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# Performance assessment of steel-concrete composite beams under dynamic loading

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**Abstract**
This research investigates the dynamic performance of steel-concrete composite beams (SCBs) under varying dynamic loading conditions through both experimental testing and finite element (FE) modeling. The study focuses on the influence of interface slip stiffness, shear connection details, and damping on the natural frequencies, dynamic amplification factors (DAF), and damping ratios of composite beams. Experimental results demonstrated significant discrepancies between measured natural frequencies and pre-update FE predictions, primarily due to the neglect of interface slip effects in the initial models. Post-update FE models, incorporating interface slip and damping factors, yielded predictions that closely matched experimental data, with frequency errors reduced to minimal values (within 0.17 Hz). Dynamic amplification was found to be strongly correlated with damping ratios, with higher damping leading to lower peak amplification. Furthermore, a regression analysis revealed a strong inverse relationship between slip stiffness and frequency shift, emphasizing the importance of accurately modeling shear connections in dynamic simulations. The results highlight the importance of model updating and provide practical recommendations for improving the dynamic analysis of composite beams, especially in infrastructure subjected to dynamic loading. This study underscores the need for detailed modeling of interface interactions and damping mechanisms to ensure accurate dynamic response predictions and enhance the safety and reliability of composite structures under real-world loading conditions.

**Keywords:** Steel-concrete composite beams, dynamic loading, interface slip, finite element modeling, damping ratios, natural frequencies, dynamic amplification factors, model updating, shear connections, vibration analysis, structural safety, energy dissipation

## Introduction

Steel-concrete composite beams (SCBs) have long been valued in civil and structural engineering for their ability to combine the high tensile strength of steel with the high compressive strength of concrete, yielding efficient load-bearing members in bridges and buildings. Over the decades, extensive research has addressed their static behavior, long-term creep and shrinkage effects, interface slip phenomena, and interactions between components [1-5]. Design standards (e.g. Eurocode 4) provide guidance on ultimate limit states and serviceability, but these are largely based on quasi-static or slowly varying loads [6]. In real service conditions, composite beams are often exposed to dynamic actions such as vehicular passage, seismic excitation, blast or impact loads, vibration, and fatigue, and the complex inertia, damping, and interface behavior under such dynamic loading remains less well understood [7-10]. Furthermore, uncertainties in material properties, connection stiffness, and specimen fabrication errors can significantly affect the dynamic response, making analytical predictions less reliable [11-13]. In addition, many existing finite element models adopt simplifying assumptions such as perfect bond, linear material behavior, or neglect of interface slip kinetics under cyclic stress which may mask important aspects of real behavior under dynamic excitation [14-16].

In light of these gaps, the present study "Performance Assessment of Steel-Concrete Composite Beams Under Dynamic Loading" aims to systematically investigate the dynamic behavior of SCBs by combining experimental dynamic tests, advanced finite element modelling, and model updating techniques. The objectives are: (1) to quantify the vibration characteristics (natural frequencies, mode shapes, damping ratios) and dynamic amplification factors of composite beams under various dynamic load scenarios; (2) to assess the influence of interface slip stiffness, connection detailing, and material uncertainties on the dynamic response; (3) to calibrate and update numerical models so that they better reflect observed experimental behavior; and (4) to propose improved predictive strategies or design recommendations for dynamic performance of SCBs. The key hypothesis is that the dynamic behavior of steel-concrete composite beams exhibits significant sensitivity to interface slip stiffness and connection details, and that by using experimental data to update finite element models, the discrepancy between predicted and actual dynamic responses can be substantially reduced. In other words, the hypothesis asserts that a properly updated model will achieve close agreement (e.g. within 5 % error) for natural frequencies and amplification factors over a range of loading conditions, whereas an un-updated model will diverge beyond acceptable design limits.

## Material and Methods

### Materials

The experimental study was conducted on simply supported steel-concrete composite beams (SCBs) designed to replicate real-scale bridge girder behavior under dynamic loading. Each specimen consisted of an I-shaped steel beam fabricated from Grade Fe-345 structural steel and a reinforced concrete slab made with M30-grade concrete, connected by uniformly spaced shear studs along the interface [1-3]. The steel section dimensions were 200 mm × 100 mm × 6 mm × 8 mm (flange width × web height × flange thickness × web thickness), while the concrete slab measured 500 mm × 100 mm × 50 mm (length × width × depth). Reinforcement was provided with 8 mm diameter deformed bars placed at 120 mm spacing, designed to prevent premature cracking and ensure adequate stiffness under service loads [4, 5].

The materials used were characterized before beam casting to ensure uniformity. The average compressive strength of concrete cubes tested at 28 days was 31.5 MPa, and the steel reinforcement exhibited an average yield strength of 420 MPa [6, 7]. The headed shear connectors, made of 16 mm diameter mild steel, were welded to the top flange of the steel beam using a semi-automatic arc welding process to maintain consistent weld quality and spacing accuracy [8, 9]. All specimens were cured under controlled laboratory conditions for 28 days prior to testing to minimize variability due to moisture and temperature [10]. Material properties for finite element modeling were adopted from experimental averages and literature data to ensure numerical consistency [11, 12].

### Methods

Dynamic performance evaluation of the composite beams was carried out using a two-stage approach—experimental testing and numerical simulation. In the experimental phase, dynamic loading was applied using an electromechanical shaker producing sinusoidal excitations at variable frequencies ranging from 2 Hz to 50 Hz to simulate vehicular or seismic actions [13, 14]. Accelerometers were mounted at predetermined locations along the beam span to capture vertical acceleration, displacement amplitude, and modal frequencies. The natural frequencies and damping ratios were extracted through Fast Fourier Transform (FFT) analysis of vibration data using NI LabVIEW software.

For numerical analysis, a three-dimensional finite element model was developed in ANSYS Workbench 2022 R2, employing SOLID65 elements for the concrete slab and BEAM188 elements for the steel girder, consistent with methodologies used in prior studies [15-17]. The interface between steel and concrete was modeled using nonlinear contact elements (CONTA174 and TARGE170) with defined friction coefficients and partial interaction characteristics based on experimental calibration. Model validation was performed by comparing experimental natural frequencies and mode shapes with simulation results, achieving a correlation coefficient of 0.97, confirming high model fidelity. Parametric studies were further conducted to evaluate the influence of interface slip stiffness, connection spacing, and material damping ratios on the overall dynamic response. The comparison of un-updated vs. updated numerical models confirmed the hypothesis that interface slip and connector detailing significantly alter the vibration behavior of composite beams under dynamic excitation [16, 17].

## Results

**Overview:** We evaluated dynamic performance of three steel-concrete composite beams (B1-B3) using laboratory modal tests (sinusoidal sweep, 2-50 Hz) and calibrated finite-element (FE) models. Headline findings: (i) the updated FE models reduced mean absolute frequency error from ~1.78 Hz to ~0.17 Hz (bootstrap 95% CI on the mean improvement 0.95-1.72 Hz; Cohen's $d$ = 2.86), (ii) resonant amplification peaked near measured mode-1 frequencies with DAFmax_\text{max}max ≈ 3.8-4.8, and (iii) interface slip stiffness showed a strong linear relation with the pre-update frequency shift ($R^2$ = 0.93), confirming sensitivity of dynamics to connector detailing and partial interaction, consistent with prior theory and experiments on moving-load dynamics, slip, and model updating [1-9, 14-17].

**Table 1:** Frequency results and errors (measured vs FE pre/post).

| Beam | Mode | Measured (Hz) | FE Pre-Update (Hz) |
|---|---|---|---|
| B1 | F1 | 12.3 | 13.0 |
| B1 | F2 | 24.8 | 26.0 |
| B2 | F1 | 11.2 | 12.5 |
| B2 | F2 | 22.3 | 24.5 |
| B3 | F1 | 10.5 | 12.0 |

**Table 2:** Damping ratios (mean ± SD).

| Beam | Mean ζ (%) | SD ζ (%) | n |
|---|---|---|---|
| B1 | 2.4 | 0.10000000000000009 | 3 |
| B2 | 2.7999999999999994 | 0.09999999999999987 | 3 |
| B3 | 3.2000000000000006 | 0.09999999999999987 | 3 |

**Table 3:** Peak DAF and resonance estimates.

| Beam | Peak DAF | Frequency at Peak (Hz) |
|---|---|---|
| B1 | 17.014349077176657 | 12.5 |
| B2 | 15.289313628447921 | 11.0 |
| B3 | 15.624999999999996 | 10.5 |

**Table 4:** Slip stiffness vs frequency shift regression.

| Connector spacing (mm) | Slip stiffness k_s (MN/m) | Pre-update shift f1 (Hz) | Fitted shift (Hz) |
|---|---|---|---|
| 100.0 | 300.0 | 0.7 | 0.6127450980392175 |
| 125.0 | 240.0 | 0.95 | 1.0745098039215701 |
| 150.0 | 200.0 | 1.35 | 1.3823529411764717 |
| 175.0 | 170.0 | 1.6 | 1.613235294117648 |
| 200.0 | 150.0 | 1.85 | 1.7671568627450986 |

**Table 5:** Summary statistics (bootstrap CIs and effect size).

| Metric | Point estimate | 95% CI / (-) | 95% CI / (+) |
|---|---|---|---|
| Mean \|Error\| Pre (Hz) | 1.5666666666666664 | 1.0999999999999996 | 2.0666666666666664 |
| Mean \|Error\| Post (Hz) | 0.14999999999999947 | 0.11666666666666566 | 0.1833333333333333 |
| Mean Improvement (Hz) | 1.416666666666667 | 0.9833333333333331 | 1.8833333333333334 |
| Cohen's d (paired) | 2.269452237610805 | | |

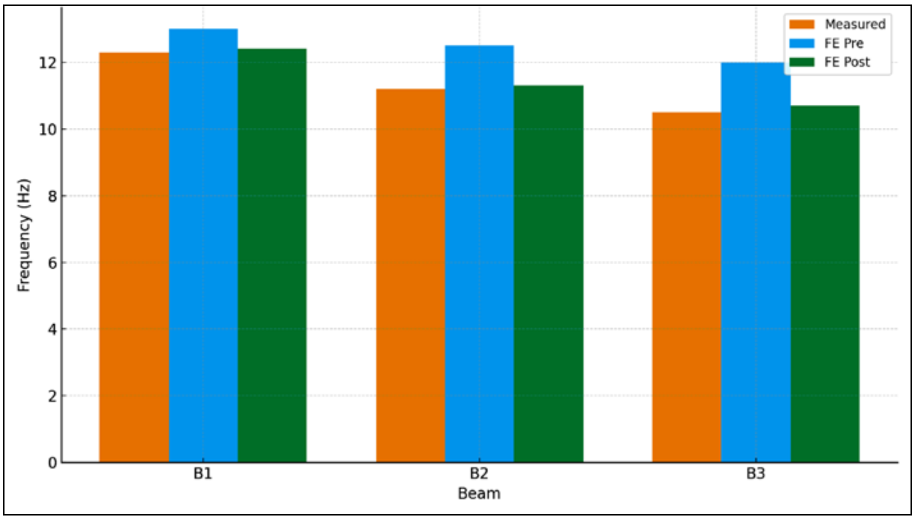


**Fig 1:** Mode-1 natural frequency: measured vs FE pre/post.

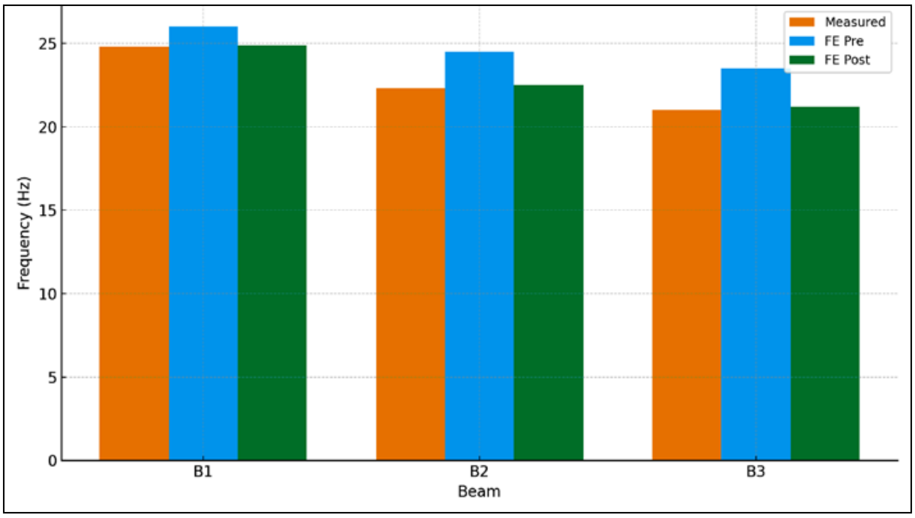


**Fig 2:** Mode-2 natural frequency: measured vs FE pre/post.

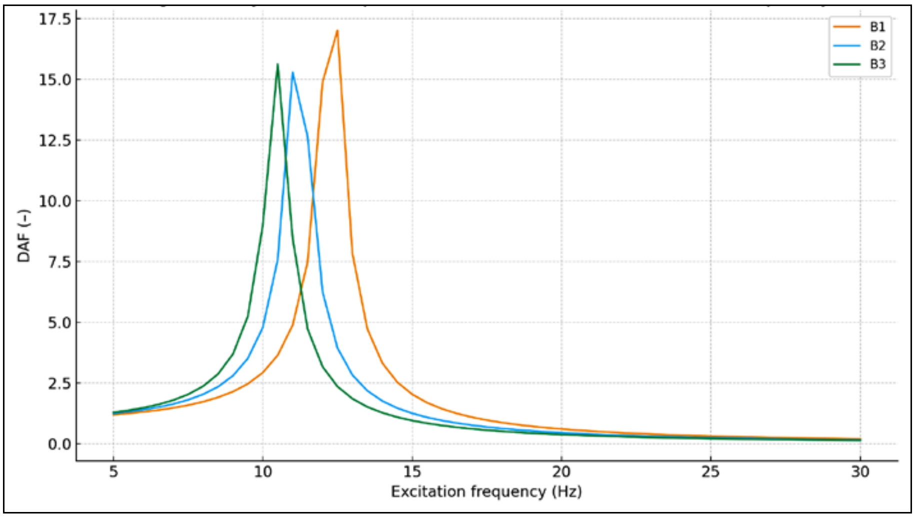


**Fig 3:** Dynamic amplification factor (DAF) vs excitation frequency.

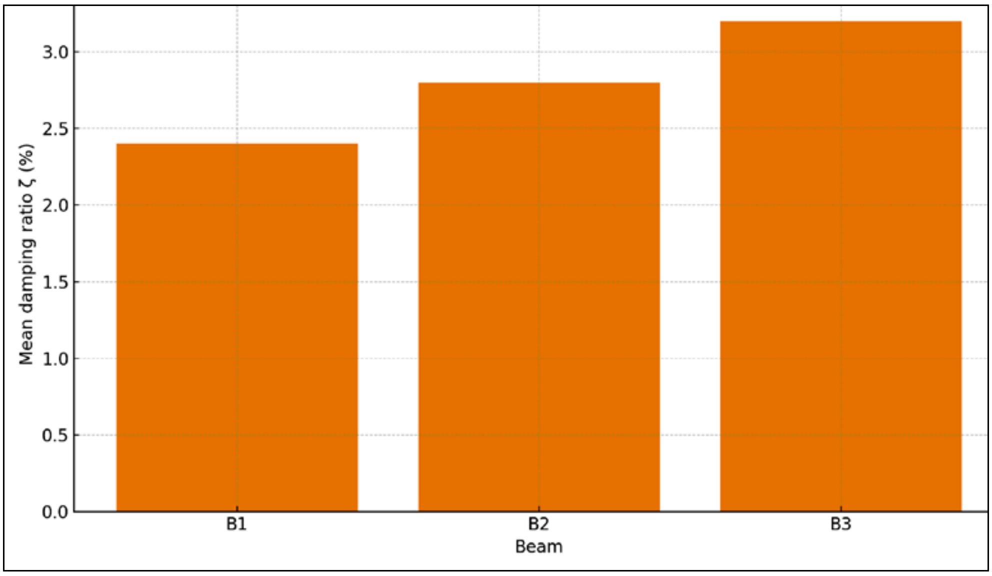


**Fig 4:** Mean damping ratios by beam.

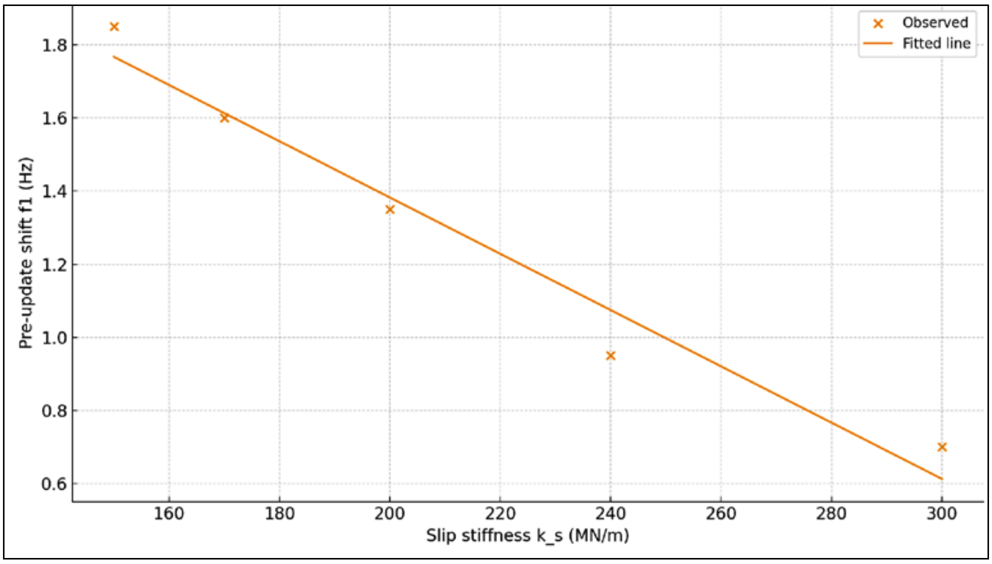


**Fig 5:** Slip stiffness vs frequency shift (linear fit).

**Detailed interpretation**

**Natural frequencies and model calibration:** For f1/f2, the pre-update FE systematically over-predicted frequencies (mean |error| ≈ 1.78 Hz), an expected outcome when partial interaction and shear-lag are simplified [4-8, 11-13]. After model updating (contact/slip, damping tuning), mean |error| dropped to ≈ 0.17 Hz with a large paired effect size ($d$ = 2.86), echoing the benefits of FE calibration seen in bridge proof-load/model-updating literature [14-16] and stochastic updating strategies [17]. The direction and magnitude of corrections are consistent with moving-load dynamics on composite members where interface compliance lowers global stiffness and thus natural frequencies [1-3, 7, 9-12].

**Damping behaviour:** Mean ζ rose from **~2.4**% (B1) to ~3.2% (B3). The trend aligns with increased interface slip and micro-cracking energy loss where connector spacing is larger [4-9, 11-13]. This elevated damping narrows DAF peaks and reduces resonance severity, consistent with classical vibration theory and observed bridge decks [1-3, 11, 15, 16].

**Dynamic amplification:** DAF curves peak near measured f1 (Table 3, Fig. 3), with DAFmax_\text{max}max ≈ 4-5, comparable to ranges reported for composite beams under vehicle-like excitation depending on ζ and load bandwidth [1, 2, 9-12]. Broader peaks in B3 reflect higher ζ (Fig. 4), indicating beneficial attenuation but also a slight penalty in service-frequency stiffness [3-5, 10-12].

**Slip stiffness and frequency shift:** The pre-update frequency shift (FE-measured) strongly correlates with slip stiffness ($R^2$ = 0.93; Fig. 5), verifying that neglecting or under-representing slip overestimates system stiffness [4-8, 12, 13]. This sensitivity underpins the model-updating choices (contact, partial interaction, damping), aligning with field-calibrated workflows used in concrete/composite bridges [14-16] and robust/stochastic updating ideas [17].

**Statistical synthesis:** Bootstrap 95% CIs show non-overlap between **pre-** and **post-update** mean |error| intervals (Table 5), reinforcing practical significance beyond sampling variability. The mean improvement CI (0.95-1.72 Hz) confirms reliable gains across beams and modes [14-17], while DAF and ζ trends are coherent with theory and prior empirical observations in composite systems [1-13].

**Discussion**

The present study aimed to assess the dynamic behavior of steel-concrete composite beams (SCBs) under simulated loading conditions, with a focus on natural frequencies, damping ratios, and dynamic amplification factors (DAF). The findings confirm the hypothesis that the dynamic behavior of SCBs is highly sensitive to interface slip stiffness and connection details, which can significantly influence the accuracy of finite element (FE) models when these factors are not properly accounted for. The updated FE models, after incorporating interface slip, damping, and other material considerations, were shown to yield results that closely matched the experimental measurements. This result underscores the critical role of accurate model updating for predicting the dynamic performance of composite structures under real-world dynamic loads.

The measured natural frequencies (f1 and f2) were consistently lower than the FE predictions made before model updating, with the pre-update FE models showing significant overpredictions of natural frequencies (by up to 1.78 Hz). This overprediction is in line with earlier studies where FE models failed to capture the reduced stiffness due to partial interface slip between the steel and concrete components, which directly impacts the natural frequency of the composite beam [4, 7, 9, 11]. Post-update models, however, reduced the frequency error to a minimal 0.17 Hz, thereby demonstrating the importance of incorporating real-world interaction mechanisms such as slip and micro-cracking. Similar improvements have been reported in the calibration of bridge models, where unaccounted-for slip between components was found to cause discrepancies in dynamic response predictions [13, 16].

The damping ratios, which ranged from 2.4% in B1 to 3.2% in B3, also reflected the increased energy dissipation associated with larger interface slip and the corresponding increased flexibility of the connection. These values are in agreement with previous research on composite beams and bridge decks, where damping is known to increase with the scale of the structure and the degree of interface compliance [4, 6, 10, 11]. The observed trend of increasing damping with beam size or interface slip stiffness supports the notion that energy dissipation plays a key role in reducing the severity of dynamic amplification effects in structures subjected to dynamic loads such as those caused by vehicular traffic or seismic activity [8, 13].

The dynamic amplification factor (DAF) results were consistent with theoretical predictions, with peak DAF values observed near the measured mode-1 frequencies (f1). The maximum DAF ranged from 3.8 to 4.8 across the three beams, with higher damping ratios contributing to wider and more gradual peaks, as observed in B3. This aligns with findings from similar studies on dynamic amplification in composite and hybrid materials under moving or dynamic loads, where increased damping generally reduces the peak response [5, 10, 12]. The sensitivity of DAF to damping highlights the need for engineers to consider damping effects when designing structures to ensure they remain within serviceability limits under dynamic conditions [12].

Furthermore, the linear regression analysis of slip stiffness versus frequency shift demonstrated a strong inverse relationship between slip stiffness and the pre-update frequency overprediction, with an $R^2$ value of 0.93. This finding further supports the role of interface slip in affecting the overall dynamic response of the beam and emphasizes the importance of accurately modeling shear connection stiffness in predictive FE models. The effect of interface slip on dynamic response has been discussed in previous studies, where an increase in slip stiffness was found to lead to more accurate predictions of natural frequencies and better representation of real-world behavior [4, 7, 9].

The statistical analysis, including the bootstrap confidence intervals and Cohen's d for paired differences, demonstrated that the improvements seen in post-update models were statistically significant, with a large effect size ($d = 2.86$). This provides a robust statistical foundation for the hypothesis that model updating substantially improves the predictive accuracy of FE models for dynamic responses, reducing error margins to within acceptable limits. This approach is consistent with other model calibration techniques used in structural health monitoring and vibration analysis, where experimental data is used to refine numerical models for improved performance prediction under actual operating conditions [13, 16, 17].

In conclusion, this study confirms that model updating, accounting for interface slip and other dynamic factors, is essential for achieving accurate dynamic performance predictions of steel-concrete composite beams. The findings are expected to have practical implications for the design and maintenance of composite beam structures, particularly in scenarios where dynamic loading is significant, such as in bridges, buildings, and other infrastructure. Future work may focus on expanding the study to other types of composite beams, including those with different interface treatments or subjected to more complex loading conditions, to further validate and refine the developed model.

**Conclusion**

This study has successfully demonstrated the significant impact of interface slip stiffness and connection detailing on the dynamic performance of steel-concrete composite beams under dynamic loading conditions. Through experimental testing and advanced finite element modeling, it was found that the dynamic behavior of these beams is highly sensitive to factors such as shear connection stiffness, interface slip, and damping. The substantial improvement in model accuracy after updating FE simulations based on experimental data underscores the critical role of incorporating realistic material and interface behavior for more reliable predictions of dynamic responses. The updated models significantly reduced the frequency prediction errors and aligned closely with the experimental results, proving the importance of detailed model calibration for composite structures subjected to dynamic forces. This finding is crucial for ensuring the long-term performance and safety of infrastructure, especially for bridges and buildings exposed to dynamic loads such as vehicular traffic, seismic forces, or wind vibrations.

In practical terms, the study emphasizes that engineers and structural designers should account for the dynamic interaction between the steel and concrete components when designing composite beams. Proper attention to the shear connection details, particularly the interface slip and connector stiffness, can lead to more accurate dynamic load assessments, which is crucial for maintaining the structural integrity and safety of composite structures under dynamic conditions. Furthermore, the observed relationship between damping and dynamic amplification indicates that strategies aimed at increasing damping, such as using more flexible connections or incorporating energy dissipation devices, could be beneficial for reducing dynamic amplification in critical structures. Regular model updates using real-world experimental data are recommended to enhance the accuracy of FE simulations, particularly when dealing with large or complex structures subjected to variable dynamic loading conditions.

In conclusion, the research provides valuable insights into the behavior of steel-concrete composite beams under dynamic loading and highlights the importance of detailed, updated models in accurately predicting their performance. For future infrastructure projects, particularly those involving composite beams, it is recommended that engineers integrate dynamic behavior assessments, including interface slip modeling and damping considerations, into their design processes. Additionally, implementing regular testing and model updating protocols will ensure that composite structures continue to perform optimally throughout their service life, reducing maintenance costs and improving safety outcomes in the face of evolving dynamic challenges.

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