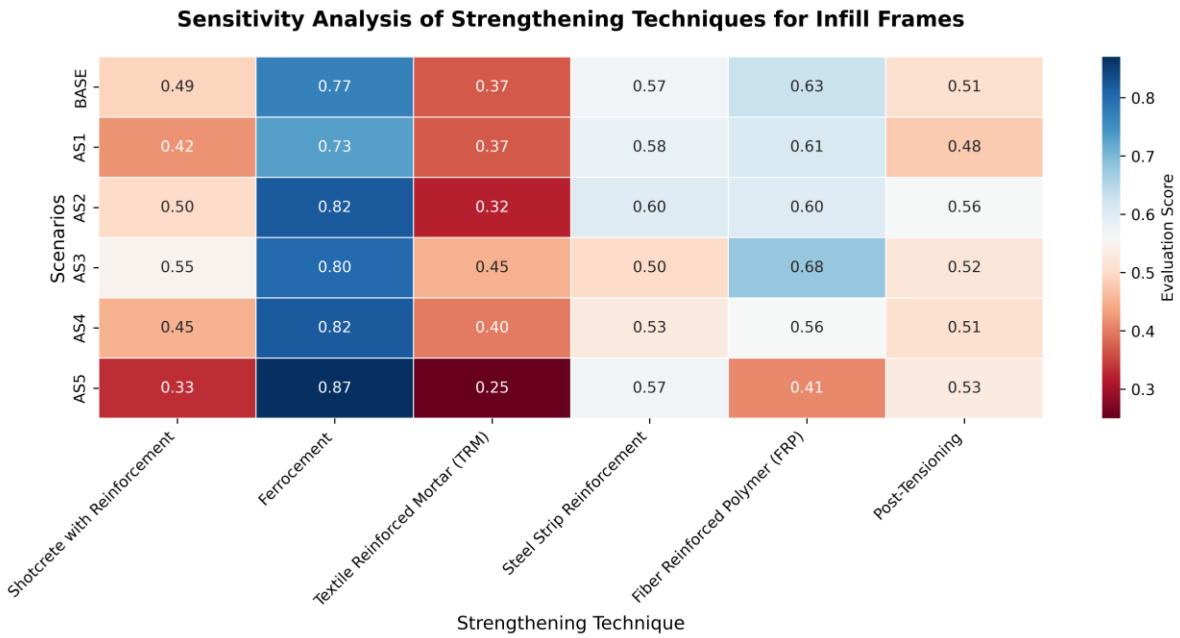

Fig. 9. Sensitivity analysis result

Fiber Reinforced Polymer (FRP) performed competitively in scenarios emphasizing performance and analytical models, securing the second position in both AS.1 and AS.3, with scores of 0.61 and 0.68, respectively. This reflects its superior shear capacity (normalized score 1.00) and mature analytical models. However, FRP dropped to third place in AS.2—the economically oriented scenario—where its high cost (Rp760,960.40/m^2, normalized score 0.82) and poor ease of application (normalized score 0.00) became significant disadvantages. In the base scenario, FRP ranked second with a score of 0.63. Shotcrete with Reinforcement exhibited notable sensitivity to the durability criterion. Its ranking varied between third and fifth positions depending on the weight assigned to durability. In scenarios where durability was de-emphasized (AS.2 and AS.4), Shotcrete performed relatively better, but it consistently remained below Ferrocement and FRP. Its limited heat resistance and corrosion vulnerability in humid environments constrained its overall competitiveness.

Steel Strip Reinforcement exhibited a marked sensitivity to the 'availability of analytical models' criterion. Despite its excellent shear capacity (214%, normalized score 0.65), it dropped to fifth place (0.50) in AS.3 because it entirely lacks a validated equivalent strut model (score 2 out of 4, normalized score 0.00). This inability to perform reliable design calculations presents a significant engineering risk and explains its intermediate ranking (third place) in other scenarios. Textile Reinforced Mortar (TRM) and Post-Tensioning consistently occupied the bottom ranks. TRM's primary disadvantage is its prohibitive cost (Rp3,650,718.41/m^2, the most expensive among all techniques), resulting in a normalized score of 0.00 for the economic criterion. TRM, despite its well-developed analytical models (normalized score 1.00), consistently remained at the lowest rank across all scenarios due to its prohibitive cost and poor ease of application. Post-Tensioning, while economically competitive (Rp225,935.00/m^2, normalized score 0.97), was significantly constrained by its limited ease of application (requires specialized hydraulic equipment, normalized score 0.00) and moderate durability (score 3 out of 4, normalized score 0.50). The sensitivity analysis confirms that the proposed framework is both robust and recalibratable for different stakeholder priorities and regional contexts. The stable performance of Ferrocement across all scenarios provides high confidence in its recommendation as the optimal strengthening technique for Aceh.

5. Discussion

This section interprets the findings in relation to the study's objectives. It begins by discussing the main findings and their practical implications, followed by a comparison with previous research. The limitations of the study are then acknowledged to provide a balanced perspective on the conclusions drawn.

5.2 Main Findings and Implications

Before discussing the MCDA rankings, it is essential to interpret the AHP findings that underpin the entire decision framework. The pairwise comparison matrix (Matrix 15) revealed a ratio of 1.00 between the Performance and Economic Aspect criteria, indicating that local experts in Aceh consider these two criteria to be equally important. This is not a coincidence or a methodological artifact; rather, it reflects the unique socio-economic and seismic context of Aceh Province. On one hand, Aceh is one of the most earthquake-prone regions in Indonesia, having experienced the devastating 2004 Sumatra-Andaman earthquake (Mw 9.3) [3] and the 2016 Pidie Jaya earthquake (Mw 6.5) [4]. These events have caused massive casualties, destroyed thousands of buildings, and forced the revision of Indonesia's seismic design code (SNI 1726:2019). Consequently, local engineers and policymakers are acutely aware that structural performance—particularly shear capacity—is non-negotiable for ensuring life safety during future earthquakes. This awareness is reflected in the 25.51% weight assigned to the Performance criterion, the highest among all criteria.

On the other hand, Aceh faces significant economic constraints. According to the Indonesian Central Statistics Agency (BPS), Aceh's poverty rate in 2024 was approximately 14-15%, which is above the national average. The province's Gross Regional Domestic Product (GRDP) per capita remains below the national average, and reconstruction budgets are heavily reliant on central government funding. In this context, the Economic Aspect criterion received a weight of 24.81%, which is statistically comparable to that of Performance. This near-equal weighting demonstrates that local experts cannot afford to prioritize seismic safety at any cost. Strengthening techniques must be both effective and economically feasible for widespread adoption in Aceh's resource-limited settings. The AHP results (CR = 0.0246, well below the 0.10 threshold) confirm that this balanced prioritization is not based on random responses but reflects a consistent and logically coherent judgment among the ten experts from government, academia, and practice. The small difference of only 0.7% between Performance and Economic weights underscores a pragmatic 'safety-budget balance'—a trade-off that is particularly acute in developing regions where financial resources allocated to retrofitting must be balanced against other pressing social and economic needs.

This AHP finding has a direct and profound implication for the MCDA results that follow. Because local experts value performance and economy almost equally, the optimal strengthening technique cannot be the one with the highest shear capacity (FRP, 249%) or lowest cost alone (e.g. Polypropylene, although excluded from the final analysis). Instead, the ideal technique must offer the best compromise between these two dominant criteria, while also performing well in the other three criteria (durability, ease of application, and analytical model availability). As the subsequent MCDA ranking demonstrates, Ferrocement achieves this balance: it provides a 161% shear capacity increase (moderate but effective) at the lowest material cost (Rp120,243.73/m^2 ≈ USD 7.20), while excelling in durability and ease of application. In essence, Ferrocement is the optimal solution precisely because it aligns with Aceh's priority of achieving seismic safety within tight economic constraints—a finding that is not merely technical but deeply rooted in the socio-economic realities of the region.

The sensitivity analysis robustly supports the study's core sustainability claim. Selecting the most applicable technique, as opposed to solely the strongest one, represents a strategic prioritization rather than a performance compromise. The framework successfully filters out high-performance but contextually unsuitable materials (e.g., FRP's high cost and application difficulty; Steel Strip's lack of validated models) while elevating Ferrocement, which offers an optimal balance of structural safety, economic feasibility, local material availability, and engineering reliability.

The stability of Ferrocement as the best option and the consistent positioning of TRM among the lowest ranks provide high confidence in the final recommendation for implementation in Aceh. The adaptability of the framework, evidenced by the stable rankings despite substantial weight variations, confirms that the proposed AHP-MCDA framework is both robust and recalibratable for different stakeholder priorities and regional contexts. In summary, the sensitivity analysis confirms that sustainability—defined as selecting the most applicable technique rather than simply the strongest—is best achieved by balancing technical performance with local-context criteria such as economic feasibility, durability, ease of application, and analytical model availability. Ferrocement's consistent performance across all scenarios demonstrates that it represents the optimal balance for Aceh's specific conditions.

5.2 Comparison with Previous Studies

This study confirms the effectiveness of Ferrocement reported in earlier experimental work, while simultaneously extending it through a decision framework that incorporates local expert judgment and context-specific criteria. The findings highlight distinct trade-offs: FRP, despite its superior shear capacity, was penalized by moderate durability and high cost, while TRM, despite excellent durability and mature analytical models, was constrained by its prohibitive material cost (Rp3,650,718.41/m^2). This demonstrates that high-performance materials are not necessarily ecologically appropriate, particularly in resource-limited settings like Aceh.

5.3 Limitations

While this study provides a robust and recalibratable AHP-MCDA framework for selecting sustainable seismic strengthening techniques, several limitations should be acknowledged to ensure a balanced interpretation of the findings and to guide future research directions. The exclusion of Bamboo Reinforcement and Polypropylene Fiber Reinforcement from the MCDA analysis, though justified by existing absence of valid experimental data for standalone applications in reinforced concrete frames with masonry infill walls, represents a notable gap. Bamboo, in particular, is a rapidly renewable material widely available in Aceh and other tropical regions, offering significant potential for low-carbon, cost-effective seismic retrofitting; however, the absence of quantitative data on its bond-slip behavior, durability under quasi-static or cyclic seismic loading in humid tropical climates precluded its inclusion. Similarly, while polypropylene fibers have demonstrated benefits in hybrid systems (e.g., combined with shotcrete), their standalone effectiveness for infill wall strengthening remains insufficiently documented, and future experimental campaigns should prioritize these materials to facilitate their integration into the framework as new evidence becomes available.

The performance evaluation relied on arithmetic means of shear capacity increases derived from a limited number of experimental studies (21 studies identified for the Performance criterion), which, while necessary to avoid optimistic bias, inherently masks the statistical variability and methodological heterogeneity across studies. The selected experimental studies employed varying test setups, including different loading protocols (cyclic versus monotonic), specimen scales (full-scale vs. reduced-scale), masonry types, and frame configurations, all of which may influence the reported shear capacity increases and complicate direct comparisons between techniques. Furthermore, for certain techniques such as Steel Strip Reinforcement and Post-Tensioning, the performance data were drawn from only one or two studies, reducing the statistical robustness of their mean values, and future research should quantify performance variability more accurately and establish more reliable effect sizes for each technique.

The durability assessment employed a binary scoring system based on the presence of evidence in the literature rather than the degree or rate of degradation, which, while aligning with the MCDA framework's requirement for discrete scores, simplifies complex, continuous degradation phenomena. For instance, FRP's heat vulnerability is described in Section 2 as a loss of up to 90% effectiveness at 150 °C, yet it receives a binary "not resistant" score alongside Shotcrete, whose compressive strength declines markedly above 150 °C, failing to capture the rate of degradation, temperature thresholds, or time-dependent performance losses critical for service life predictions. Moreover, the literature surveyed for durability (75 studies) may not fully encapsulate Aceh's specific micro-climatic conditions characterized by persistent high humidity, elevated ambient temperatures, and potential exposure to saline coastal environments; consequently, the corrosion resistance of steel fibers in shotcrete, for instance, may be more severely compromised under Aceh's specific conditions than reported in temperate-climate studies, and localized durability testing replicating Aceh's tropical humid climate would serve to validate and refine the scoring system.

The economic assessment was limited to direct material costs, including shipping costs to ensure consistent treatment across all techniques, but it excluded several critical cost components such as labor costs (since specialized techniques like TRM, FRP, and Post-Tensioning require trained crews commanding higher wages), equipment rental (e.g., pneumatic sprayers for shotcrete and hydraulic jacks for Post-Tensioning, which may not be readily available in Aceh), scaffolding and site preparation, and business interruption costs for occupied buildings. Consequently, the economic ranking presented in this study represents a material-cost-centric perspective, and a full life-cycle cost analysis incorporating labor, equipment, maintenance, and downtime costs would provide a more comprehensive economic evaluation and may alter the rankings, particularly for labor-intensive or specialized techniques.

The AHP weights were derived from pairwise comparisons by ten local experts representing government officials, academics, and practicing structural engineers in Aceh, and while the high consistency ratio validates the logical coherence of their judgments, the resulting weights are context-specific to Aceh's regulatory environment, economic constraints, and construction practices, and may not be directly transferable to other earthquake-prone regions with different socioeconomic conditions, seismic hazard levels, or material supply chains. However, this limitation also represents the study's key strength, as the framework is explicitly designed to be fully recalibratable by adjusting criteria weights through local expert elicitation, and the sensitivity analysis confirms that Ferrocement consistently ranked first or second across all weighting scenarios, demonstrating the robustness of the final recommendation even under varying stakeholder priorities. However, the application of this framework to other regions must involve re-elicitation of local expert weights to ensure contextual relevance.

The performance criterion focused exclusively on in-plane shear capacity improvement, as measured by the increase in lateral load resistance of infill walls, which, while a critical indicator of seismic performance, does not capture other important structural attributes such as out-of-plane stability, ductility, and energy dissipation, all of which may be affected differently by various strengthening techniques and are essential for a holistic seismic assessment. These aspects were not explicitly included as sub-criteria in the MCDA framework, primarily due to the limited availability of quantitative data in the reviewed literature, and future studies should expand the performance criterion to include multiple seismic response indicators to enable a more comprehensive structural evaluation. Finally, while Aceh serves as a representative case study for earthquake-prone regions in developing countries with limited resources, the findings—particularly the highest ranking of Ferrocement—may not be universally applicable, as other regions with different material supply chains, construction traditions, or regulatory frameworks may find alternative techniques more suitable; nevertheless, the methodological framework itself is readily transferable and provides a structured approach for evidence-based decision-making in any seismic region. Despite these limitations, the consistency of Ferrocement's first-place ranking across all sensitivity analysis scenarios provides strong confidence that it is the most sustainable and resilient choice for Aceh's specific conditions, and the limitations identified above do not undermine the robustness of this conclusion but rather highlight opportunities for refinement and validation in future research.

6. Conclusions

This study successfully developed an integrated Analytic Hierarchy Process (AHP) and Multi-Criteria Decision Analysis (MCDA) framework to select the most sustainable seismic strengthening technique for masonry infill walls in earthquake-prone regions, using Aceh, Indonesia as a case study. The framework incorporated five criteria—structural performance, economic aspect, durability, application ease of use, and availability of analytical models—weighted by ten local construction experts through pairwise comparisons.

A key finding of this research is that strengthening techniques with exceptionally high shear capacity improvement are not necessarily the optimal choices when other sustainability-related criteria are considered. Fiber Reinforced Polymer (FRP), despite its superior structural performance and mature analytical models, was constrained by limited durability and low ease of application, and its high material cost further penalized its economic performance. These limitations resulted in FRP securing second place overall. Similarly, Shotcrete with Reinforcement, despite demonstrating moderate structural performance and mature analytical models, was penalized by limited heat resistance and notable corrosion risk in humid environments, leading to a lower ranking. Steel Strip Reinforcement, despite its excellent structural performance and good economic characteristics, was limited by poor heat resistance and limited analytical model availability, which presents a significant engineering risk for design applications. These results confirm that a balanced assessment across multiple criteria is essential for sustainable decision-making.

Ferrocement was identified as the most optimal technique overall. Its advantages, based on the evaluation, include: effective structural performance; the lowest material cost among all techniques, making it economically competitive; superior durability, being resistant to heat, moisture, and corrosion, with a long service life; outstanding ease of application, as it can be performed with locally available materials and does not require specialized equipment; and mature analytical models that enable reliable structural design. Its minimal maintenance requirements further enhance its practical feasibility, making it particularly suitable for resource-limited settings. Its balanced performance across all criteria makes ferrocement the most sustainable and resilient choice for Aceh, particularly when considering the near-equal importance placed on performance and economic aspects by local experts.

The AHP results revealed that local experts prioritize structural performance and economic aspects as the most decisive criteria, followed by durability, availability of analytical models, and application ease of use. The MCDA procedure proved robust, with sensitivity analysis across five alternative weighting scenarios confirming that ferrocement consistently ranked first or second in all scenarios, while Textile Reinforced Mortar (TRM) consistently ranked last due to its prohibitive cost and low ease of application. This demonstrates that the proposed framework is stable and adaptable to different stakeholder priorities.

The main contribution of this research is a scientific, robust, and structured decision framework that enables stakeholders, academics, and practitioners to select the most appropriate infill wall strengthening technique based on local conditions. The methodology is fully recalibratable and transferable to other seismic regions through adjustment of criteria weights using local expert judgment. By prioritizing techniques that extend building lifespan, minimize demolition waste, and conserve embodied energy, the framework directly supports post-earthquake urban restoration and energy-saving construction. The explicit inclusion of application ease of use and local material availability ensures practical feasibility in resource-limited settings such as Aceh.

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