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STRUCTURAL PERFORMANCE EVALUATION OF REINFORCED CONCRETE BEAMS AFTER REINFORCEMENT SPECIFICATION REDUCTION IN THE SMK KARYA BHAKTI BREBES BUILDING

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ABSTRACT

Specification changes in reinforced concrete structural members may occur during construction and can affect the conformity, strength, and serviceability of structural elements. This study evaluates the structural performance of the reinforced concrete beam at Grid E of the SMK Karya Bhakti Brebes building under the as-built reinforcement specifications based on the requirements of SNI 2847:2019. The study employed secondary data obtained from the Detail Engineering Design (DED), field implementation data, and structural analysis using SAP2000. The evaluation focused on the beam's flexural, shear, torsional, and reinforcement detailing performance by comparing the internal forces obtained from structural analysis with the capacity of the as-built beam section. The results show that the beam experienced specification changes, particularly in the longitudinal reinforcement, while the beam dimensions and concrete strength remained consistent with the design specifications. The as-built beam uses 3D16 longitudinal reinforcement, with an installed reinforcement area of 603.19 mm². The analysis produced a maximum negative bending moment of 32.74 kN·m at the support, while the design flexural capacity was 108.80 kN·m, indicating that the flexural capacity remained adequate. The maximum shear force at the support was 90.12 kN, while the calculated shear capacity ratio reached 3.47, indicating that the nominal shear strength was sufficient. The beam was also subjected to a torsional moment of 0.2029 kN·m, which was evaluated in accordance with SNI 2847:2019 and did not govern the structural capacity assessment. The maximum calculated deflection remained within the allowable limit, indicating acceptable serviceability performance. However, despite the beam satisfying the strength requirements for flexure and shear, the provided stirrup spacing did not comply with the required detailing provisions, with 100 mm spacing at the support exceeding the allowable 63 mm and 150 mm spacing at the span exceeding the allowable 126 mm. Therefore, the as-built beam retains adequate nominal structural capacity, but its transverse reinforcement detailing does not fully comply with SNI 2847:2019. These findings indicate that structural specification changes should be accompanied by comprehensive strength, serviceability, and detailing verification before being accepted as an alternative to the original design.

Keywords: reinforced concrete beam, specification changes, flexural capacity, shear capacity, torsion, reinforcement detailing, SAP2000, SNI 2847:2019.

1. INTRODUCTION

Reinforced concrete beams are among the primary structural components in building systems because they transfer loads from slabs to columns and subsequently to other structural elements. Their structural performance directly affects the safety, stiffness, and serviceability of a building. Failure or inadequate performance of beam members may result in excessive deflection, cracking, or loss of structural capacity, particularly under gravity and seismic loading. Therefore, beam design and evaluation must satisfy the requirements for structural strength, serviceability, and ductility in accordance with applicable design standards [2], [3], [5], [8].

The structural capacity of reinforced concrete beams depends on material properties, cross-sectional dimensions, and reinforcement detailing. Changes in these specifications, particularly reductions in reinforcement, may affect the flexural, shear, and torsional capacity of the beam. Consequently, deviations between the design specifications and the reinforcement actually installed during construction should not be assessed solely from the magnitude of the reduction, but must be evaluated based on the resulting structural capacity and compliance with applicable detailing requirements [1], [2], [8], [10].

In construction practice, modifications to structural specifications may occur during the implementation stage due to construction conditions, material availability, field adjustments, or design changes. Such conditions may result in differences between the original design specifications and the as-built configuration. Although specification modifications do not necessarily result in structural failure, unverified deviations may affect the flexural and shear capacity, deformation, ductility, and detailing of structural members. Therefore, any deviation between the design and as-built conditions requires an engineering evaluation to determine whether the modified structural member continues to satisfy the required structural performance [5], [6], [8].

To ensure structural safety following specification modifications, structural evaluation must be conducted in accordance with applicable design standards. In Indonesia, reinforced concrete design is governed by SNI 2847:2019, which specifies requirements related to structural strength, reinforcement detailing, serviceability, and durability. The evaluation of modified or as-built beam specifications therefore needs to consider not only the nominal capacity of the section but also the compliance of reinforcement detailing with the applicable provisions. Numerical structural analysis using SAP2000 provides a basis for obtaining the internal forces acting on structural members, including bending moments, shear forces, torsional moments, and deformation, which can subsequently be compared with the capacity of the as-built beam [3], [6], [8].

The beam evaluated in this study is Balok Grid E, which forms part of the main structural system of the SMK Karya Bhakti Brebes building. The beam transfers loads from the floor slab to the columns and was selected for evaluation because differences were identified between the design reinforcement specifications and the reinforcement implemented in the field. Based on the structural evaluation, Balok Grid E has a cross-section of 300 mm × 550 mm, a span length of 3,000 mm, and an effective depth of 502 mm. The beam uses concrete with a compressive strength of 20 MPa, longitudinal reinforcement with a yield strength of 420 MPa, and transverse reinforcement with a yield strength of 280 MPa. The as-built reinforcement consists of 3D16 longitudinal reinforcement and 2D10 stirrups spaced at 100 mm in the support region and 150 mm in the span region.

The evaluated beam is part of the building's Special Moment Resisting Frame (SMRF) structural system. As a component of an SMRF, the beam is required to maintain adequate strength and ductile structural behavior under seismic loading. This requirement makes reinforcement detailing particularly important because the performance of a moment-resisting frame is not determined solely by the nominal flexural and shear capacities of its members, but also by the ability of the reinforcement detailing to support the intended structural behavior. Therefore, the evaluation of Balok Grid E considers both strength and reinforcement detailing in accordance with the applicable provisions of SNI 2847:2019.

The structural analysis of Balok Grid E indicates that the beam is subjected to bending moments, shear forces, and torsion. The maximum negative bending moment at the support is 32.74 kN·m, while the positive bending moment at the support is 12.92 kN·m. At the span, the negative and positive bending moments are 3.53 kN·m and 11.04 kN·m, respectively. The maximum shear force at the support is 90.12 kN, while the shear force at the span is 10.54 kN. In addition, the beam is subjected to a torsional moment of 0.2029 kN·m, which is included in the structural evaluation to determine the effect of torsion on the beam's performance.

The preliminary evaluation indicates that the as-built longitudinal reinforcement remains adequate in terms of flexural strength. At the support, the calculated design flexural capacity is ϕMn = 108.80 kN·m, which is greater than the maximum negative bending moment of Mu = 32.74 kN·m. The span region also satisfies the flexural strength requirement because the design flexural capacity is greater than both the positive and negative bending moments obtained from SAP2000. However, structural adequacy cannot be concluded solely from the nominal capacity results. The transverse reinforcement detailing requires separate assessment because the as-built stirrup spacing is 100 mm at the support and 150 mm at the span, while the allowable spacing obtained from the evaluation is 63 mm and 126 mm, respectively. Thus, although the beam's calculated strength capacity remains adequate, the provided stirrup detailing does not fully comply with the applicable requirements.

Although previous studies have investigated reinforced concrete beam design, structural evaluation, and structural optimization separately, limited research has specifically examined as-built specification deviations in reinforced concrete beams and their implications for structural safety by simultaneously evaluating flexural, shear, torsional, serviceability, and reinforcement detailing requirements using SNI 2847:2019 and SAP2000 [2], [3], [6], [8], [10]. This gap highlights the importance of evaluating structural members based on their actual as-built conditions rather than relying solely on the original design specifications.

This study aims to evaluate the structural performance and safety of Balok Grid E following deviations in reinforcement specifications during construction. The evaluation includes flexural capacity, shear capacity, torsional behavior, serviceability, and reinforcement detailing based on SNI 2847:2019, supported by numerical structural analysis using SAP2000. The study provides an engineering assessment of whether the as-built beam continues to provide adequate structural capacity and serviceability while identifying detailing provisions that remain non-compliant. The results provide a technical basis for assessing the safety implications of as-built specification deviations and determining whether further corrective measures are required.

2. RESEARCH METHOD

2.1. Research Object

The research object was the reinforced concrete beam of the SMK Karya Bhakti Brebes building. The analyzed member, Balok Grid E, is one of the primary structural elements responsible for transferring loads from the floor slab to the columns. The evaluation focused on assessing the structural performance of the beam under the as-built reinforcement specifications and identifying the structural implications of deviations between the planned and implemented reinforcement configurations.

The as-built data were obtained through direct field observation and visual documentation of the structural elements. The observation was conducted to identify the actual condition of the reinforcement specifications implemented during construction, including the beam dimensions, reinforcement diameter and quantity, stirrup spacing, and reinforcement configuration. Field photographs were used as supporting visual evidence for verifying the observed conditions.

In addition to field observation, technical interviews and confirmation with parties involved in the project were used to verify information that was not completely available in the planning documents, including information on construction implementation and deviations between the planned and actual conditions. The as-built information was further verified by reviewing available project documents, including structural working drawings, project records, technical documentation, and shop drawings.

The planned specifications were obtained from the structural planning documents provided by the planning consultant, while information regarding actual implementation was supported by the supervising consultant and project documentation. The planned and as-built data were then compared based on beam dimensions, reinforcement diameter, number of reinforcement bars, stirrup spacing, material properties, and reinforcement detailing.

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2.2. Research Data

This study utilized secondary data obtained from the project planning documents, including:

1. Structural drawings (Detail Engineering Design/DED);
2. Beam dimensions and reinforcement details;
3. Concrete compressive strength (f'c);
4. Reinforcing steel yield strength (fy);
5. Structural loading data; and
6. Structural analysis results.

2.3. Structural Modeling

The reinforced concrete beam was modeled using SAP2000 based on the structural geometry, material properties, support conditions, and loading specifications obtained from the project documents and field data. SAP2000 was used to obtain the internal forces and deformation responses of the beam, including bending moment, shear force, torsional moment, and deflection. The software was also used to compare the structural response under the planned and as-built reinforcement configurations.

The structural model represents the reinforced concrete building as a two-story structure with a reinforced concrete structural system. The floor slab acts as part of the gravity-load-resisting system, while the beams and columns work together as a moment-resisting frame to resist lateral and seismic effects. The building is categorized as an educational building, and the structural analysis considers both gravity and earthquake loading in accordance with the applicable Indonesian standards.

Two analytical configurations were considered in the evaluation. The original design model represents the beam according to the reinforcement specifications contained in the structural planning documents, while the as-built model represents the reinforcement configuration identified from the actual construction condition. The geometry, material properties, support conditions, loading, and load combinations were maintained consistently between the models, while the reinforcement configuration was adjusted according to the respective design or as-built condition. This approach allows the structural implications of the identified reinforcement deviations to be evaluated through a direct comparison of the resulting structural responses.

The loading applied in the structural model consisted of dead load, live load, and earthquake load. Gravity loading was determined in accordance with SNI 1727:2020, while earthquake effects were considered in accordance with SNI 1726:2019. The loads were applied according to the building function as an educational facility and subsequently combined to obtain the critical loading conditions for structural evaluation.

Table 1. Load Combinations

Load Combination	Load Components	Purpose
Combination 1	As defined in SAP2000 model	Strength evaluation
Combination 2	As defined in SAP2000 model	Strength evaluation
Combination 3	As defined in SAP2000 model	Seismic evaluation
Combination 4	As defined in SAP2000 model	Seismic evaluation
Combination 5	As defined in SAP2000 model	Serviceability evaluation

2.4. Capacity Verification

The structural performance of the beam was evaluated by comparing the factored design demands obtained from SAP2000 with the corresponding design capacities calculated in accordance with **SNI 2847:2019**. The evaluation considered both the strength of the beam and the compliance of its reinforcement detailing. Because the investigated beam forms part of the reinforced concrete moment-resisting structural system, the evaluation also considered the applicable requirements for beam detailing in seismic structural systems. The following parameters were evaluated:

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Table 2. Summary of Evaluation Criteria

Evaluation parameter	SNI 2847:2019 provision	Verification criterion
Flexural strength	Section 9; Section 18.6.3	$\phi M_n \geq M_u$
Shear strength	Section 9.6; Section 18.6.5	$\phi V_n \geq V_u$
Torsional strength	Section 9.7	$\phi T_n \geq T_u$
Minimum longitudinal reinforcement	Section 9.6.1	$A_s \geq A_{s,min}$
Maximum/ductile reinforcement	Section 18.6.3	Reinforcement within prescribed limits
Transverse reinforcement	Section 18.6.4	Required configuration and spacing satisfied
Seismic shear detailing	Section 18.6.5	Required seismic shear provisions satisfied
Serviceability/deflection	Applicable SNI 2847 provisions	$\Delta \leq \Delta_{allow}$

2.5. Research Procedure

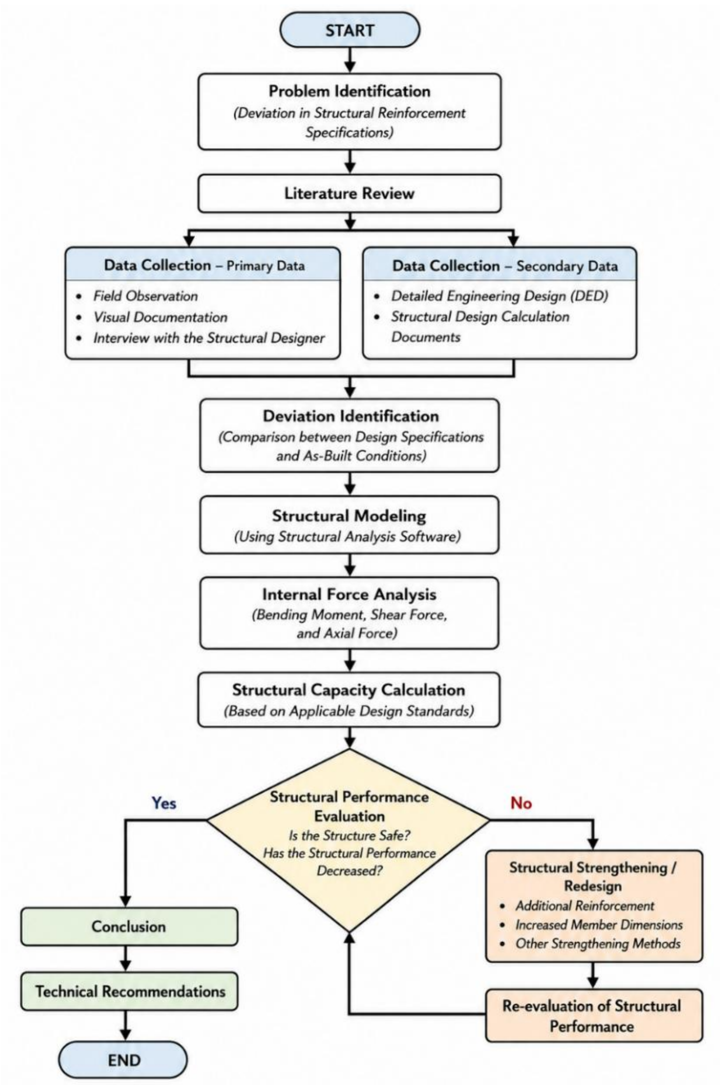

Figure 1. Research Procedure

3. RESULTS AND DISCUSSION

3.1. Comparison of Beam Data

Table 3. Comparison of Beam Data

Reinforcement	Design specification	Design As (mm^2)	As-built specification	As-built As (mm^2)	Reduction
Top bars	3D16	603.19	3D10	235.62	60.94%
Side bars	2D16	402.12	2D10	157.08	60.94%
Bottom bars	3D16	603.19	2D10	402.12	33.33%
Hanger bars	2D16	402.12	-	0.00	100.00%

Based on the comparison presented in Table 3, it was found that the beam specifications in the as-built condition were not entirely consistent with the original design documents. The primary discrepancies were identified in the longitudinal reinforcement detailing, including the top reinforcement, side reinforcement, bottom reinforcement, and hanger reinforcement of several beam types. In contrast, the beam dimensions, concrete cover, and concrete compressive strength remained consistent with the original design specifications.

Beam B2 exhibited the most significant reduction in reinforcement, with decreases of 60.94% in both the top and side reinforcement areas, 33.33% in the bottom reinforcement area, and 100% in the hanger reinforcement. From a structural engineering perspective, a reduction in the reinforcement area (As) directly decreases the beam's flexural capacity because the available tensile resistance provided by the reinforcing steel is reduced. This condition may also affect the beam's stiffness, crack control, and ductility, particularly under service and ultimate loading conditions [1], [2], [8], [10]. Therefore, a comprehensive structural capacity evaluation was performed in accordance with the provisions of SNI 2847:2019, using the internal force results obtained from the SAP2000 structural analysis as the basis for capacity verification [3], [6], [8]. The evaluation aimed to determine whether the as-built beam specifications continued to satisfy the required structural safety criteria despite the reduction in reinforcement.

3.2. Effect on Flexural Capacity

The deviation in longitudinal reinforcement directly affects the flexural resistance of reinforced concrete beams because the tensile force that can be developed by the longitudinal reinforcement is governed by the provided reinforcement area. The flexural capacity of the beam was therefore evaluated separately for the **support region**, where negative bending moment governs and the top bars act as the primary tension reinforcement, and the **span region**, where positive bending moment governs and the bottom bars act as the primary tension reinforcement. This approach provides a more representative assessment of the actual flexural behavior of the as-built beam.

According to the flexural provisions of **SNI 2847:2019**, the nominal flexural strength of a reinforced concrete beam is determined based on the longitudinal reinforcement area (As), concrete compressive strength (fc′), reinforcement yield strength (fy), beam width (b), and effective depth (d). The nominal flexural strength was calculated using:

$$a = (As\ fy)/(0.85\ f'c\ b) \quad (1)$$

and

$$Mn = As\ fy\ (d - a/2) \quad (2)$$

where a is the depth of the equivalent rectangular compression block, As is the area of tensile reinforcement, fy is the yield strength of longitudinal reinforcement, fc′ is the concrete compressive strength, b is the beam width, and d is the effective depth.

The design flexural strength was subsequently determined as:

$$\phi Mn \quad (3)$$

where ϕ is the strength reduction factor. The application of ϕ=0.90 was based on the tension-controlled flexural condition specified by **SNI 2847:2019**. The use of this factor should be verified from the calculated tensile strain of the longitudinal reinforcement. In accordance with the strain-compatibility approach, the tensile strain is determined from:

$$\varepsilon t = \varepsilon cu \, ((d - c)/c) \quad (4)$$

where εt is the tensile strain in the longitudinal reinforcement, εcu is the concrete compressive strain at nominal strength, d is the effective depth, and c is the neutral-axis depth.

For this study, the as-built beam geometry is 300 mm × 550 mm, with an effective depth of 502 mm, fc′ = 20 MPa, fy = 420 MPa, and β1 = 0.85. The as-built longitudinal reinforcement in the evaluated beam consists of 3D16, providing an installed reinforcement area of:

$$As = 3(\pi(16^2)/4) \quad (5)$$

$$As = 603.19 \text{ mm}^2 \quad (6)$$

The same longitudinal reinforcement configuration was used for the critical flexural regions.

3.2.1. Negative Flexural Capacity at the Support

At the support region, the critical action is the **negative bending moment**, for which the top bars act as the primary tensile reinforcement. The as-built section contains **3D16 top bars**, corresponding to:

$$As,support = 603.19 \text{ mm}^2 \quad (7)$$

The calculated nominal flexural strength of the section is:

$$Mn = 120.88 \text{ kN·m} \quad (8)$$

Using the strength reduction factor applied in the structural evaluation:

$$\phi = 0.90 \quad (9)$$

The design flexural strength becomes:

$$\phi Mn = 0.90(120.88) \quad (10)$$

$$\phi Mn = 108.80 \text{ kN·m} \quad (11)$$

The maximum negative bending moment obtained from SAP2000 is:

$$Mu- = 32.74 \text{ kN·m} \quad (12)$$

Therefore:

$$\phi Mn \geq Mu \quad (13)$$

$$108.80 > 32.74 \text{ kN·m} \quad (14)$$

The negative flexural capacity at the support is adequate. The installed As of 603.19 mm² also exceeds the minimum reinforcement requirements of 400.90 mm² and 502.00 mm².

3.2.2. Positive Flexural Capacity at the Span

At the span region, the critical action is the **positive bending moment**, for which the bottom bars act as the primary tensile reinforcement. The as-built section uses **3D16 bottom bars**, giving:

$$As,span = 603.19 \text{ mm}^2 \quad (15)$$

The span region uses the same longitudinal reinforcement configuration of 3D16, with an installed reinforcement area of 603.19 mm².

The positive and negative bending moments obtained from SAP2000 at the span are:

$$Mu+ = 11.04 \text{ kN·m} \quad (16)$$

and

$$Mu- = 3.53 \text{ kN·m} \quad (17)$$

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Because the same 3D16 reinforcement configuration is used and the resulting flexural capacity is substantially greater than the calculated span moments, the span region satisfies the flexural strength requirement, with all flexural checks producing $\phi Mn > Mu$.

3.2.3. Verification of the Strength Reduction Factor

The strength reduction factor should be consistent with the tensile-strain condition of the reinforced concrete section. The tensile strain εt at nominal strength is obtained from strain compatibility and compared with the strain limits prescribed by SNI 2847:2019.

The flexural evaluation uses $\phi = 0.90$, resulting in a design capacity of 108.80 kN·m. The applicability of this factor is determined from the tensile-strain condition obtained through strain compatibility in accordance with SNI 2847:2019.

3.3. Effect on Shear Strength

The modification of the beam reinforcement specifications also affects the evaluation of its shear performance. In reinforced concrete beams, shear resistance is provided by the combined contributions of the concrete and transverse reinforcement. Therefore, changes in transverse reinforcement, particularly the stirrup spacing, must be evaluated not only in terms of nominal shear strength but also in terms of the detailing requirements specified by SNI 2847:2019.

The shear evaluation was performed by comparing the factored shear force obtained from SAP2000 with the design shear strength of the as-built beam. The nominal shear strength was calculated from:

$$Vn = Vc + Vs \quad (18)$$

where Vc is the contribution of concrete and Vs is the contribution of transverse reinforcement. For vertical stirrups, the contribution of transverse reinforcement is expressed as:

$$Vs = Av\ fyt\ d/s \quad (19)$$

where Av is the area of shear reinforcement within spacing s, fyt is the yield strength of transverse reinforcement, and d is the effective depth of the beam. The design shear strength was then determined using:

$$\phi Vn \quad (20)$$

with the applicable shear strength reduction factor of ϕ=0.75.

The evaluation was conducted in accordance with the shear-strength provisions of SNI 2847:2019, particularly the provisions governing Vc, Vs, and the design shear strength, together with the applicable seismic beam detailing requirements in Section 18.6. The calculation sheet used in the structural evaluation identifies Vc and Vs using the provisions of Sections 22.5.5.1 and 22.5.10.5.3, respectively.

3.3.1. Shear Demand at the Support Region

The support region represents the critical shear zone because the reaction forces and seismic effects produce the largest shear demand. The structural analysis of Balok Grid E produced a maximum factored shear force of:

$$Vu = 90.12 \text{ kN} \quad (21)$$

at the support region. The corresponding shear force in the span region was:

$$Vu = 10.54 \text{ kN} \quad (22)$$

The higher shear demand at the support confirms that the support region requires greater attention in the evaluation of transverse reinforcement and seismic detailing.

For the as-built beam, the shear capacity was evaluated from the contributions of concrete and transverse reinforcement. The calculated design shear strength was compared directly with the factored shear demand using:

$$\phi Vn \geq Vu \quad (23)$$

A beam section was considered adequate in shear when the design shear strength was greater than or equal to the corresponding factored shear demand.

3.3.2. Shear Reinforcement Detailing

In addition to the strength calculation, the stirrup arrangement was evaluated based on the seismic detailing requirements for beams. The detailing assessment distinguishes between the plastic-hinge region near the beam-column connection and the span region outside the plastic-hinge zone.

The plastic-hinge region is particularly critical because inelastic deformation is expected to concentrate near the beam-column joint during strong seismic excitation. Consequently, closer transverse reinforcement is required to provide confinement, maintain shear resistance after cracking, and support the intended ductile response of the moment-resisting frame.

The as-built stirrup layout is represented as:

Beam-column joint → plastic-hinge region → span region → plastic-hinge region → beam-column joint

The calculation results show that the actual stirrup spacing exceeds the maximum allowable spacing in the critical regions. The support-region spacing is 100 mm, while the maximum calculated spacing is 63 mm; the detailing is therefore non-compliant.

For the span region, the as-built stirrup spacing is 150 mm, while the calculated maximum allowable spacing is 126 mm; the detailing is also non-compliant.

The assessment therefore distinguishes between two conclusions: (1) the beam satisfies the evaluated nominal shear-strength requirement, and (2) the stirrup spacing does not comply with the applicable detailing requirements.

Satisfying $\phi V_n \geq V_u$ does not automatically establish full compliance with the detailing requirements.

3.3.3. Shear Capacity and Detailing Assessment

Table 4. Shear Capacity and Detailing Assessment

Parameter	Support region	Span region
Vu	90.12 kN	10.54 kN
As-built stirrup	D10	D10
Stirrup spacing	100 mm	150 mm
Maximum allowable spacing	63 mm	126 mm
Strength check	Meets	Meets
Detailing check	Not compliant	Not compliant

The results demonstrate that the critical issue associated with the as-built transverse reinforcement is not insufficient nominal shear strength but non-compliant stirrup spacing. The beam's flexural, shear, and torsional capacities satisfy the evaluated strength requirements, while the stirrup detailing remains non-compliant.

3.4. Torsional Performance

3.4.1. Torsional Demand

In addition to flexure and shear, the torsional response of Balok Grid E was evaluated because torsional effects may interact with shear and influence the required transverse and longitudinal reinforcement. The SAP2000 analysis produced a maximum torsional moment of:

$$T_u = 0.2029 \text{ kN·m} \tag{24}$$

This torsional demand was evaluated to determine whether additional torsional reinforcement was required and whether the beam cross-section remained adequate.

3.4.2. Torsional Threshold

According to the torsional provisions of SNI 2847:2019, torsional reinforcement is required when the factored torsional moment exceeds the applicable torsional threshold. The threshold is evaluated from the cracking torsion Tcr and the applicable strength reduction factor.

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The applicable torsional threshold was compared with the factored torsional demand:

$$Tu = 0.2029\ \text{kN·m} \tag{25}$$

The governing criterion is:

$$Tu > \phi Tcr/4 \tag{26}$$

In this evaluation, the torsional demand did not govern the structural capacity assessment; additional torsional reinforcement was therefore not required based on the torsional threshold.

3.4.3. Torsional Capacity

Where torsional reinforcement is required, the nominal torsional strength is determined based on the contribution of the transverse and longitudinal torsional reinforcement in accordance with the torsion provisions of **SNI 2847:2019**. The design torsional strength is then expressed as:

$$\phi Tn \tag{27}$$

and compared with the factored torsional demand:

$$\phi Tn \geq Tu \tag{28}$$

3.4.4. Overall Shear and Torsion Interpretation

The combined evaluation indicates that the as-built beam maintains adequate shear and torsional strength under the design demands obtained from SAP2000. However, the beam does not fully comply with the required transverse reinforcement detailing. The discrepancy is therefore primarily a detailing compliance issue rather than a nominal strength failure.

This distinction is particularly important for a beam forming part of a moment-resisting seismic system. Adequate calculated shear capacity shows that the section can resist the analyzed factored shear force, while the prescribed transverse reinforcement detailing is intended to ensure confinement, ductility, and stable behavior in the plastic-hinge region during severe seismic response. The beam therefore satisfies the evaluated shear-strength demand but remains non-compliant with the transverse-reinforcement detailing requirements.

3.5. Material Utilization and Structural Performance Trade-off

The modification of the beam reinforcement specifications resulted in a reduction in the amount of longitudinal reinforcement provided in the as-built condition. The comparison between the planned and as-built configurations showed reductions in the top bars, side bars, bottom bars, and hanger bars, while the beam dimensions, concrete cover, concrete quality, and stirrup configuration remained unchanged. These deviations were subsequently evaluated in terms of their implications for structural strength, serviceability, and reinforcement detailing.

The reduction in reinforcement area should not be interpreted directly as an improvement in material efficiency because this study does not quantify the total steel weight, construction cost, or embodied material savings before and after the modification. In addition, the available project information does not establish that the reinforcement changes were implemented through a formal Value Engineering (VE) process. The changes are therefore more appropriately described as as-built specification deviations or specification modifications rather than as a verified VE outcome.

From the structural performance perspective, the as-built beam retained adequate calculated capacity under the loading conditions considered. The flexural evaluation showed that the design flexural capacity remained greater than the governing bending moments. The shear evaluation also demonstrated adequate calculated shear strength, while the torsional demand remained within the capacity of the section. The calculated deflection was likewise within the applicable allowable limit. These results indicate that the observed reinforcement deviations did not result in a calculated strength or serviceability failure under the analyzed design conditions.

However, the structural assessment also demonstrates an important trade-off between strength adequacy and detailing compliance. Although the calculated nominal capacities remain adequate, the transverse reinforcement spacing does not satisfy the applicable seismic detailing requirements of SNI 2847:2019.

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Thus, the beam cannot be considered fully compliant solely because its calculated flexural, shear, and torsional capacities exceed the corresponding design demands. This distinction is particularly important for a beam that forms part of a seismic moment-resisting structural system, where reinforcement detailing is intended to ensure confinement, ductility, and stable inelastic behavior in the plastic-hinge region.

The observed condition therefore represents a trade-off in which the as-built reinforcement configuration remains adequate with respect to the calculated strength and serviceability criteria, but does not achieve full compliance with the required transverse reinforcement detailing. In other words, strength adequacy does not necessarily imply complete code compliance. For seismic structural members, the detailing provisions are an integral part of the structural safety requirements because they contribute to ductility, confinement, crack control, and the ability of the member to sustain cyclic inelastic deformation.

3.6. Comparison with Previous Studies

The findings of this study are consistent with the general understanding reported in previous studies that changes in reinforcement configuration can influence the structural response of reinforced concrete members. Hamkah et al. investigated the improvement of flexural moment capacity by changing reinforcement configuration, demonstrating the importance of reinforcement arrangement in determining beam flexural behavior [2]. In comparison, the present study focuses on the opposite condition, namely a reduction in the as-built longitudinal reinforcement configuration, and evaluates whether the remaining reinforcement is still adequate under the actual design demands.

Similarly, Zulfikri et al. evaluated reinforced concrete beams with variations in span, dimensions, and reinforcement [8]. Their study emphasizes the relationship between member geometry, reinforcement, and structural capacity. The present research extends this perspective by evaluating an actual as-built deviation in reinforcement specifications while maintaining the existing beam geometry and material properties.

Furthermore, Tamayo and Garcia reassessed the flexural behavior of reinforced concrete beams under short-term loading [10]. Their work provides a basis for understanding the relationship between reinforcement and flexural response, whereas the present study evaluates a broader set of performance criteria, including flexure, shear, torsion, serviceability, and reinforcement detailing.

These previous studies show that reinforcement configuration and member characteristics are important factors governing structural behavior. The contribution of the present study lies in evaluating an actual as-built reinforcement deviation and examining not only calculated strength but also serviceability and code-based detailing compliance. This approach provides a more comprehensive assessment of the safety implications of specification modifications in an existing construction condition.

3.7. Structural Implications of the Modification

The results indicate that the as-built beam retains sufficient calculated structural capacity under the loading conditions analyzed. Nevertheless, the reduction in longitudinal reinforcement reduces the theoretical reserve capacity compared with the original reinforcement configuration. Therefore, the conclusion that the beam is adequate applies specifically to the design demands and structural conditions considered in this study and should not be interpreted as evidence that any further reduction in reinforcement would remain acceptable.

More importantly, the non-compliance in transverse reinforcement detailing represents a separate structural concern. The support region requires closer transverse reinforcement because it corresponds to the region where high shear demand and potential plastic-hinge formation may occur. Excessive stirrup spacing may compromise confinement and ductile behavior even when the calculated nominal shear strength remains adequate. Consequently, for seismic structural systems, compliance with reinforcement detailing requirements is necessary in addition to satisfying nominal strength criteria.

The principal finding of the material-utilization assessment is not that the reinforcement modification constitutes a verified material-saving or VE solution. The investigated as-built configuration maintains

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adequate calculated strength and serviceability under the analyzed loading conditions but remains partially non-compliant because of transverse reinforcement detailing.

Any future modification to reinforcement specifications should therefore be evaluated through a complete structural assessment covering strength, serviceability, ductility**,** reinforcement detailing, and applicable seismic requirements before the modification is accepted for construction or considered technically feasible.

4. CONCLUSION

Based on the structural evaluation of the as-built reinforced concrete beam of the SMK Karya Bhakti Brebes building, the following conclusions can be drawn:

1. Strength Performance

The as-built beam satisfies the evaluated nominal flexural, shear, and torsional strength demands under the loading conditions considered in this study. The calculated design flexural strength exceeds the governing bending moment, while the calculated shear and torsional capacities remain greater than their respective factored design demands. Therefore, no nominal strength failure was identified in the evaluated beam.

2. Serviceability Performance

The calculated beam deflection remains below the applicable allowable deflection limit specified by SNI 2847:2019. This indicates that the as-built reinforcement configuration satisfies the evaluated serviceability requirement under the considered loading conditions.

3. Code Compliance and Seismic Detailing

Although the beam satisfies the evaluated nominal strength and serviceability demands, it cannot be considered fully code-compliant because the transverse reinforcement detailing does not satisfy the seismic detailing requirements of SNI 2847:2019. In particular, the provided stirrup spacing in the evaluated beam exceeds the applicable maximum spacing requirements in the critical beam regions. This finding demonstrates that adequate calculated strength alone is insufficient to establish full compliance for a beam forming part of a seismic structural system.

4. Overall Assessment

The observed as-built reinforcement modification does not result in failure of the evaluated nominal strength or serviceability criteria under the design conditions considered. However, the non-compliance in transverse reinforcement detailing remains an important structural concern, particularly with respect to confinement and ductile behavior under seismic actions. Therefore, the beam should be regarded as satisfying the evaluated strength and serviceability demands but requiring improvement or verification of its transverse reinforcement detailing to achieve compliance with the applicable provisions of SNI 2847:2019.

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