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Examination of Deflection and Cracking in Classroom 1A's Concrete Structures: a Case Study and Retrofit Approaches

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Abstract

Providing an emphasis on the second-floor slab and beams, this study provides a thorough investigation of the bending and cracking seen in the concrete structures of Classroom 1A at SDIT Auliya Balikpapan. In multi-story buildings, excessive deflection and critical fracture widths can seriously jeopardize serviceability, user comfort, and structural integrity. The present state of the structure was evaluated in detail utilizing a combination of Finite Element Method (FEM) analysis using LISA FEA and Non-Destructive Testing (NDT) techniques, such as Ultrasonic Pulse Velocity (UPV), Crack Width Test, Rebar Scanner Test, and Schmidt Hammer Test. The results showed that although the majority of the beams had acceptable crack widths and deflection, the second-floor slab had a considerable 30 mm deflection, which was more than the 19.44 mm allowed by SNI 2847:2019, and some of the beams (R1.B1, R1.B2, and R2.B4) also had crack widths that were greater than the 0.41 mm threshold. Additionally, FEM analysis revealed stress concentrations in the slab that exceeded the nominal compressive strength of the concrete. In order to restore the classroom building's structural safety and long-term durability, a retrofitting solution utilizing Fiber Reinforced Polymer (FRP) is suggested, along with ongoing monitoring and possible reevaluation of design criteria.

Keywords: *Cracking, Concrete Structure, Deflection, Finite Element Method (FEM), Fiber Reinforced Polymer (FRP)*

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1. Introduction

The structural integrity and serviceability of reinforced concrete buildings are paramount for ensuring safety and comfort, particularly in educational facilities such as schools [1][2][3][4][5][6]. Control over structural deflection and cracking is a critical aspect of evaluating building performance [7][8][9][10][11][12][13]. Excessive deflection in structural elements like beams and floor slabs can lead to various negative impacts, ranging from cracking in non-structural components (e.g., partitions, finishes) to discomfort for occupants [5], [14], [15]. Similarly, uncontrolled cracking can compromise the durability of concrete by allowing ingress of moisture and aggressive substances, leading to reinforcement corrosion and reduction in the structure's service life [16]. Therefore, a detailed analysis of actual geometric data and a comparison against deflection and crack width limits stipulated by national technical standards are essential.

This report documents the analysis of deflection and cracking within the second-floor structure of the "Classroom 1A" project, based on actual elevation data of beam-children and floor slab elements [17]. The evaluation specifically compares actual deflections and crack widths against permissible limits under serviceability conditions as outlined in SNI 2847:2019[4], "[18][19] Requirements for Buildings" . The investigation employed a multi-faceted approach, combining Non-Destructive Testing (NDT) methods with advanced numerical analysis through the Finite Element Method (FEM) to provide a comprehensive understanding of the structural behavior. NDT techniques are crucial for assessing the quality and condition of existing materials or structures without causing permanent damage [20]. In civil engineering, especially for reinforced concrete structures, NDT is a fundamental requirement for evaluating concrete quality, structural assessment, retrofitting planning, and quality control during construction projects[19][20][21][22][23][24][25]. Furthermore, for in-depth structural behavior analysis, the Finite Element Method (FEM) with software like LISA FEA is a powerful tool [26][27]. For structural strengthening, Fiber Reinforced Polymer (FRP) technology offers an effective and efficient solution in the field [28][29][30][31][32][33]. This study aims to present the findings of this structural assessment and propose appropriate recommendations for remediation, focusing on ensuring the long-term safety and serviceability of the classroom, shown in figure 1.

2. Research Method

This section outlines the theoretical principles underpinning the investigation and the detailed methodology employed for data acquisition, analysis, and proposed remediation. The investigation combined in-situ non-destructive testing with advanced computational modeling to thoroughly assess the structural condition.

A. Structural Data and Deflection Limits

The structural investigation of Classroom 1A at SDIT Aulia Balikpapan focused on a module measuring 7 x 8 meters. The main beams in this structure span 8 meters (8000 mm). For the floor system, slab modules are 4 x 3 meters, with the shorter 3-meter direction serving as the primary span. However, for the specific analysis of the slab's deflection, a 7-meter span was utilized, based on the overall slab distribution [34].

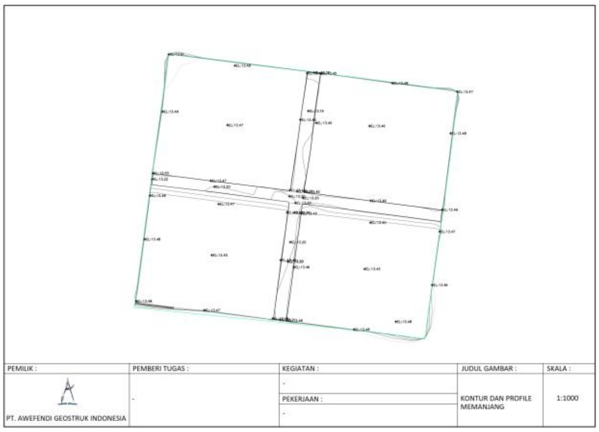

Figure 1. Elevation of room

Actual elevation data were meticulously collected to determine the existing deflection of key structural components. For Secondary beam1, elevations were recorded at the initial edge (0 m) as 13.22 m, the middle (4 m) as 13.20 m, and the final edge (8 m) as 13.22 m. Secondary beam2 showed elevations of 13.21 m at the initial edge (0 m), 13.20 m at the middle (4 m), and 13.19 m at the final edge (8 m). The second-floor slab's edge elevation was measured at 13.48 m, with its middle elevation at 13.45 m.

Deflection evaluation was carried out by calculating the difference between the average edge elevation and the mid-span elevation for each element. These measured deflections were then compared against permissible limits established by SNI 2847:2019, which mandates a maximum deflection of L/360 for both beams and floor slabs under serviceability conditions [2]. Based on this standard, the allowable deflection for an 8000 mm beam is 22.22 mm, while for a 7000 mm slab, the permissible deflection is 19.44 mm.

Deflection evaluation was performed by calculating the difference between the average edge elevation and the mid-span elevation. Permissible deflection limits were determined based on SNI 2847:2019, which specifies a maximum deflection of L/360 for beams and floor slabs under serviceability conditions [35].

- **Beam (L = 8000 mm):** L/360 = 22.22 mm
- **Slab (L = 7000 mm):** L/360 = 19.44 mm [14].

The results are summarized in Table 1.

Table 1. Deflection values from room and floor geometry measurements

Structural Element	Dimension (L)	Initial Edge Elevation (m)	Middle Elevation (m)	Final Edge Elevation (m)	Calculated Actual Deflection (mm)	Permissible Deflection (SNI 2847:2019, L/360) (mm)
Main Beams	8000 mm	N/A	N/A	N/A	N/A	22.22
Slab Modules	4 x 3 meters	N/A	N/A	N/A	N/A	N/A
Slab (for analysis)	7000 mm	N/A	N/A	N/A	N/A	19.44
Secondary beam1	8000 mm	13.22	13.20	13.22	20	22.22
Secondary beam2	8000 mm	13.21	13.20	13.19	0	22.22
Second Floor Slab	7000 mm	13.48 (Edge)	13.45	N/A	30	19.44

B. Non-Destructive Testing (NDT) Methods

Non-Destructive Testing (NDT) methods were extensively used to gather information about the existing concrete structure without causing damage. Several NDT techniques were employed in this study:

Ultrasonic Pulse Velocity (UPV) is an NDT method that utilizes ultrasonic waves to assess concrete integrity [36], [37], [38], [39], [40]. The principle involves transmitting ultrasonic pulses from a transmitting transducer through the concrete, which are then received by a receiving transducer on the other side. The wave propagation velocity is calculated from the travel time and the distance between the transducers [41]. A higher wave propagation velocity generally indicates better concrete quality and density [42]. SNI 8491:2018 and ASTM C597 provide guidelines for interpreting UPV results, where values >4.5 km/s indicate excellent concrete quality, while values <3 km/s suggest significant voids or porosity [43]. UPV can also predict concrete compressive strength when calibrated with hammer test or core drill data. It is effective in detecting internal cracking, delamination, honeycomb, or variations in concrete quality. Limitations include penetration issues with large aggregates and susceptibility to moisture variations.

Crack Width Test According to SNI 2847:2019 Article 24.3.2, the allowable crack width for reinforced concrete structures is ≤0.41 mm for elements not directly exposed to aggressive environments, and ≤0.3 mm for elements exposed to humid or aggressive environments [5], [44], [45], [46], [47], [48], [49]. Crack widths exceeding these values can reduce structural durability, accelerate rebar corrosion, and diminish structural performance over the design service life. Crack width tests measure the opening width of cracks on the concrete surface, typically caused by tensile strain exceeding concrete's tensile capacity, shrinkage, thermal movement, or excessive loading. Measurements are performed using a crack width meter or digital crack microscope with an accuracy of up to 0.01 mm, shown in figure 2. Controlling crack width is crucial as wide cracks allow water and chloride ions to penetrate, causing rebar corrosion and reducing durability. Crack measurement also forms the basis for planning strengthening or repair injections using epoxy or FRP wrapping[6], [50].

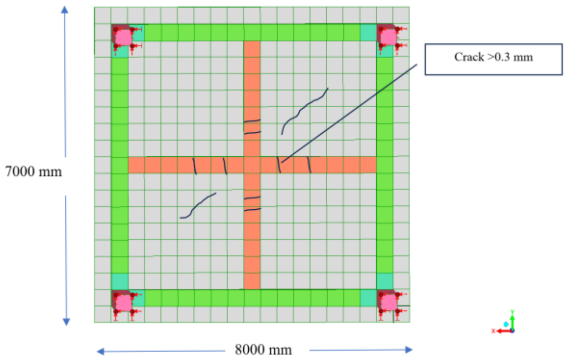

Figure 2. Crack location

The rebar scanner test is an NDT method used to detect the location, diameter, and cover of reinforcement bars within concrete. This tool operates on the electromagnetic principle (pulse induction) to detect ferromagnetic metal materials in concrete. The measurements provide vital information regarding rebar layout, spacing, and concrete cover depth. This information is critical for drilling, core sampling, anchor placement, and strengthening with FRP or external post-tensioning. It also verifies construction compliance with shop drawings. Insufficient cover (<20 mm) increases corrosion risk, while excessive cover (>50 mm) can reduce bond strength between concrete and rebar [51], [52].

C. Finite Element Method (FEM) with LISA FEA

The Finite Element Method (FEM) is a numerical technique for analyzing structural behavior under specific loading conditions by subdividing the structure into small elements (mesh)[53], [54], [55], [56], [57]. LISA FEA is a lightweight FEM software used for linear and non-linear analysis of steel, concrete, composite, and polymer structures [40]. In the context of reinforced concrete structural evaluation, LISA FEA is utilized for:

1. Analyzing stress and strain distribution in beams, slabs, columns, and structural connections [58], [59].
2. Predicting rebar yielding and potential flexural and shear cracking .
3. Simulating retrofitting with FRP wrapping or plate bonding.
4. Calculating maximum deformations (deflections) under combined 3D loading models . LISA FEA's advantages include its user-friendly interface and support for non-isotropic materials like Carbon Fiber Reinforced Polymer (CFRP). Accurate determination of elastic modulus, Poisson's ratio, and stress-strain relationships is crucial for realistic results in reinforced concrete modeling [46]. FEM results provide strong justification for structural strengthening needs.

D. Structural Strengthening with Fiber Reinforced Polymer (FRP)

Fiber Reinforced Polymer (FRP) is a composite material consisting of fibers (e.g., carbon, glass, aramid) embedded in a polymer resin [60]. FRP is widely used for external strengthening of reinforced concrete structures, enhancing flexural, shear, and torsional capacities by increasing stiffness and nominal moment capacity (Mn).

Fiber Reinforced Polymer (FRP) composites offer significant advantages for structural strengthening, notably their low self-weight, making them easy to apply without adding substantial dead load. Their inherent corrosion resistance ensures high durability, while their ease of installation allows for application to existing structural surfaces without requiring additional reinforcement. Furthermore, FRP, especially Carbon Fiber Reinforced Polymer (CFRP), boasts exceptionally high tensile strength, exceeding 3000 MPa, which is crucial for enhancing structural capacity. These materials are applied using common methods such as Externally Bonded Reinforcement (EBR), where FRP is adhered to the surface with epoxy for flexural strengthening of beams or slabs; Near Surface Mounted (NSM), involving embedding FRP into concrete grooves to improve tensile force transfer in beams for flexural and torsional strengthening; and Wrapping, where FRP encases elements like columns to increase confinement and axial compressive capacity. The typical installation process for FRP systems involves thorough surface preparation, careful mixing and application of epoxy resin and FRP laminates or fabrics, followed by proper curing and essential quality control checks, including hammer tap tests and pull-off tests[61], [62], [63], [64], [65].

3. Results and Discussion

This section presents the findings from the conducted investigations and analyses, highlighting key observations regarding deflection, cracking, and stress distribution in the Classroom 1A structure.

A. Deflection Analysis

The deflection analysis for Classroom 1A revealed varying conditions across its structural elements. Secondary beam1 showed an actual deflection of 20 mm, calculated from an average edge elevation of 13.22 m and a mid-span elevation of 13.20 m. This value falls within the permissible limit of 22.22 mm as per SNI 2847:2019, indicating that this beam meets the structural requirements. Similarly, Secondary beam2 exhibited no significant deflection, with both its average edge elevation (13.20 m) and mid-span elevation (13.20 m) being identical, confirming its safe and stable condition [59]. In contrast, the second-floor slab presented a critical concern, with an actual deflection of 30 mm, derived from an edge elevation of 13.48 m and a mid-span elevation of 13.45 m. This significantly exceeds the permissible limit of 19.44 mm set by SNI 2847:2019, thereby necessitating immediate intervention and strengthening measures for the slab[34].

B. Concrete Homogeneity Test (UPV)

The Ultrasonic Pulse Velocity (UPV) test was performed to assess the homogeneity and quality of the concrete components. A summary of the velocity values is presented in Table 1 (referencing the original document's table). The overall average velocity value was approximately 3.37 km/s. According to SNI 8491:2018 and ASTM C597, concrete with UPV values between 3.0-3.5 km/s typically indicates fair quality, while values above 4.5 km/s indicate excellent quality. The average value suggests generally acceptable homogeneity, but individual readings, especially those below 3 km/s (e.g., R2.b1b -0.98, R2.b2c 1.60, Blk2.a 1.74, Blk1.c 2.32, R2.P1c 2.72, R2.b2b 2.87, Blk1.a1 2.91, R3p1-2c 2.91), point to localized areas of poor quality or significant voids that warrant further investigation. The results are summarized in Table 2.

Table 2. Ultrasonic Pulse Velocity Result

No	Component Name	Velocity (km/s)
1	R2.b1b	-0.98
2	R2.b2c	1.60
3	Blk2.a	1.74
4	Blk1.c	2.32
5	R2.P1c	2.72
6	R2.b2b	2.87
7	Blk1.a1	2.91
8	R3p1-2c	2.91
9	R3p1-2b	3.22
10	R2.P1d	3.28
11	R3p1-2	3.29
12	R2.P1b	3.45
13	flat1.c	3.60
14	flat1.b	3.63
15	flat1.a	3.70

16	R3b1.1c	3.83
17	Blk1.b	3.92
18	R3b1.1b	4.13
19	R3b1.1a	4.15
20	R2.b2a	4.20
21	R2.b1c	4.24
22	Blk2.d	4.26
23	R2.b1a	4.32
24	R3b2-1b	4.38
25	R3b2-1c	4.43
26	R3b2-1a	4.48
27	Blk2.c	4.52

C. Crack Width Test Results

Crack width measurements were performed at locations with the most significant cracks. The results are summarized in Table 2.

Table 3. Maximum Crack Width Test Results

Component	Location	Max. Crack Width (mm)	Permissible Limit SNI (mm)	Status
Beam	R1.B1	0.81	0.41	Unsafe
Beam	R1.B2	0.58	0.41	Unsafe
Beam	R1.B3	0.40	0.41	Critical
Beam	R2.B4	0.64	0.41	Unsafe
Slab	R1 P1-P3	0.21	0.41	Safe
Slab	R2 P1-4	0.22	0.41	Safe

The results in Table 2 indicate that three of the eight beams tested (R1.B1, R1.B2, R2.B4) have crack widths significantly exceeding the permissible limit of 0.41 mm. These wide cracks are typically flexural cracks occurring in areas of maximum moment. This condition poses a significant risk to the durability of the structure, as it provides pathways for aggressive agents such as water and chlorides to enter and initiate corrosion of the reinforcement steel. Rebar corrosion will lead to expansion, spalling (flaking of the concrete cover), and ultimately a significant reduction in the cross-sectional capacity. In contrast, the crack widths in the slab elements are still within the safe category, indicating that although the slab experienced significant deflection, the damage mechanism is more related to plastic deformation rather than wide surface cracks.

Further analysis of crack widths in Classroom 1A's structural elements revealed specific areas of concern. In the beam crack test, summarized in Table 2 of the original document, Beams R1.B1, R1.B2, and R2.B4 exhibited crack widths of 0.81 mm, 0.58 mm, and 0.64 mm respectively, all exceeding the permissible limit of 0.41 mm. This suggests excessive tensile strain, potentially due to suboptimal load distribution or insufficient distributed reinforcement. Beam R1.B3, with a crack width of 0.40 mm, was very close to the limit and warrants regular monitoring, while other beams (R1.B4, R2.B1, R2.B2, and R2.B3) demonstrated acceptable crack widths.

Conversely, the slab crack test, detailed in Table 3 of the original document, showed that Flat R1 P1-P3 (0.21 mm) and Flat R2 P1-4 (0.22 mm) both had crack widths well within the safe limit of less than 0.3 mm for elements exposed to humid environments, indicating adequate casting quality and sufficient reinforcement distribution in these slab sections.

D. Finite Element Method (FEM) Analysis Results

A 3D model of the slab structure with a 4-column support system at the corners and boundary beams was analyzed using FEM software (likely LISA FEA). The analysis provided insights into the deformation and stress distribution within the structure, shown in figure 3.

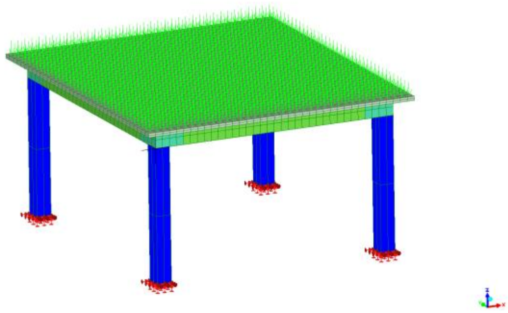

Figure 3. 3D Modeling of Classroom with LISA FEA

The FEM analysis results for deformation visually confirmed the deflection patterns. While the exact numerical values were cross-referenced with the direct elevation measurements, the FEM model's deformation contours would qualitatively support the observed excessive deflection in the slab, indicating areas where maximum displacement occurs under simulated loading conditions, shown in figure 4.

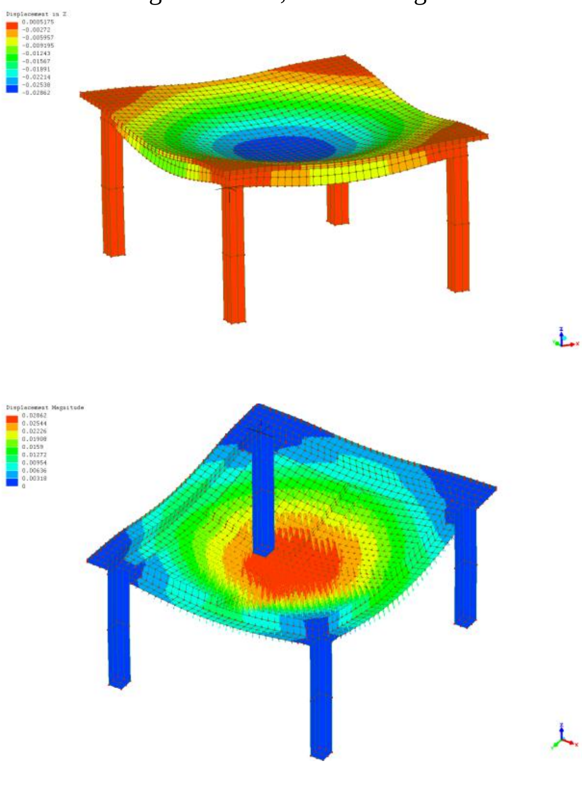

Figure 4. Deflection result

The stress distribution contour (Von Mises Stress) revealed critical areas of stress concentration. The color legend indicated a range from 519 kN/m² (minimum, blue) to 25,049.16 kN/m² (maximum, red), shown in figure 5.

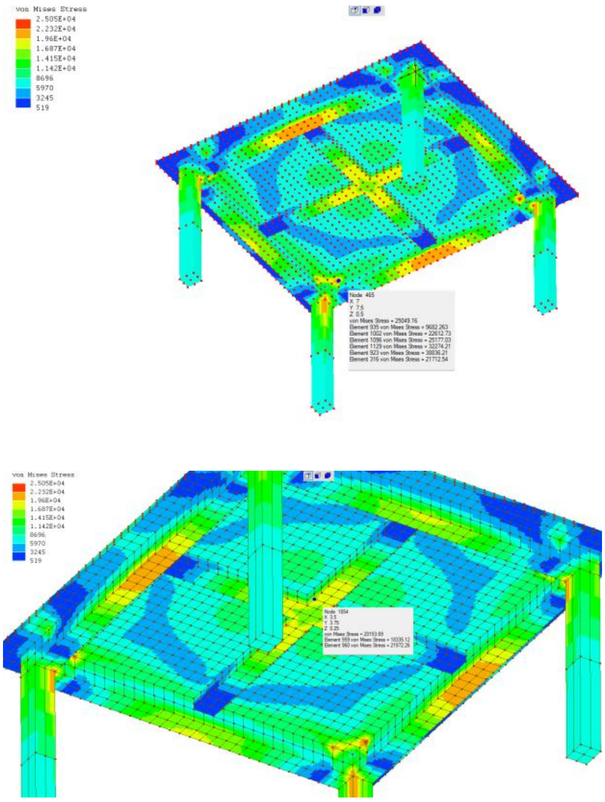

Figure 5. The stress distribution contour (Von Mises Stress)

Finite Element Method (FEM) analysis of Classroom 1A revealed that the maximum Von Mises Stress reached 25,049.16 kN/m², equivalent to 25.049 MPa [70]. This value significantly exceeds the nominal compressive strength of normal concrete (f'c = 20 Mpa). According to SNI 2847:2019, the maximum allowable stress in concrete for Ultimate Limit State Design (LRFD) is 0.85 * f'c, which equates to 17 Mpa, while for serviceability conditions, concrete stress is generally limited to below 0.45 * f'c, or 9 Mpa, to prevent compressive cracking and excessive deformation, shown in figure 6.

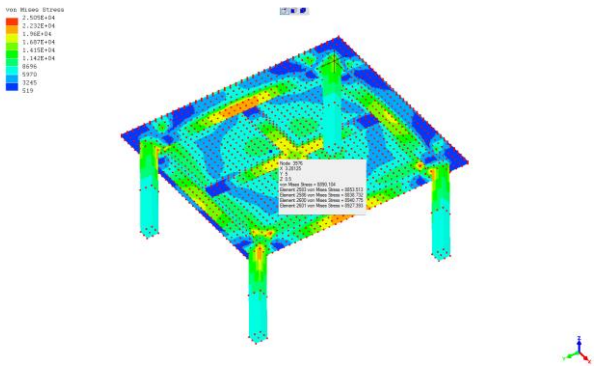

Figure 6. Beam Stress

The FEM results indicated that while the majority of the slab (represented by green-blue contours) experienced low to medium stresses 8890.104 kN/m², areas highlighted by yellow-red contours, particularly at 25.5 MPa, indicated severe stress concentrations. These high-stress zones were typically found at column punching areas due to concentric compressive force transfer and at slab edges experiencing maximum deflection, shown in figure 7.

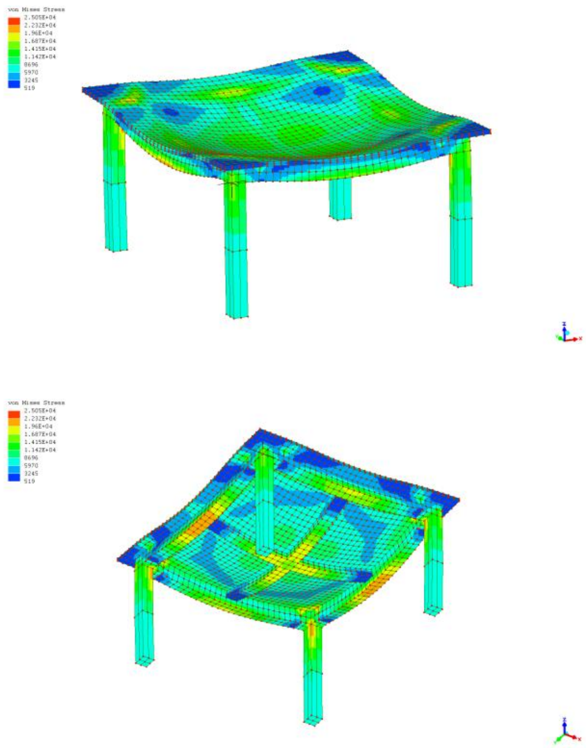

Figure 7. The stress distribution contour (Von Mises Stress)

E. CFRP Strengthening for Cracked Concrete Structures

The rehabilitation of cracked concrete classroom beams and floor slabs often necessitates the application of Carbon Fiber Reinforced Polymer (CFRP) to restore and enhance structural integrity. This strengthening process typically commences with meticulous surface preparation, which is crucial for achieving optimal bond strength. This involves thoroughly cleaning the concrete surface to remove all loose debris, dust, oil, and any other contaminants that could inhibit adhesion. Following preparation, the existing cracks undergo injection and grouting to fill voids and consolidate the concrete, shown in figure 8.

Figure 8. Cleaning the concrete surface

This step often utilizes epoxy resins or micro-cementitious grouts, carefully injected under pressure to ensure complete penetration and bonding within the crack network, thereby restoring the concrete's monolithic action.

Once the injected material has cured, a layer of epoxy resin is precisely applied to the prepared concrete surface, shown in figure 9.

Figure 9. Utilizes epoxy resins or micro-cementitious grouts

This resin acts as a bonding agent for the subsequent application of the CFRP material. While the epoxy is still fresh, the pre-cut CFRP sheets or laminates are carefully laid onto the coated surface, meticulously pressed to eliminate air voids and ensure full contact with the epoxy. Finally, a finishing layer of epoxy or a protective coating is applied over the CFRP to safeguard it from environmental degradation and mechanical damage, followed by a general finishing and neatening of the repaired area to ensure a smooth and aesthetically pleasing outcome. This comprehensive approach ensures a durable and effective repair, significantly enhancing the load-carrying capacity and longevity of the concrete elements, shown in figure 10.

Figure 10. The application of Carbon Fiber Reinforced Polymer (CFRP)

F. Discussion of Findings

The combined results from NDT and FEM analysis present a clear picture of the structural health of Classroom 1A. While the deflection in Secondary beam1 was acceptable and Secondary beam2 showed no deflection, the second-floor slab's excessive deflection (30 mm vs. 19.44 mm allowable) is a critical concern, indicating a serviceability issue and potential long-term structural degradation. This is corroborated by the FEM analysis showing areas where the Von Mises stress far exceeds the concrete's design compressive strength, suggesting that the slab is overstressed under current loading conditions. Such high stresses in compression zones can lead to crushing failure of concrete if not addressed.

Furthermore, the crack width analysis revealed that specific beams (R1.B1, R1.B2, and R2.B4) have cracks exceeding the permissible limits, indicating structural issues that could compromise durability by allowing moisture penetration and accelerating reinforcement corrosion. Although the slab cracks were within limits, the excessive deflection is a more immediate concern for functionality and structural stability. The UPV results, particularly the isolated low values, further support the presence of localized inconsistencies or defects within the concrete, which could contribute to the observed deficiencies [61].

The discrepancies between the safe crack widths in the slab and its excessive deflection suggest that the slab might be experiencing larger overall deformation than anticipated by its design, possibly due to underestimated loads, material properties, or construction tolerances. The stress concentrations identified by FEM analysis confirm that the existing structural capacity in these areas is insufficient for the current demand.

4. Conclusion

Based on the combined evaluation using Non-Destructive Testing (NDT) and Finite Element Method (FEM) analysis, the structural performance of Classroom 1A shows both satisfactory and critical conditions. The secondary beams remain within permissible deflection limits, indicating adequate serviceability performance. However, the second-floor slab exhibits excessive deflection exceeding the SNI 2847:2019 serviceability limit, which identifies a significant serviceability issue. Crack width evaluation further indicates that several beams have exceeded allowable crack limits, suggesting potential durability concerns. FEM results support these findings by revealing stress concentrations in the slab that approach or exceed the material capacity, indicating localized overstressing.

Overall, the structure is not in an immediate failure condition, but certain elements require attention to ensure long-term safety, serviceability, and durability. The study demonstrates that the integration of field measurements, NDT methods, and FEM analysis provides an effective framework for assessing existing reinforced concrete structures and identifying elements requiring strengthening or monitoring.

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