DESIGN ANALYSIS OF REINFORCED CONCRETE BRIDGES BASED ON STRUCTURAL PERFORMANCE, COST EFFICIENCY, AND TRAFFIC LOAD RESISTANCE

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Abstract
This study aims to analyze reinforced concrete bridge design based on structural performance, cost efficiency, and resistance to traffic loads. A quantitative approach was employed through structural analysis simulations and comparisons of three bridge design alternatives with a span of 12 meters and a width of 7 meters. The evaluated parameters included flexural capacity, shear forces, deflection, material requirements, and estimated construction costs. Hypothetical simulation results indicated that all alternatives satisfied the assumed structural assessment criteria. Alternative B achieved a flexural utilization ratio of 0.896, a deflection of 11.10 mm, and an estimated cost of IDR 208,850,000, representing 5.73% savings compared with the reference design. This study demonstrates the potential of integrated evaluation to improve bridge design efficiency.
Keywords: Reinforced Concrete Bridge; Structural Performance; Cost Efficiency; Traffic Loads; Bridge Design.

INTRODUCTION

Bridges are among the transportation infrastructures that play a strategic role in supporting interregional connectivity, improving public accessibility, and facilitating the distribution of goods and services. Bridges not only serve as connecting structures between areas separated by rivers, valleys, or other geographical barriers but also constitute essential infrastructure supporting social activities and economic growth. Within road transportation networks, bridges must provide safe, comfortable, and sustainable transportation services throughout their design life. Therefore, bridge structural design requires comprehensive technical considerations, particularly regarding the ability of the structure to withstand various load combinations. Thakkar et al. (2023) explained that bridges are vital components of modern transportation systems; however, they are vulnerable to various factors that may reduce structural performance and safety. This condition indicates that the quality of bridge design is a critical factor in ensuring the sustainability of transportation infrastructure.

The development of road and bridge infrastructure requires the implementation of structural systems capable of accommodating transportation demands while considering technical and economic aspects. One of the most widely used construction types is reinforced concrete bridges, as concrete has a high capacity to resist compressive forces, while reinforcing steel enhances the structural capacity to withstand tensile forces. The combination of these two materials enables the development of structural elements capable of resisting applied loads and being designed in various geometric configurations. Nevertheless, the use of reinforced concrete does not automatically guarantee construction efficiency and safety if element dimensions, material properties, and reinforcement requirements are not properly designed. Kaveh et al. (2022) demonstrated that the optimization of reinforced concrete bridge structures can be achieved by adjusting geometric dimensions, concrete compressive strength, and reinforcement configurations to obtain designs with lower costs and environmental impacts. Therefore, the selection and design of reinforced concrete structures should be based on a balance between structural capacity and the efficient utilization of construction resources.

Structural performance is one of the primary indicators in determining the effectiveness of reinforced concrete bridge design. This performance relates to the ability of a structure to maintain its strength, stiffness, stability, and serviceability under loads acting throughout its design life. Structural performance analysis is generally conducted by evaluating the responses of bridge elements to bending moments, shear forces, stresses, deformations, and potential concrete cracking. Furthermore, the interaction between the bridge deck slab, main girders, diaphragms, bearings, and substructure must be considered to ensure effective load transfer mechanisms. Zhou and Chen (2024) explained that the structural response of reinforced concrete bridges to vehicular loading may be influenced by dynamic vehicle–bridge interactions. Therefore, structural evaluation requires an understanding of both global structural responses and the local behavior of bridge components. This demonstrates that structural performance analysis should not rely solely on nominal strength capacity but must also consider structural behavior under operational loading conditions.

In the bridge design process, loading is a major factor determining the magnitude of internal forces and the required dimensions of structural elements. Loads acting on bridges may originate from the self-weight of the structure,

superimposed dead loads, vehicular traffic, braking forces, environmental effects, and other specific conditions. Bridge design must account for relevant load combinations to ensure that the structure satisfies safety and serviceability requirements. In Indonesia, SNI 1725:2016 concerning Loading for Bridges is widely used as a technical reference for bridge loading analysis, including provisions related to loads, load factors, and load combinations (Badan Standardisasi Nasional [BSN], 2016). Proper application of loading provisions is essential because errors in identifying or combining loads may result in overly conservative designs or structures with inadequate capacity. Therefore, loading analysis must be conducted systematically according to the characteristics of the proposed bridge.

Traffic loading is one of the aspects requiring particular attention in reinforced concrete bridge design because it is moving, variable, and repeatedly applied. Differences in vehicle types, axle configurations, vehicle weights, speeds, and positions on the bridge deck may produce variations in structural responses. Under certain conditions, heavy vehicles may generate dynamic effects that increase stresses and deformations in bridge elements compared with static loading conditions. Zhou and Chen (2024) reported that repeated traffic loading can cause fatigue damage accumulation in reinforced concrete bridge decks, particularly when influenced by vehicle–bridge interaction, road surface irregularities, and the proportion of heavy vehicles. Accordingly, structural resistance to traffic loading should be evaluated not only based on the capacity to withstand maximum loads but also by considering structural responses to loading patterns that may affect bridge serviceability and durability.

In addition to structural strength and resistance to traffic loads, serviceability is an important consideration in evaluating the feasibility of a bridge design. A structure with adequate strength capacity may not necessarily provide optimal service performance if it experiences excessive deflection, uncontrolled cracking, or changes in stiffness that affect user comfort. Such conditions may reduce service quality and potentially accelerate structural deterioration over time. Stoilova (2024) explained that reinforced concrete bridges may undergo various deterioration processes caused by environmental influences and damage mechanisms developing during their operational life. Therefore, bridge design must consider the relationship between structural strength, serviceability, and material durability. Evaluating these parameters is essential to ensure that the proposed design not only meets initial construction requirements but also supports the long-term functionality of the bridge throughout its service life.

Cost efficiency is another essential aspect of bridge design, particularly in infrastructure projects with limited construction budgets. The construction cost of reinforced concrete bridges is influenced by several components, including concrete volume, reinforcing steel quantities, formwork, construction methods, and material and labor requirements. Excessively large structural dimensions may increase material consumption and construction costs, whereas reducing dimensions without adequate analysis may compromise structural capacity. Therefore, cost efficiency should not be understood merely as an effort to achieve the lowest construction cost but rather as a process of developing an economical design while satisfying all technical and safety requirements. Kaveh et al. (2022) demonstrated that optimization approaches applied to reinforced concrete bridge elements enable the identification of more efficient design configurations through adjustments to structural parameters. These findings emphasize the importance of integrating technical analysis and cost considerations into bridge design decision-making.

The relationship between structural performance and cost efficiency becomes increasingly important because every modification to design parameters may affect material requirements and structural responses. Increasing girder dimensions, for example, may improve stiffness and certain structural capacities, but it also increases self-weight and concrete volume. Similarly, changes in concrete strength or reinforcement quantities may affect cross-sectional capacity and material procurement costs. Therefore, selecting an optimal design requires evaluating several design alternatives using measurable technical and economic parameters. A study on the optimization of highway bridge superstructure configurations published in Heliyon (2024) demonstrated that structural configuration selection can be conducted using a decision-support approach that considers construction costs, implementation time, and technical characteristics. This approach indicates that selecting the most appropriate structural alternative should be based on systematic comparisons rather than a single design parameter.

One of the common challenges in reinforced concrete bridge design is determining a structural configuration that satisfies safety requirements while ensuring efficient material utilization. An overly conservative design may produce a structure with substantial reserve capacity but potentially increase construction costs without providing benefits proportional to the additional material consumption. Conversely, a design that places excessive emphasis on cost reduction may introduce risks if flexural capacity, shear capacity, deflection, and responses to traffic loading are not comprehensively evaluated. This challenge becomes increasingly complex when variations in vehicle loading must be considered alongside changes in structural dimensions and reinforcement requirements. Kaveh et al. (2022) emphasized the importance of optimizing bridge structural design parameters, while Zhou and Chen (2024) highlighted the need to consider responses resulting from traffic–structure interactions in structural analysis. These studies indicate that design evaluation integrating mechanical and economic aspects plays an important role in developing rational bridge design alternatives.

Previous studies have contributed significantly to the development of methods for analyzing and optimizing bridge structures. Kaveh et al. (2022) developed an optimization approach for reinforced concrete bridge columns and pier caps by considering construction costs and carbon emissions. Zhou and Chen (2024) investigated fatigue damage assessment of reinforced concrete bridge decks through a dynamic vehicle–bridge interaction approach. Meanwhile, Stoilova (2024) reviewed various deterioration processes affecting reinforced concrete bridges that may influence structural performance throughout their service life. These studies demonstrate the advancement of bridge evaluation approaches in terms of

material optimization, structural behavior under vehicle loading, and structural durability. However, each study has a different focus and scope, indicating that opportunities remain to develop a design assessment framework that integrates structural performance parameters, cost efficiency, and responses to variations in traffic loading.

Based on the preceding discussion, the research gap underlying this study is the need for a comparative evaluation that simultaneously integrates structural performance, construction cost requirements, and the responses of reinforced concrete bridges to variations in traffic loading. Previous studies have addressed these aspects using different approaches and research objects; however, selecting a design for a particular bridge project still requires an integrated assessment based on consistent parameters and constraints. The proposed novelty of this study lies in the application of a multicriteria evaluation framework to compare design alternatives based on flexural and shear capacities, deflection, concrete and reinforcing steel requirements, cost estimates, and changes in structural responses under different traffic loading scenarios. Through this approach, the relationship between changes in design parameters and their technical and economic consequences is expected to be explained more quantitatively, ensuring that the selected alternative not only prioritizes the lowest cost but also satisfies safety and serviceability requirements.

Based on the aforementioned background, this study aims to analyze reinforced concrete bridge design based on three primary aspects: structural performance, cost efficiency, and resistance to traffic loading. The analysis focuses on evaluating the capacity and responses of structural elements, calculating material requirements and estimating construction costs, and comparing the effects of traffic loading variations on bridge behavior. The evaluation results are subsequently used to identify design alternatives that satisfy technical requirements while achieving greater efficiency in material utilization and construction costs. This study is expected to contribute scientifically to the development of an integrated reinforced concrete bridge design approach and provide technical considerations for engineers, designers, and infrastructure construction practitioners in selecting bridge designs that are safe, economical, and capable of delivering sustainable transportation services.

RESEARCH METHODOLOGY

3.1. Research Design and Approach

This study employed a quantitative research approach using descriptive and comparative analytical methods based on structural modeling. The quantitative approach was adopted to examine the relationships among reinforced concrete bridge design parameters, loading characteristics, structural responses, and construction cost requirements. The comparative method was applied to evaluate different structural configurations based on structural safety, serviceability, and material efficiency. The research involved structural mechanics calculations, numerical modeling, and construction cost estimation to ensure that each parameter could be evaluated objectively using measurable indicators. The methodology was developed based on limit state design principles commonly applied in bridge engineering, as outlined in the technical guidelines issued by the Directorate General of Highways (2021). The research focused on the superstructure of a reinforced concrete highway bridge, particularly the bridge deck slab, main girders, and structural stiffening elements. The evaluation considered bridge geometry, material properties, support conditions, and vehicular loading characteristics. To ensure consistency and comparability, all design alternatives were assessed using the same bridge span, width, loading provisions, and structural safety criteria. This approach enabled a systematic investigation of how variations in structural configurations influence bridge performance and construction costs.

3.2. Data and Data Sources

The data used in this study consisted of structural analysis results, numerical modeling outputs, and secondary information obtained from engineering design documents, technical standards, scientific publications, and construction unit price references. Geometric parameters included bridge span length, total bridge width, deck slab thickness, main girder dimensions, girder spacing, and bearing system characteristics. Material properties consisted of concrete compressive strength, reinforcing steel yield strength, material density, and modulus of elasticity. Loading data included structural self-weight, additional permanent loads, and vehicular traffic loads determined according to the applicable bridge design standards. Material requirements were estimated by calculating concrete volumes and reinforcing steel quantities for each structural configuration. Construction costs were determined using unit prices appropriate to the project location and implementation period. All collected data were organized systematically to establish consistent input parameters for structural modeling, design evaluation, and comparative analysis. The use of standardized parameters ensured that differences in analytical results could be attributed primarily to variations in structural configurations rather than inconsistencies in the underlying assumptions.

3.3. Structural Design and Modeling Procedures

The structural design process began with the development of a reinforced concrete bridge model based on predetermined geometric dimensions, material properties, and structural system characteristics. The model represented the interaction among the bridge deck slab, main girders, diaphragms, and supporting elements to simulate the distribution of loads throughout the bridge superstructure. Numerical structural analysis was designed to be conducted using finite element modeling software, such as SAP2000 or equivalent structural analysis applications. The modeling procedure included defining structural element properties, establishing boundary conditions, specifying bearing characteristics, and applying

appropriate load distributions. Particular attention was given to ensuring that the structural model adequately represented the actual load transfer mechanisms and expected structural behavior. Model verification was incorporated through examinations of force equilibrium, support reactions, and comparisons between numerical results and simplified structural mechanics calculations. This verification procedure was intended to minimize potential modeling errors and improve the reliability of the analytical results. Following verification, the structural models were evaluated under relevant loading combinations to determine internal forces, displacements, and other structural responses required for subsequent performance assessments.

3.4. Bridge Loading Analysis

Bridge loading analysis was conducted by identifying the permanent and variable actions affecting the structure under serviceability and ultimate limit state conditions. Permanent loads included the self-weight of reinforced concrete components, pavement layers, safety barriers, and other fixed structural elements. Variable loads primarily consisted of vehicular traffic actions, including the effects of vehicle positioning and load distribution across the bridge deck. Traffic loading was evaluated by considering critical loading positions capable of generating maximum structural responses in the main girders and deck slab. Dynamic effects were also considered where required by applicable bridge design provisions. The loading analysis referred to SNI 1725:2016 concerning bridge loading requirements and the practical bridge design guidelines published by the Directorate General of Highways (Badan Standardisasi Nasional, 2016; Directorate General of Highways, 2021). The evaluation followed the principles of Load and Resistance Factor Design (LRFD), in which the effects of factored loads are compared with the available design resistance of structural elements. Load factors and resistance factors were selected according to the relevant technical requirements to ensure that the proposed bridge configurations satisfied structural safety criteria. This procedure provided a consistent basis for determining critical internal forces and evaluating the adequacy of structural elements under different loading conditions.

3.5. Structural Performance Analysis

Structural performance analysis was conducted to assess the ability of reinforced concrete bridge components to withstand applied loads while maintaining acceptable serviceability conditions. The evaluation focused on maximum bending moments, shear forces, cross-sectional strength capacities, structural deflections, and reinforcement requirements. Flexural performance was assessed by comparing the bending moment demand resulting from factored loads with the available design flexural capacity of the structural elements. Similarly, shear performance was evaluated by comparing the calculated shear force demand with the corresponding design shear resistance. Structural elements were considered to satisfy strength requirements when the calculated demands did not exceed their respective design capacities. In addition to strength verification, serviceability performance was examined by evaluating structural deflections under relevant loading combinations and comparing the results with the allowable limits established by applicable technical standards. Variations in girder dimensions, deck slab thickness, and reinforcement arrangements were examined to identify their influence on structural stiffness, strength capacity, and material consumption. The results provided a basis for evaluating the relationship between structural adequacy and design efficiency, particularly in identifying configurations capable of achieving satisfactory structural performance without unnecessary increases in material requirements.

3.6. Analysis of Resistance to Traffic Loading

The resistance of reinforced concrete bridge structures to variations in traffic loading was evaluated through a loading sensitivity analysis involving three loading scenarios. The first scenario, designated S1, represented a reduced traffic loading condition equivalent to 80% of the reference traffic load. The second scenario, S2, represented the reference condition corresponding to 100% of the specified traffic load. The third scenario, S3, represented an increased loading condition equivalent to 120% of the reference traffic load. These scenarios were applied to the same structural models to examine changes in bending moments, shear forces, deflections, and structural capacity utilization. The evaluation focused on determining the extent to which increased traffic loading intensity affected the structural responses and available strength reserves of the bridge components. Structural capacity utilization was assessed by comparing the calculated load effects with the corresponding design resistance, while serviceability performance was evaluated through changes in deflection. The loading variation factors were adopted specifically for sensitivity analysis and were not intended to replace the standard load factors specified in bridge design regulations. Accordingly, the assessment of traffic load resistance was limited to structural strength and serviceability responses under different loading intensities. Fatigue resistance and the remaining service life associated with repeated traffic loading were not evaluated within the scope of this study.

3.7. Construction Cost Efficiency Analysis

Construction cost efficiency was evaluated by estimating the material quantities and associated construction costs for each reinforced concrete bridge design alternative. The analysis focused on construction components affected by differences in structural configurations, including structural concrete, reinforcing steel, formwork, and other relevant direct construction activities. Concrete requirements were determined based on the geometric dimensions of the deck slab, main girders, and other structural elements, while reinforcing steel quantities were estimated by considering reinforcement diameters, lengths, quantities, anchorage requirements, and reinforcement arrangements. The estimated construction cost

of each alternative was obtained by multiplying the calculated quantities of individual work items by their corresponding unit prices and combining the resulting costs. To ensure comparability, consistent unit price references were applied across all design alternatives, considering the same construction location and implementation period. Cost efficiency was assessed by comparing the estimated cost of each alternative with the reference design. An alternative was considered more cost-efficient when it achieved a lower estimated construction cost while continuing to satisfy all structural strength and serviceability requirements. Conversely, alternatives requiring higher costs were evaluated to determine whether the additional expenditure was justified by improvements in structural performance. The cost analysis was limited to the construction components included in the evaluation and did not incorporate comprehensive life-cycle costs, such as long-term maintenance, rehabilitation, or replacement expenses.

3.8. Comparative Analysis of Design Alternatives

The comparative evaluation was conducted by integrating structural performance indicators, responses to traffic loading variations, and estimated construction costs. Each design alternative was assessed based on flexural strength, shear strength, maximum deflection, structural capacity utilization, concrete volume, reinforcing steel requirements, and total construction costs. The evaluation was performed in two main stages. The first stage involved verifying whether each structural configuration satisfied the minimum strength and serviceability requirements established by the applicable design standards. Alternatives that failed to satisfy these technical requirements were excluded from further consideration as feasible design options, regardless of their potential cost advantages. The second stage involved comparing technically acceptable alternatives based on material consumption, cost efficiency, and sensitivity to increased traffic loading. This integrated assessment was intended to identify a structural configuration that provided an appropriate balance between engineering performance and economic considerations. Rather than selecting an alternative solely because it required the lowest construction expenditure, the evaluation emphasized the importance of maintaining adequate structural capacity, acceptable deformation behavior, and efficient material utilization. The findings were subsequently used to determine the most suitable design alternative within the scope and limitations of the study.

3.9. Research Implementation Stages

The research implementation was organized into a systematic sequence beginning with a literature review and the collection of technical data related to bridge geometry, material characteristics, loading requirements, structural design criteria, and construction unit prices. Following the preliminary data collection, three structural design configurations were established and designated as Alternative A, Alternative B, and Alternative C. These alternatives were developed to represent variations in structural dimensions and reinforcement requirements while maintaining consistent bridge geometry and loading assumptions. Structural models were then prepared to evaluate the responses of each alternative under the specified load combinations. The resulting bending moments, shear forces, deflections, and capacity utilization levels were examined to determine compliance with structural strength and serviceability requirements. When a particular design configuration failed to satisfy the adopted technical criteria, modifications to the relevant structural parameters were considered, followed by repeated analysis until an acceptable configuration was obtained. Subsequently, technically feasible alternatives were evaluated based on concrete quantities, reinforcing steel requirements, formwork volumes, and estimated construction costs. The results were compiled and compared to determine the configuration offering the most favorable balance among structural performance, traffic loading resistance, and construction cost efficiency. The final stage involved interpreting the comparative results and formulating conclusions and design recommendations based on the established evaluation criteria.

3.10. Data Processing and Interpretation Techniques

The data obtained from structural calculations, numerical modeling, and construction cost estimation were processed using descriptive and comparative quantitative analysis techniques. The analytical results were classified according to structural performance indicators, variations in traffic loading responses, material requirements, and estimated construction costs. Structural performance data were interpreted by examining differences in bending moments, shear forces, deflections, and capacity utilization ratios among the proposed alternatives. The effects of traffic loading variations were evaluated by observing changes in structural responses under reduced, reference, and increased loading scenarios. Material efficiency was assessed by comparing concrete and reinforcing steel requirements, while economic performance was evaluated through differences in estimated construction costs. The processed data were intended to be presented using comparative tables, graphical representations of structural responses, and diagrams illustrating construction cost differences among design alternatives. The final interpretation emphasized the relationship between changes in structural configuration, engineering performance, and economic efficiency. Conclusions were drawn by considering compliance with technical design requirements, sensitivity to traffic loading variations, and opportunities for construction cost savings. Through this analytical framework, the study aimed to provide a systematic understanding of the technical and economic implications of alternative reinforced concrete bridge designs while maintaining a clear distinction between structural compliance assessments, loading sensitivity evaluations, and construction cost comparisons.

RESULTS AND DISCUSSION

3.1 Bridge Characteristics and Design Alternatives

The bridge considered in this hypothetical study was a reinforced concrete highway bridge with a simply supported span of 12 meters and an overall width of 7 meters. The superstructure consisted of a reinforced concrete deck slab, longitudinal main girders, and diaphragm elements designed to support and distribute traffic loads. The specified concrete compressive strength was 30 MPa, while the yield strength of the reinforcing steel was 420 MPa. These material properties were maintained consistently across all design alternatives to ensure that differences in structural responses and material requirements could be attributed primarily to variations in girder configurations and cross-sectional dimensions.

Three structural configurations were developed for comparative evaluation. Alternative A was established as the reference design, consisting of five main girders with a width of 350 mm and a depth of 800 mm. Alternative B consisted of four main girders with larger cross-sectional dimensions of 400 mm in width and 900 mm in depth. Meanwhile, Alternative C employed five main girders with a width of 400 mm and a depth of 1,000 mm. All three alternatives maintained the same bridge span, overall width, and deck slab thickness of 220 mm. The variation in girder quantity and dimensions was intended to represent different structural arrangements and examine their potential influence on stiffness, load-carrying capacity, material consumption, and construction costs.

The comparison of these configurations indicated that increasing girder dimensions could theoretically improve structural stiffness and load-carrying capacity, although such modifications might also increase structural self-weight and material requirements. Conversely, reducing the number of main girders could potentially decrease material consumption while increasing the tributary loads and structural demands acting on individual girders. Alternative B represented a configuration in which the reduction in the number of girders was compensated for by increasing their cross-sectional dimensions. Alternative C represented a more substantial structural configuration designed to provide greater stiffness and strength capacity. These differences demonstrated the importance of evaluating the behavior of the entire structural system rather than assessing individual structural dimensions independently.

3.2 Structural Performance Analysis of Reinforced Concrete Bridges

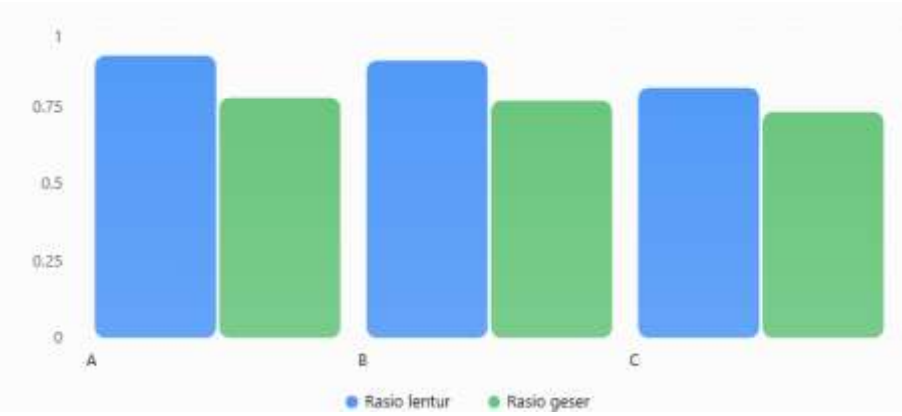
Structural performance was evaluated by comparing the assumed flexural and shear demands with the corresponding design capacities of the main structural elements. The hypothetical results indicated that Alternative A experienced a factored bending moment of 620 kN·m and had a design flexural capacity of 680 kN·m, resulting in a flexural capacity utilization ratio of 0.912. Alternative B exhibited a factored bending moment of 645 kN·m and a design flexural capacity of 720 kN·m, producing a utilization ratio of 0.896. Meanwhile, Alternative C had the highest factored bending moment of 670 kN·m but also provided the greatest design flexural capacity of 830 kN·m, resulting in the lowest utilization ratio of 0.807.

These simulated results indicated that all three alternatives maintained flexural capacity utilization ratios below the threshold of 1.00. Alternative A exhibited the highest utilization level, suggesting that its assumed flexural capacity was utilized more extensively under the reference loading condition. Alternative C demonstrated the greatest relative reserve of flexural capacity, while Alternative B showed a slightly lower utilization ratio than the reference design despite having fewer main girders. However, a lower utilization ratio does not necessarily indicate a more efficient design because additional structural capacity may require greater material consumption and higher construction costs.

The hypothetical shear strength evaluation produced a similar pattern. Alternative A experienced a factored shear force of 395 kN and had a design shear capacity of 510 kN, resulting in a shear utilization ratio of 0.775. Alternative B exhibited a factored shear force of 410 kN and a design shear capacity of 535 kN, corresponding to a utilization ratio of 0.766. Alternative C experienced the highest factored shear force of 430 kN but also provided the greatest design shear capacity of 590 kN, producing the lowest shear utilization ratio of 0.729. These values indicated that the assumed shear demands remained below the corresponding design capacities for all alternatives.

The comparative results suggested that Alternative B could potentially provide a favorable balance between structural capacity and configuration efficiency. Although this alternative employed fewer main girders, its increased cross-sectional dimensions were associated with acceptable flexural and shear utilization ratios in the hypothetical model. Alternative C provided the greatest reserve capacity but required larger structural elements. Nevertheless, the reported capacities were assumed for conceptual comparison and were not derived from detailed reinforcement design or verified structural modeling. Therefore, comprehensive assessments of transverse load distribution, reinforcement detailing, torsion, connections, and other structural components would be necessary before establishing actual compliance with bridge design requirements.

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3.3 Evaluation of Bridge Deflection and Serviceability

The serviceability evaluation focused on the maximum vertical deflection of the bridge superstructure under the reference traffic loading condition. Deflection was considered an important indicator of structural stiffness and service performance because excessive deformation may affect user comfort and the long-term functionality of bridge components. For this hypothetical assessment, the allowable deflection was assumed to be one-eight-hundredth of the bridge span, referring to the standard bridge design criteria published by the Directorate General of Highways (2017). For the assumed bridge span of 12 meters, this criterion corresponded to a maximum allowable deflection of 15 mm. The criterion was adopted specifically for the simulation and would require confirmation against the applicable requirements for an actual bridge design.

The hypothetical analysis indicated that Alternative A experienced a maximum deflection of 12.40 mm, corresponding to a deflection utilization ratio of 0.827. Alternative B produced a maximum deflection of 11.10 mm and a utilization ratio of 0.740, while Alternative C exhibited the smallest deflection of 9.40 mm and a utilization ratio of 0.627. All three alternatives remained below the assumed allowable deflection limit of 15 mm, indicating satisfactory serviceability performance within the simplified simulation framework.

The comparison revealed that Alternative C demonstrated the greatest stiffness-related advantage, as reflected by its relatively small vertical deflection. This behavior could be conceptually associated with the larger girder dimensions and the resulting increase in structural stiffness. Alternative B also exhibited improved serviceability performance compared with Alternative A, with a reduction in maximum deflection of approximately 10.48%. This result suggested that reducing the number of girders does not necessarily increase structural deformation when the reduction is accompanied by appropriate adjustments to cross-sectional dimensions and overall system stiffness.



Nevertheless, these relationships remain illustrative because actual bridge deflections depend on several interacting factors, including transverse load distribution, deck slab stiffness, girder spacing, support conditions, and the positioning of vehicular loads. Accordingly, the assumed deflection values should not be interpreted as verified results from a finite element analysis. A detailed structural model would be required to confirm whether the proposed configurations achieve the predicted serviceability performance under the relevant design loading conditions.

3.4 Effects of Traffic Loading Variations on Structural Responses

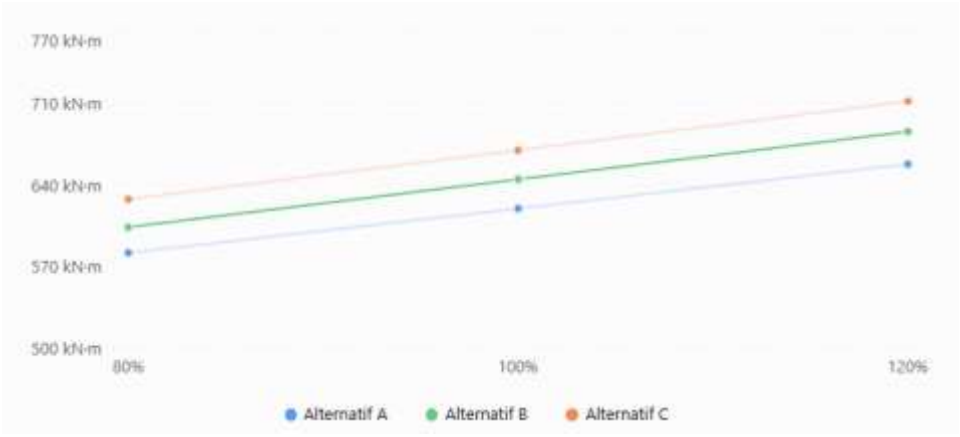
The effects of traffic loading variations were evaluated using three hypothetical loading scenarios representing 80%, 100%, and 120% of the reference traffic load. The 100% scenario was established as the baseline condition, while the 80%

and 120% scenarios were introduced to examine structural sensitivity to decreases and increases in traffic loading intensity. In this simplified analysis, permanent load effects were assumed to remain constant, whereas the traffic load contribution was varied proportionally according to the assigned loading scenario. This approach was adopted to illustrate the relationship between traffic loading intensity and structural response rather than to replace the load combinations specified in bridge design standards.

Under the reference condition, Alternative A had an assumed permanent-load bending moment contribution of 430 kN·m and a traffic-load contribution of 190 kN·m. Alternative B had corresponding contributions of 440 kN·m and 205 kN·m, while Alternative C had contributions of 460 kN·m and 210 kN·m. Under the reduced traffic loading scenario of 80%, the total factored bending moments were 582 kN·m for Alternative A, 604 kN·m for Alternative B, and 628 kN·m for Alternative C. At the reference traffic loading level of 100%, the corresponding bending moments increased to 620 kN·m, 645 kN·m, and 670 kN·m, respectively.

When traffic loading intensity was increased to 120%, the simulated bending moments reached 658 kN·m for Alternative A, 686 kN·m for Alternative B, and 712 kN·m for Alternative C. Compared with the reference loading condition, these changes represented increases of approximately 6.13%, 6.36%, and 6.27%, respectively. The results indicated that increasing traffic loading intensity produced higher bending moment demands in all three structural configurations. However, the magnitude of the total bending moment alone was insufficient to determine which alternative provided the greatest structural safety margin because each configuration possessed a different assumed flexural capacity.

To obtain a more meaningful comparison, the bending moment demands under each loading scenario were evaluated relative to the corresponding design flexural capacities. Under the 80% traffic loading scenario, the flexural utilization ratios were 0.856 for Alternative A, 0.839 for Alternative B, and 0.757 for Alternative C. Under the reference loading condition, these ratios increased to 0.912, 0.896, and 0.807, respectively. At the highest traffic loading scenario of 120%, the utilization ratios reached 0.968 for Alternative A, 0.953 for Alternative B, and 0.858 for Alternative C.



The hypothetical results showed that all three alternatives maintained flexural utilization ratios below 1.00 under the analyzed loading scenarios. Alternative C exhibited the greatest relative reserve capacity, while Alternative A approached the assumed design capacity most closely under the increased loading condition. Alternative B maintained a utilization ratio of 0.953 at the 120% traffic loading level, indicating that its assumed flexural resistance remained greater than the corresponding demand within the simplified model. These findings demonstrated the usefulness of sensitivity analysis in identifying differences in structural responses and capacity utilization among alternative bridge configurations.

However, the 120% loading scenario should not be interpreted as evidence that the bridge could safely accommodate overloaded vehicles in actual operating conditions. Such an assessment would require comprehensive evaluation of vehicle axle configurations, load distribution, relevant load combinations, and the behavior of all critical structural components. Furthermore, repeated traffic loading may introduce fatigue-related deterioration that cannot be evaluated solely through changes in maximum bending moment or capacity utilization. Therefore, the results should be interpreted as a conceptual representation of short-term structural sensitivity rather than a comprehensive assessment of long-term traffic loading resistance.

3.5 Construction Cost Efficiency Analysis

Construction cost efficiency was evaluated by comparing the assumed quantities of structural concrete, reinforcing steel, and formwork required for each bridge design alternative. These components were selected because they were directly influenced by differences in girder dimensions and structural configurations. The analysis excluded foundations, abutments, bearings, pavement works, mobilization, and other supporting construction activities. Therefore, the estimated costs represented only the selected bridge superstructure components rather than the total cost of constructing a complete bridge.

The hypothetical material quantity estimates indicated that Alternative A required 40.00 m³ of structural concrete, 5,800 kg of reinforcing steel, and 210 m² of formwork. Alternative B required 37.00 m³ of concrete, 5,500 kg of reinforcing

steel, and 200 m² of formwork. Meanwhile, Alternative C required 44.00 m³ of structural concrete, 6,500 kg of reinforcing steel, and 220 m² of formwork. Compared with the reference design, Alternative B demonstrated reductions of 7.50% in concrete volume, 5.17% in reinforcing steel quantity, and 4.76% in formwork requirements. These differences suggested that reducing the number of main girders could potentially improve material efficiency when accompanied by an appropriate adjustment of structural dimensions.

For the construction cost simulation, uniform hypothetical unit prices were adopted for all three alternatives. Structural concrete was assigned a unit price of IDR 1,550,000 per cubic meter, reinforcing steel was valued at IDR 19,000 per kilogram, and formwork was estimated at IDR 235,000 per square meter. These values were assumptions developed for comparative analysis and did not represent verified market prices or officially established regional construction unit prices.

Based on these assumptions, the estimated structural concrete cost was IDR 62.00 million for Alternative A, IDR 57.35 million for Alternative B, and IDR 68.20 million for Alternative C. Reinforcing steel costs were estimated at IDR 110.20 million, IDR 104.50 million, and IDR 123.50 million, respectively. Formwork costs were estimated at IDR 49.35 million for Alternative A, IDR 47.00 million for Alternative B, and IDR 51.70 million for Alternative C. Consequently, the total estimated construction costs were IDR 221.55 million for Alternative A, IDR 208.85 million for Alternative B, and IDR 243.40 million for Alternative C.

The comparison indicated that Alternative B provided the lowest estimated construction cost among the three configurations. Relative to Alternative A, the estimated cost reduction was IDR 12.70 million, equivalent to approximately 5.73%. Conversely, Alternative C required an additional IDR 21.85 million, representing an increase of approximately 9.86% compared with the reference design. Reinforcing steel constituted the largest cost component in all alternatives, suggesting that changes in reinforcement quantity could significantly influence the overall estimated construction cost of the bridge superstructure.

These results indicated that Alternative B had the greatest potential for construction cost savings within the hypothetical comparison. However, the material quantities were assumed rather than derived from detailed reinforcement drawings or verified quantity take-offs. Consequently, the reported cost savings should be interpreted as illustrative estimates rather than confirmed economic benefits. An actual construction cost assessment would require detailed structural design, verified material quantities, current regional unit prices, and consideration of other relevant construction activities.

3.6 Relationship Among Structural Performance, Cost Efficiency, and Traffic Loading Resistance

The integrated evaluation demonstrated a relationship among structural configuration, capacity utilization, traffic loading responses, and estimated construction costs. Alternative C exhibited the lowest flexural and shear utilization ratios, indicating the greatest assumed reserve capacity among the three configurations. It also produced the smallest maximum deflection, suggesting comparatively greater structural stiffness. However, these advantages were accompanied by increased concrete consumption, reinforcement requirements, formwork quantities, and construction costs. This finding illustrated that improvements in structural capacity do not necessarily produce corresponding improvements in economic efficiency.

Alternative B demonstrated a different balance between structural and economic performance. Under the reference loading condition, its flexural utilization ratio was 0.896, while its shear utilization ratio was 0.766. The maximum simulated deflection was 11.10 mm, remaining below the assumed allowable limit of 15 mm. Under the increased traffic loading scenario of 120%, the flexural utilization ratio reached 0.953, which remained below the limiting value of 1.00. At the same time, Alternative B produced the lowest estimated construction cost of IDR 208.85 million, representing a potential reduction of 5.73% compared with the reference design.

The comparative findings suggested that Alternative B offered the most favorable balance between the evaluated structural performance indicators and construction costs within the hypothetical simulation. This result indicated that reducing the number of main girders does not necessarily compromise structural performance when the resulting changes in load distribution, girder dimensions, and cross-sectional capacity are appropriately considered. However, the conclusion was limited to the assumed parameters and simplified evaluation criteria. It did not establish that Alternative B would be the optimal configuration for an actual bridge project.

From a conceptual perspective, these results highlighted the importance of integrating structural performance assessment with construction cost analysis during bridge design. The practical bridge design guidelines published by the Directorate General of Highways (2021) emphasize limit state design principles based on the relationship between structural demands and available resistance. Within the context of this study, such principles were complemented by comparative material quantity and cost assessments to identify alternatives with potentially greater economic efficiency while maintaining acceptable structural performance.

Nevertheless, the selection of Alternative B as the most cost-efficient configuration remains provisional because the evaluation was based on hypothetical data and a limited number of performance indicators. The reliability of the findings would need to be established through verified numerical modeling, comprehensive analysis of transverse load distribution between the deck slab and main girders, detailed reinforcement design, and structural verification according to applicable bridge design standards. Furthermore, the resistance of reinforced concrete bridges to repeated traffic loading requires fatigue assessment, which was not included in the present simulation. Accordingly, the findings are more appropriately

interpreted as a demonstration of an integrated comparative evaluation methodology than as a final engineering design recommendation.

3.7 Implications of the Findings for Bridge Design

From an academic perspective, the hypothetical results demonstrated how structural performance, construction cost efficiency, and sensitivity to traffic loading can be evaluated within a unified comparative framework. Strength assessment provided information regarding the utilization of structural element capacities, while deflection analysis represented the serviceability characteristics of each design alternative. Construction cost estimation complemented these technical indicators by identifying the potential economic consequences associated with different structural configurations. Integrating these aspects enabled a more comprehensive assessment than approaches focusing exclusively on structural capacity or construction expenditure.

In practical applications, the proposed evaluation framework could support decision-making during the preliminary design stage of reinforced concrete bridge projects. By considering multiple structural configurations, engineers may identify opportunities to reduce material consumption and construction costs without disregarding essential structural performance requirements. However, the application of this framework to actual bridge projects must also account for site-specific conditions, soil characteristics, foundation requirements, seismic actions, hydrological conditions, scour potential, structural durability, construction methods, and overall project costs. These factors may significantly influence the suitability and economic feasibility of a particular bridge configuration.

The potential contribution of this study lies in the integration of structural performance evaluation, construction cost efficiency assessment, and traffic loading sensitivity analysis as a basis for comparing reinforced concrete bridge design alternatives. Although the hypothetical results suggested that Alternative B could offer a favorable technical and economic balance, this finding requires validation using actual bridge design parameters and verifiable structural analyses. Further investigation could strengthen the proposed approach by incorporating sensitivity assessments related to material strength, structural dimensions, construction unit prices, and traffic loading configurations. Such developments would provide a more reliable basis for identifying reinforced concrete bridge designs that satisfy structural safety, serviceability, and economic efficiency requirements.

CONCLUSIONS

Based on the simulation results of a reinforced concrete bridge design with a span of 12 meters and a width of 7 meters, it can be concluded that variations in structural configurations influence flexural performance, shear capacity, deflection, and construction cost requirements. The comparison of three design alternatives demonstrated that increasing structural element dimensions does not necessarily result in the most economically efficient configuration. Alternatives A, B, and C exhibited flexural capacity utilization ratios of 0.912, 0.896, and 0.807, respectively, while their corresponding shear capacity utilization ratios were 0.775, 0.766, and 0.729. All these values remained below the limiting ratio of 1.00 within the hypothetical model. Alternative C provided the greatest reserve capacity but required higher material quantities and estimated construction costs compared with the other alternatives.

In terms of serviceability, the simulation indicated that the maximum deflections of Alternatives A, B, and C were 12.40 mm, 11.10 mm, and 9.40 mm, respectively. All three values remained below the assumed allowable deflection limit of 15 mm. Under the scenario in which traffic loading was increased to 120% of the reference condition, the flexural capacity utilization ratios increased to 0.968 for Alternative A, 0.953 for Alternative B, and 0.858 for Alternative C. These findings illustrated that increased traffic loading affects structural strength demands, highlighting the importance of evaluating loading variations to determine the sensitivity of each structural configuration. Nevertheless, the analysis did not include an assessment of structural fatigue caused by repeated loading over an extended service period.

From an economic perspective, Alternative B demonstrated the greatest potential for cost efficiency, with an estimated construction cost of IDR 208,850,000, compared with IDR 221,550,000 for Alternative A and IDR 243,400,000 for Alternative C. The adoption of Alternative B resulted in an estimated cost saving of 5.73% relative to the reference design. Therefore, based on the indicators and assumptions applied in the simulation, Alternative B could be considered the most cost-efficient candidate configuration, as it required the lowest construction expenditure while maintaining capacity utilization ratios and deflection values within the adopted limited evaluation criteria. This study demonstrated that integrating structural performance evaluation, responses to traffic loading variations, and cost efficiency assessment can provide a useful approach for comparing reinforced concrete bridge design alternatives. However, the definitive determination of an optimal design requires verified structural analysis, detailed cross-sectional assessments, loading evaluations in accordance with applicable standards, and construction quantity calculations based on engineering design drawings. Accordingly, all numerical findings presented in this study should be regarded as hypothetical simulation results rather than verified evidence of actual bridge performance.

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