A COMPREHENSIVE FINITE ELEMENT ANALYSIS APPROACH FOR ENHANCING UHPC DESIGN UNDER DYNAMIC LOADING

Siti Shahirah Saidin[1,*], Anis Azmi[2], Umi Nadiah Nor Ali[3], Mariati Taib[1]
[1]*School of Housing, Building and Planning, Universiti Sains Malaysia, MALAYSIA.*
[2]*Jabatan Kejuruteraan Awam, Universiti Kebangsaan Malaysia*
[3]*Faculty of Engineering, Built Environment, and Information Technology, Mahsa University, Malaysia*

*Corresponding author: sitishahirah@usm.my

Abstract
Ultra-High Performance Concrete (UHPC) is gaining prominence in bridge construction due to its superior mechanical properties and durability. However, most studies have focused on static analysis, while dynamic analysis, such as cyclic vehicle loading and environmental impact, has been neglected. This work expands the traditional finite element analysis (FEA) to perform modal analysis for ascertaining natural frequencies, mode shapes, deflection behavior, and the influence of cross-sectional moment of inertia. A numerical model was developed, incorporating detailed material properties and boundary conditions across three different girder geometries to simulate real-world structural conditions. The results indicate that the optimized designs of the UHPC girder exhibit high natural frequency in the range of 2.4–2.5 Hz for a 50-meter span, higher moment of inertia, and lower deflections. The findings show that UHPC enhances structural stiffness, extends service life, and reduces maintenance costs compared to conventional concrete materials. In summary, this study conducts a modal analysis of a UHPC bridge by integrating vibrational performance and including a cyclic moving load to provide a comprehensive assessment of its structural performance. This study contributes to the literature on the advancement of UHPC application in bridge design, promoting the adoption of sustainable and high-performance construction materials.

Keywords: Ultra-High Performance Concrete (UHPC), Finite Element Analysis (FEA), Modal Analysis, Bridge Girders, Natural Frequency.

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INTRODUCTION

Ultra-High-Performance Concrete (UHPC) is one of the advanced cementitious construction materials that contribute to transformative innovation in the field of structural engineering. With its exceptional strength, such as the compressive strength value exceeding 150MPa, low permeability, and high durability, UHPC offers an alternative to conventional reinforced concrete (RC). The application of UHPC in bridge construction offers significant benefits in geometric design, longer life span, and reduced environmental degradation. These advantages gained global attention in UHPC as an ideal advanced material to be used in critical infrastructure application particularly in bridge construction where long term and high durability structure are desired (Graybeal, 2006). From several previous studies has shown UHPC structure presents significant in static and flexural application, however the dynamic behaviour specifically on the UHPC girder design under service and operation loading remains underexplored (Voo & Foster, 2015). In order to leveraging UHPC in practice, it requires thorough computational and experimental research to ensure that it behaves reliably under dynamic and cyclic loads.

Finite element analysis (FEA) is a valuable method for studying UHPC structural behaviour, since full-scale testing is difficult and costly (Naaman, 2018). In recent years, there have been significant developments in FEA approaches for UHPC modelling. Singh et al. used FEA to explore the flexural load-deflection behaviour of UHPC beams, whereas Chen & Graybeal modelled UHPC I-girders to examine their bending performance (Haghighi & Urgessa, 2024). Bahij et al. performed numerical simulations on ultra-high-performance concrete (UHPC) beams under shear conditions (Singh, Sheikh & Ali, 2017). A recent comparative study by Oravbiere et al. using field-validated finite element analysis revealed that ultra-high-performance concrete (UHPC) bridge sections, even when constructed with reduced dimensions, did not exhibit excessive vibrations or dynamic amplification due to the material's superior stiffness (Oravbiere, 2025). These studies show the potential of UHPC, however thorough research is needed to fully understand the dynamic performance characteristics, particularly for full-scale prestressed UHPC bridge girders.

Ensuring adequate dynamic performance such as vibration characteristics and stability is another crucial component of bridge design. This gap emphasises the need for thorough modelling studies that include material nonlinearity, prestressing, and dynamic load application to fully exploit UHPC's promise in bridge applications. Dutta and Talukdar used the Lanczos algorithm in FEA to precisely determine the modal characteristics such as natural frequencies and mode shape of a bridge for the purpose of damage identification. The outcome of the study indicates Ultra-High Performance Concrete (UHPC) has greater stiffness, resulting in increased natural frequencies when compared to standard concrete elements of similar design (Dey & Talukdar, 2016). The eigenvalue techniques such as subspace iteration or the Lanczos method in modern FEA solver is particularly well-suited to capture lower vibration modes and is extensively used in structural modal analysis especially bridges due to its efficiency in handling large-scale sparse system (Christian, 2022).

Although some prior studies have focused on static, shear and dynamic behavior of UHPC elements, very few have investigated the extensively finite element analysis approach to study prestressing effects, dynamic loading and how design variations in geometry affect the modal performance. Therefore, the objective of this study is to conduct a comprehensive dynamic modal analysis of UHPC bridge girders using the finite element method. Specifically, the study aims to:

1. Integrate a comprehensive finite element modelling methodology for ultra-high-performance concrete (UHPC) bridge girders with Abaqus, including material nonlinearity, prestressing strands, and authentic boundary conditions.
2. Perform modal analysis on various girder designs to determine their natural frequencies and mode shapes, assessing the impact of cross-sectional changes on dynamic properties.
3. Determine the deflection characteristics and frequency response of a typical long-span (50 m) UHPC U-girder under free-vibration conditions and compare its dynamic deflections with serviceability standards and those of conventional concrete girders.

The findings from this study are expected to provide a comprehensive finite element analysis approach for enhancing UHPC prestressed design and demonstrating that optimized UHPC girders design can enhanced the structure performance, thereby facilitating the optimisation of UHPC design methods used in modern construction practices.

LITERATURE REVIEW

UHPC Girder Geometry and Design

Three distinct bridge girder shapes were analysed to examine the influence of cross-sectional design on dynamic performance. The UHPC girder, designated Type A, Type B, and Type C, are all 50-meter span U shape section but exhibit different flange and web thicknesses (see Figure *1*). The girder depth remains constant at roughly 1.75 m, with an overall width of around 2.5 m, whereas Types B and C propose different flanges and webs compared to the baseline Type A. The geometric variations substantially impact the moment of inertia of the cross-section, subsequently affecting load-bearing capacity, stress distribution, and deflection properties. Type A serves as a baseline, according to the specifications of a conventional UHPC girder design (Voo & Tadros, 2016). Type B and Type C include enhanced flange/web thickness (maintaining same outside dimensions) to improve rigidity. This research aims to determine a UHPC girder design that optimises stiffness and performance while ensuring material efficiency via the evaluation of various designs.

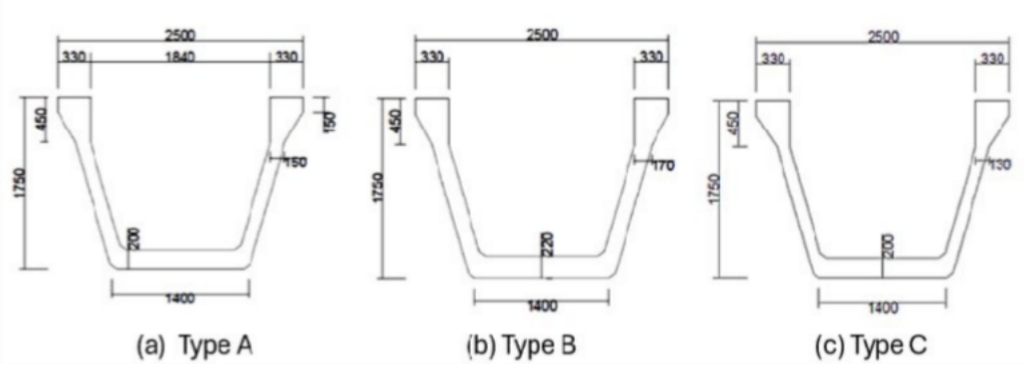
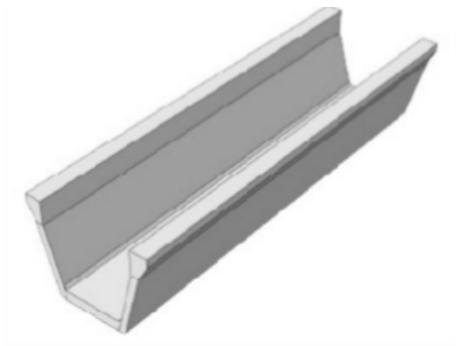


Figure 1 Cross sections of U Bridge Girders with various geometries

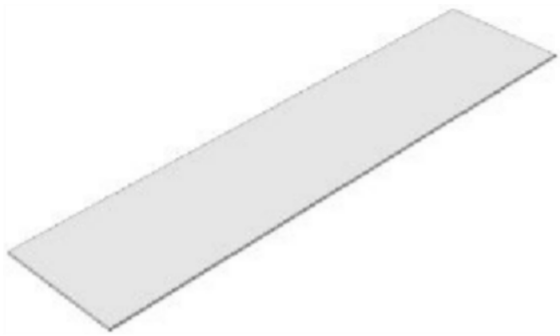
Finite Element Model Setup

A three-dimensional model of the UHPC bridge girder including a composite bridge deck was modelled to perform dynamic modal analysis. The UHPC girder and concrete deck were modelled with appropriate element types such as eight-node solid elements (C3D8R), represent a detailed concrete continuum. The steel prestressing strands were represented as one-dimensional tension-only truss elements, while the non-prestressed steel reinforcement, stirrups and longitudinal rebars in the girder was included using beam or truss elements as suitable Figure 2. All components were combined to represent a composite girder-deck section, where the interface between the UHPC girder and the cast-in-place regular concrete deck was assumed to be entirely composite as illustrated in Figure 2 and Figure 3.

A tied contact condition was used at the interface, simulating the influence of shear connections that facilitate composite action in reality. The prestressing steel was pretensioned in the model, with an initial strain or comparable thermal contraction approach, to provide the necessary compressive prestress in the UHPC girder before the application of external loads. This prestress implementation ensured that the advantageous impact of prestressing on dynamic stiffness was reflected in the modal analysis.



(a) Solid Element C3D8R



(b) Solid Element C3D8R

(c) Truss element

Figure 2 UHPC Girders model in Abaqus

Figure 3 A three dimensional UHPC Bridge model in Abaqus

Material Properties

The material properties assigned to the model are summarized in Table 1. Four material types were defined: Ultra-High Performance Concrete (UHPC) for the girder, conventional concrete for the deck slab, high-strength steel for prestressing strands, and Grade 500 steel for mild reinforcing. UHPC was characterised by a high Young's modulus of 50 GPa and a compressive strength of about 150 MPa, including a tensile post-cracking strain-hardening behaviour to represent the ductility conferred by fibre reinforcement. The standard-strength concrete deck used the usual characteristics of C40 concrete (E =35 GPa). Prestressing strands and rebar were represented as steel with an elastic modulus of 200 GPa; an elastic–plastic (bilinear) stress–strain curve was used to account for yielding (the ultimate tensile strength of the strand is 1860 MPa). All material values were selected in compliance with applicable Eurocode 2 for concrete material Standard (Qin, Zhang, Huang, Gao, Bao, 2022).

Table 1 Material Properties Assigned in the FEA Model (Qin, Zhang, Huang, Gao, Bao, 2022).

Material	Young's Modulus (GPa)	Density (kg/m³)	Poisson's Ratio	Remarks
UHPC (girder)	50	2400	0.20	Compressive strength-150 MPa, tensile strain-hardening behaviour.
Concrete (deck slab)	35	2500	0.20	Conventional C40 concrete for composite deck.
Prestressing Steel	200	7850	0.30	High-tensile 7-wire strand (ultimate strength-1860 MPa).
Reinforcing Steel	200	7850	0.30	Grade 500 rebar for stirrups and longitudinal bars.

Significantly, the elastic modulus of UHPC in this model is about 40% superior to that of normal concrete, hence enhancing stiffness and elevating the natural frequencies of the UHPC girder (Oravbiere, 2025). The density of UHPC about 2400 kg/m³ was somewhat lower than that of regular concrete approximately 2500 kg/m³ owing to UHPC's optimised particle packing and decreased coarse aggregate content (Qin, Zhang, Huang, Gao, Bao, 2022). These material specifications ensure that the finite element model accurately represents both the stiffness and inertial characteristics essential for dynamic analysis. Prestress was given to the strands, simulating pre-tensioning such that the UHPC girder sustained the needed compressive prestress before to the dynamic modal analysis, hence replicating in-service prestressed conditions.

Mesh and Convergence

A systematic mesh convergence study was conducted to determine the optimal seed size for this model. Table 2 shows three mesh iterations: seed sizes of 0.4, 0.2, and 0.1 were analysed. The natural frequency of Mode 1 stabilized at 2.4251 Hz for the finest mesh (seed size = 0.1), with a 2.64% change compared to the previous iteration (seed size = 0.2). This value falls below the 5% tolerance threshold, indicating sufficient convergence. The seed size of 0.1 was selected as the final choice, balancing computational efficiency (76,800 elements) with accuracy. While finer meshes would marginally improve precision, they would significantly increase computational costs. The adopted mesh resolution ensures reliable results in critical regions such as the mid-span and post-tension strands, where deformation and stress patterns are most sensitive to discretization. This value was selected to balance computational efficiency and solution accuracy well, where a finer seed size could improve precision but increase computational time. In comparison, a coarser seed size could reduce accuracy. The chosen seed size allows for an optimal level of detail, particularly in critical regions such as the mid-span and the post-tension strands.

Table 2 Convergence study of mesh size for modal analysis

Mesh Iteration	Seed Size	Nodes Count	Elements Count	Mode 1 (Hz)	% Change (Mode 1)
Coarse Mesh (1)	0.4	9751	6112	1.9833	-
Medium Mesh (2)	0.2	29779	20600	2.3628	19.13
Fine Mesh (3)	0.1	104256	76800	2.4251	2.64

In this case, the 2.64% change between the seed sizes 0.2 and 0.1 (Mesh 2 to 3) confirmed convergence, as the marginal improvement fell below the predefined threshold. By adopting this method, the study systematically balances computational effort (e.g., element count) with accuracy, ensuring that the final mesh (seed size = 0.1) provides reliable results without unnecessary computational overhead. The mesh control for the solid parts was carefully chosen, with the element shape set to Hex (hexahedral elements), the technique as sweep, and the algorithm as a medial axis, as shown in Figure 4. The sweep technique ensures that the mesh follows the geometry of the solid parts, while the medial axis algorithm provides a high-quality mesh even in complex geometries. This combination was ideal for capturing the structural behaviour of the end and internal segments and the concrete deck, ensuring smooth transitions and accurate stress distributions throughout the model. Due to geometric complexity, the final mesh has around 9,700 nodes and 8,500 elements for one girder model.

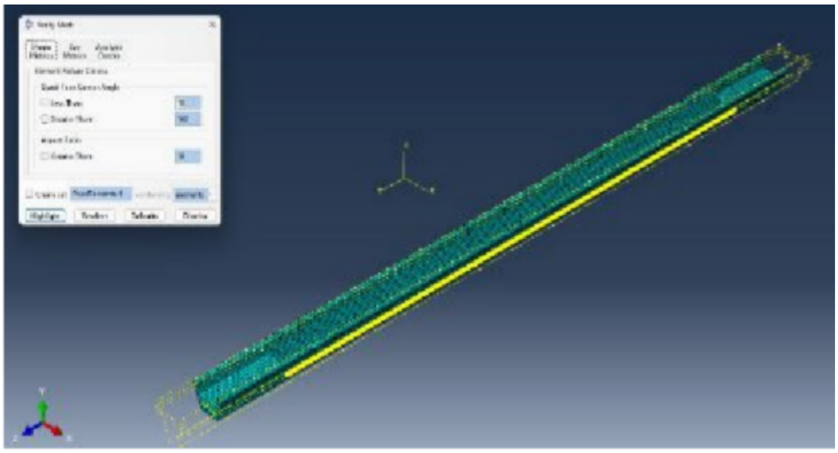


Figure 4 UHPC Mesch Convergence

BOUNDARY CONDITION

In order to simulate actual structural performance under service circumstances, the girder was idealised as a simply-supported beam. All translational degrees of freedom (U1 = U2 = U3 = 0) were constrained at one end of the girder to provide a pinned support, while all rotational degrees of freedom remained unrestrained. This arrangement resembles a hinge state by preventing any rigid body translation at the support and allowing unrestricted rotation of the girder.

At the other end, a roller support was applied to limit vertical and lateral displacement while allowing longitudinal movement. As therefore, the longitudinal displacement (U1) and all rotations remained free, but the vertical (U2 = 0, U3 = 0) translations were constrained. The roller condition allows the structure expand or contract along the girder's axis because of pressure or temperature changes, preventing unrealistic restraint forces from developing.

The embedded constraint, as seen in Figure 5, is applied to represent the relationship between the post-tension strands (red) and the solid girder body (blue). In this case, the post-tension strands are defined as embedded elements, while the girder body is treated as the host element. The embedded constraint ensures that the strands remain within the solid body and are subject to the same displacements and deformations as the surrounding concrete. This type of constraint is crucial for accurately modelling post-tensioning systems, where cables or strands are placed within a concrete structure to provide additional strength.

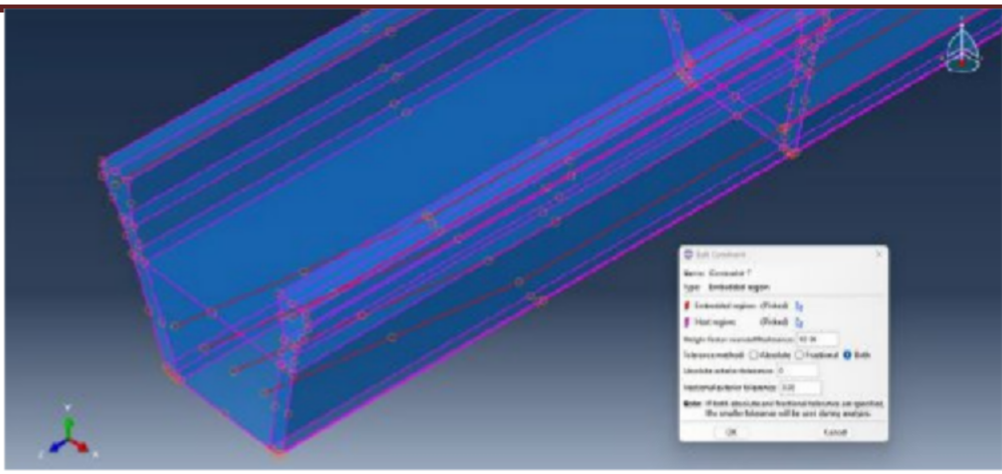


Figure 5 Embedded constraint for strand-girder

DYNAMIC LOADING SIMULATION USING LANCZOS EIGENSOLVER

In order to replicate the structural response under dynamic loading, the dynamic characteristics of the girders were determined by perform modal analysis using the Lanczos eigenvalue solver in Abaqus Standard. Instead of using a particular time-varying load, the modal analysis determines the free-vibration modes of the structure, which are inherent characteristics that determine the bridge's response to any dynamic excitation.

The model creation process started where the structure's geometry, boundary conditions, and material characteristics such as density, elastic modulus, and Poisson's ratio were assigned. These inputs made sure that the system accurately reflected both stiffness and inertial effects. To increase the accuracy of the solution, the structure was discretised using appropriate finite elements and mesh refinement was done in areas of interest. Abaqus automatically produced the global stiffness and mass matrices upon assembly, which were then used to formulate the generalised eigenvalue problem, which was written as

$$K\phi = \lambda M\phi \qquad \text{[Equation 1]}$$

Where, **λ** represents an eigenvalue and **φ** the corresponding mode shape vector. The square root of each eigenvalue gives the natural frequency $f = \sqrt{\lambda} / (2\pi)$. The Lanczos method is well-suited for large-scale structural models, efficiently extracting the lowest eigenmodes which are of primary interest for bridges (Cristian, 2022).

In order to capture the basic flexural mode and a number of higher modes, including possible torsional modes, the analysis stipulated for the first five eigenmodes for each of the girder models (A, B, and C). No external loads were imposed during the frequency extraction phase, since the aim was to determine the natural frequencies and mode shapes under free vibration conditions. The prestress in the girder was already present as a starting condition, which effectively stiffened the structure and influenced the modal findings. In order to compare the dynamic behaviours of the various girder types, the result of the Lanczos analysis was post-processed to include the eigenfrequencies and mode shape vectors for each mode.

Modal Analysis Results

Natural Frequencies

The natural frequency analysis of the three UHPC girder models (A, B, C) demonstrated that even modest changes in cross-sectional stiffness result in significant variations in dynamic characteristics. Table *3* summarizes the natural frequencies (Modes 1 through 5) for Girder Type A (baseline), Type B, and Type C, and Figure *6* illustrates the variation of frequency with mode number for each type. The fundamental bending frequency (Mode 1) of the UHPC girder increases from approximately 2.396 Hz in Type A to 2.532 Hz in Type C (about a 5.7% increase), with Type B in between at 2.428 Hz. Type C, with the highest moment of inertia, exhibited the greatest fundamental frequency at 2.532 Hz. This was followed by Type B at approximately 2.428 Hz, while Girder A showed the lowest value at 2.396 Hz. Modifications that enhanced the cross-sectional area and stiffness (Type C) increased the natural frequencies by about 5–10% relative to the baseline (Type A).

Although the percentage differences appear single-digit, in the context of dynamic performance such increases can be meaningful for avoiding resonance. Higher modes (Modes 2–5) also show variations, though not strictly increasing for all modes due to mode shape differences and mass distribution effects. For instance, Mode 2 (likely the second bending mode) is around 3.95–4.0 Hz for all types, with Type C slightly lower than Type B, indicating some mode shape redistribution. Mode 3 and Mode 4 (which could correspond to torsional or lateral bending modes) occur in the 5–8 Hz range and also vary among the designs (see Table 3). Overall, Type C tends to have the highest frequencies for the primarily bending-dominated modes (1 and 5), reflecting its superior stiffness, whereas some higher modes are more complex. Nonetheless, the fundamental frequency is often the governing concern for serviceability, and in this regard Type C provides about a 5% increase over the baseline Type A.

Such improvements may be required in preventing resonance with common excitation sources. These results indicate that global bending modes show the most significant variation in response to changes in structural conditions which is critical for evaluating a structure's susceptibility to dynamic stresses. For example, vibration loading caused by people walking on the ground are generally below 3 Hz. These UHPC girders have a basic frequency in the mid-2 Hz range, which gives them a buffer above normal human loading frequencies. In the same way, many vehicle-induced dynamic loads have frequencies of up to 4–5 Hz for rough road contact (Oravbiere, 2025). In terms of wind excitation, turbulence wind gusts over a 50-meter span tend to have a lot of energy at lower frequencies, around 0.1 to 1 Hz. The bridge's fundamental frequency is around 2.4 to 2.5 Hz, which makes it stiff and hard for the main wind turbulence frequencies to excite, which keeps large resonance effects from happening.

Table 3 Material Properties Assigned in the FEA Model

Mode	Natural Frequency, (Hz)		
	Type A	Type B	Type C
1	2.395	2.428	2.5316
2	3.948	3.995	3.8728
3	5.444	5.608	5.74
4	8.687	7.348	8.718
5	9.385	8.756	9.838

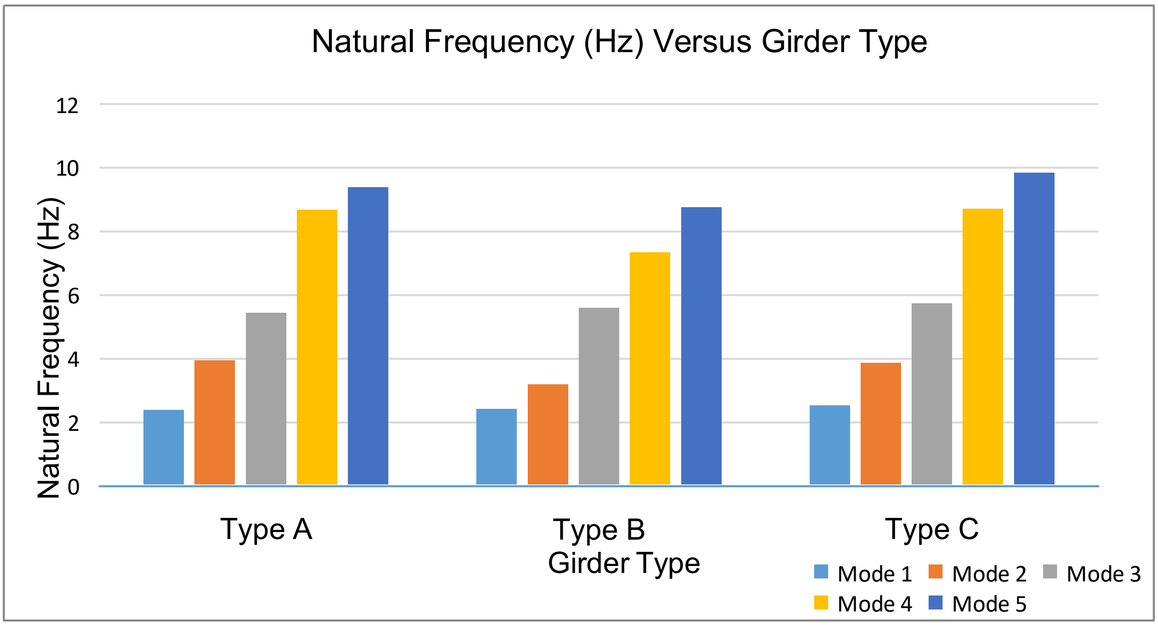


Figure 6 Natural Frequency vs. Mode Numbers for UHPC Bridge Girders A, B, C

Mode Shape for UHPC

The mode shape of the UHPC girder were investigated in order to better understand their deformation patterns. The fundamental vertical bending mode is the first mode. Figure 7 shows Fundamental Mode Shape of Girder Type A vibrates in a half-sine form that is symmetrical. The highest deflection happens in the middle of the span; the red area in the contour, while the supports at the ends stay stable with little movement; the blue areas. This global bending mode defines how the bridge moves when it is loaded vertically. As can be seen from the colour gradient in Figure 7, the deformation is mostly flexural with very little torsion or local distortion. Due to UHPC's exceptional strength, this bending form occurs with very little strain on the girder's outer sections since the bending is minimal when vibration is mild. This implies that the UHPC girder will experience little stress during typical operation which is excellent for avoiding vibration damage.

Higher modes included the second vertical bending mode (Mode 2), which occurs between 3.2 and 3.9 Hz depending on the girder type. This mode had a complete sine wave form, with one internal node at the midpoint. Furthermore, the first torsional mode developed around Mode 3 or 4, often in the range of 5-8 Hz, and was defined by twisting in opposing directions across the two sides of the U-shaped girder cross-section.

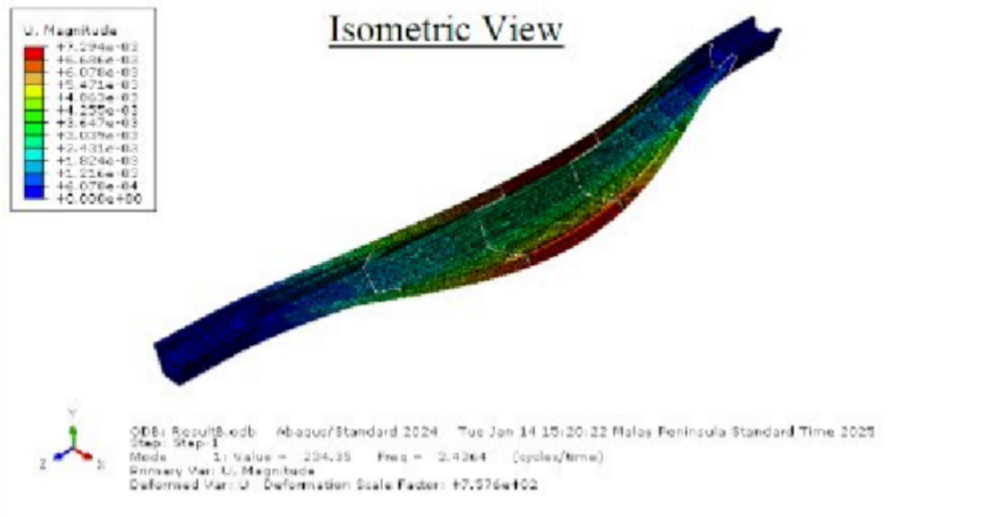
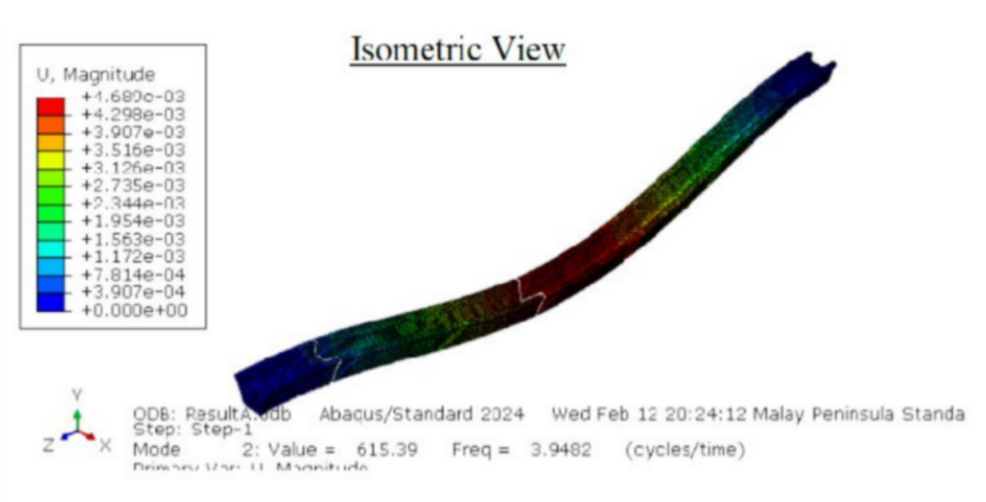
	(a) 1st Bending Mode Shape
	(b) 2nd Bending Mode Shape

Figure 7 1st Mode Shape of Girder Type A

Deflection

Although modal analysis primarily gives relative mode shapes, the normalized mode shapes can be scaled to estimate deflection magnitudes under a given excitation. To assess serviceability, we examined the maximum dynamic deflection in the fundamental mode for each girder type under a notional unit modal mass participation. Table 5 compares the peak deflection at mid-span for the three girders type, Type A, B, and C when the Mode 1 shape is normalized to a consistent reference. The results show a clear correlation between girder stiffness (geometry) and deflection, the stiffest girder, Type C had the lowest maximum deflection, about 44.7 mm at mid-span, whereas the most flexible design, Type A deflected about 46.9 mm under the same modal normalization. Type B was intermediate with 45.5 mm. In relative terms, Type C's peak deflection is roughly 10% lower than that of Type A, and Type B's is about 5% lower, reflecting the benefits of increased flange/web thickness on reducing displacement. All UHPC girders easily satisfy typical deflection serviceability limits, for instance, span/800 limit for live load deflection in bridges (Eurocode, 2005). For a 50 m span, the allowable deflection for live load is around 62.5 mm (L/800), so even the most flexible UHPC girder Type A with 47 mm under the considered dynamic loading scenario remains well within this limit (Eurocode, 2005). Moreover, when comparing to conventional concrete girders of the same span, the dynamic deflections of UHPC girders are significantly lower. A standard RC girder of 50 m might exhibit on the order of 60–65 mm deflection under similar loading, meaning the UHPC design achieves roughly 25–30% reduction in deflection due to its higher stiffness (Eurocode, 2025). This improved deflection performance indicates that UHPC girders can offer superior serviceability, experiencing smaller vibrations and deflections under moving loads, which in turn reduces fatigue damage accumulation and improves long-term durability.

Table 4 Displacement of different type of girders

Type	Maximum Deflection (mm)	Relative Reduction vs baseline
A	46.89	-
B	45.47	5%
C	44.70	10%

In summary, the deflection study emphasises the significance of optimising girder shape in order to maximise the advantages of UHPC. The findings show that optimum flange and web thickness (Type C design) may significantly reduce dynamic deflection. This is consistent with the overarching objective of developing safe, efficient, and robust bridge designs: UHPC, when paired with appropriate cross-sectional design, may significantly increase serviceability performance under dynamic loads.

Implications for Design and Codes

The above findings carry important implications for bridge design practices and code provisions when it comes to UHPC girders. First, the study demonstrates that performance-based design criteria for vibrations can be met and even comfortably exceeded by UHPC bridge girders. Current bridge design codes primarily address RC and steel structures, with limited specific guidance for UHPC. Serviceability limits such as for deflection and vibration often do not account for the higher stiffness of UHPC, leading designers to adopt conservative approaches. The results here suggest that UHPC girders, due to their high natural frequencies and low amplitudes of vibration, can maintain excellent serviceability under realistic dynamic conditions. This supports the development of design guidelines explicitly incorporating dynamic performance for UHPC structures. For example, design codes could be calibrated to recognize that UHPC girders inherently satisfy deflection and vibration limits for longer spans, potentially allowing for slenderer designs without comfort penalties.

Another key implication is the utility of advanced FEA using Lanczos modal analysis for large-scale UHPC bridge evaluation. The successful application of the Lanczos Eigensolver in this study provides a computationally efficient pathway for practicing engineers to predict dynamic characteristics of UHPC bridge designs. As UHPC adoption expands to longer spans and innovative girder shapes, having a reliable numerical modelling approach for modal analysis is crucial. The methodology outlined including detailed material modelling, prestress incorporation, mesh convergence checking, and appropriate boundary condition can serve as a blueprint for engineers performing similar analyses. By verifying that the first few mode shapes and frequencies are favourable, engineers can prevent resonance issues early in the design phase.

Evaluating multiple girder geometries (A, B, C) also offers insight into the influence of cross-sectional design on dynamic and fatigue performance. The findings clearly demonstrate that increasing the section's moment of inertia (as in Type C) yields higher natural frequencies and lower dynamic deflections, which in turn implies superior resistance to vibrations and fatigue. In practical terms, a slightly heavier or thicker UHPC girder section can be justified by the significant gains in stiffness and reduction in stress range under cyclic loads. This is particularly relevant for long-span bridges or those subject to heavy traffic and wind loads. Designers can employ such geometric optimization to achieve slender yet dynamically robust UHPC bridges. This aligns with recent research by Oravbiere et al., who showed that widening flanges or webs in UHPC sections improved weak-axis bending stiffness and increased lateral–torsional buckling capacity by up to 10%, thereby enhancing overall dynamic stability (Oravbiere, Chorzepa, & Kim, 2025). The current study's results reinforce that concept: geometry optimization (Type C vs. Type A) not only raises frequencies but also reduces torsional responses and modal participation in undesirable modes. Such improvements contribute to safer bridges with greater reliability against phenomena like lateral–torsional buckling under dynamic loads.

Conclusion

This paper presented a comprehensive finite element modelling approach to investigate the dynamic behaviour of prestressed UHPC bridge girders. A detailed 3D Abaqus model was developed, encompassing realistic material properties, proper boundary conditions, and prestress effects, across multiple girder geometries. Using an eigenvalue analysis with the Lanczos solver, the study extracted natural frequencies and mode shapes, and evaluated deflection tendencies for each design. The key findings and conclusions are as follows:

1. UHPC girders exhibited high fundamental natural frequencies, 2.4–2.5 Hz for a 50 m span, about 5–10% higher than an equivalent conventional concrete girder design. The superior material stiffness of UHPC raises the structure's resistance to vibrational excitation, meaning UHPC girders are less prone to resonance and excessive vibration under common dynamic loads such as traffic, wind, pedestrians.
2. Among the UHPC designs studied, the girder with the largest moment of inertia (Type C) achieved the highest frequencies and the lowest modal deflections. Reducing flange and web thickness by a moderate amount led to 10% reduction in mid-span deflection and a noticeable frequency increase compared to the baseline design
3. The study demonstrated the efficacy of using advanced finite element techniques to predict UHPC bridge behaviour. The mesh convergence analysis ensured accurate modal results, and the Lanczos Eigensolution provided rapid convergence on the critical modes. The modelling approach including how prestress was applied and how composite action was handled can serve as a reference for future analytical studies and design validations of UHPC structures. It shows that engineers can reliably simulate complex UHPC systems and obtain insights that would be challenging to glean from experiments alone.

In closing, the integrated FEA approach detailed in this paper provides a holistic evaluation of UHPC prestressed bridge girders under dynamic loading. The results affirm that UHPC, when combined with careful design, yields bridge superstructures with superior stiffness, lower deflections, and improved vibration characteristics relative to conventional materials. These advantages translate into longer service life and reduced maintenance, bolstering the case for UHPC as a next-generation solution in bridge engineering. It is recommended that future work include field testing of UHPC girder bridges to validate these analytical predictions and to further study aspects like damping and fatigue under real traffic conditions. Additionally, extending the FEA to include time-domain dynamic analyses such as moving vehicle load simulations and seismic response would provide even more insight into UHPC girders' performance. Such continued research will pave the way for updated design codes and broader implementation of UHPC in the pursuit of sustainable, resilient infrastructure.

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