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Vibration-Based Finite Element Model Analysis on Dynamic Characteristics of Ultra-High Performance Concrete Beam

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Abstract: Dynamic load analysis of Ultra-High-Performance Concrete (UHPC) beams is crucial, given the material's widespread use in bridges, enabling engineering feats like 100 meter single-span bridges. Structural vibration monitoring aids in evaluating a structure's ability to withstand dynamic loads, employing finite element (FE) model analysis for verification and enhancement. This study utilizes ANSYS for finite element modelling (FEM) and modal analysis, assessing the UHPC beam's structural integrity. An undamaged UHPC beam model validates dynamic properties, reducing disparities between analytical and experimental results. Modal properties of the first cracked and damaged UHPC beam are updated to represent actual conditions. Vibration analysis reveals inherent vibration modes, frequencies, and forms. Structural stiffness analysis verifies the relationship between stiffness and dynamic qualities. Experimental data updates the UHPC beam model, establishing a connection between structural stiffness and natural frequency under various conditions. In conclusion, ANSYS was employed for FEM, modal analysis, and parameterization verification, revealing the importance of accurate UHPC feature identification and meshing size. Discrepancies highlight the need for experimental tests, reducing differences between FEM and empirical findings. The numerical analysis in ANSYS underscores the correlation between structural stiffness and natural frequency, enabling precise structural health monitoring for UHPC beam damage or deterioration identification.

Keywords: Ultra-high-performance concrete, finite element modelling, model updating, vibration, modal analysis, natural frequency, mode shape, structural stiffness

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1. Introduction

One of the most frequent causes of structural disturbance is vibration. Nevertheless, technological advances in vibration analysis can help to monitor and anticipate civil structure health. Structural strains from vibrations can vary widely, even in buildings built to Eurocode 2 or structural design norms, which have been shown to have the highest reliability of building components against typical failures. Structural health monitoring (SHM), also known as vibration monitoring, has recently seen a surge in attention due to its potential usefulness in identifying problems with civil structures. When employed as the primary building material, concrete is vulnerable to the physical scaling and chemical interactions between reactive aggressive chemicals caused by environmental exposures [1]. As a result of its low tensile strength and flexibility, ordinary concrete is often blamed for structural failures such as those in beams and slabs [1]. A new type of concrete with improved workability, compressive and tensile strengths, and flexibility has been designed to address the problem. Thus, the newly produced concrete is more resistant to environmental threats than ordinary concrete. This modern concrete goes by a few names, but the most common are Ultra-High-Performance Concrete (UHPC) and Reactive Powder Concrete (RPC). The term describes its impressive qualities, including its high early and final strengths, and long lifespan. The UHPC's strength, flexibility, and durability come from the synergistic combination of small particles, silica fume, water, steel fibres, Portland cement, and superplasticisers [2]. However, environmental vibration is one of the common factors in jeopardising the safety of a building's structure. Table B.2 in BS5228-2:2009 [3] shows ground vibrations greater than 15 mm/s can compromise structural integrity.

Early detection and structural integrity assessment ensure the structures meet life-safety criteria. Thus, dynamic characterisation from the actual systems is essential for updating the numerical modelling for more accurate and reliable design analysis with optimisation techniques. It is crucial to optimise parameters to acquire the inherent frequency of a preexisting structure without compromising its stability. Modal parameters, such as natural frequencies and mode shapes, were derived from optimising these variables to track any differences in value between the damaged and undamaged concrete structures in SHM.

Conducting a modal analysis of the structure enables one to investigate the behaviour of the design concerning vibration [4]. An analytical model must be created to examine the dynamic features of a structure. The analysis for estimating the damaged structure's modal properties without further weakening the system relies heavily on numerical analysis based on finite element modelling (FEM). Moreover, it has become a popular SHM method due to its efficiency in identifying damage. Numerous assumptions, parameterisations, idealisations, and discretisation in numerical modelling prevent the gained modal characteristics from reflecting the actual structural behaviour [5]. Hence, parameterisation data must be used to update structural dynamic parameters.

Policies for general structure maintenance typically depend on visual inspections, which make it challenging to spot deterioration in its early stages and can lead to catastrophic outcomes if not carefully determined. Deriving appropriate models for modern structural dynamic performance analyses is complex. The general behaviour of the structure is modified by dynamic properties like eigenvalues, eigenvectors, and damping [6]. Accurate numerical modelling is employed in many areas of civil engineering, including structural evaluation and assessment, and this can be accomplished by regularly checking and updating relevant parameters. It is common practice to make assumptions when developing FE models. Due to the engineering-centric idealisation of FEM, the physical features of civil constructions are often misrepresented. The vulnerability to ill-posedness and ill-conditioning was also emphasised, making model updates extremely sensitive to even little errors. These issues might reduce the FEM's dependability and strength.

Resonance occurs in a structure when there is a mix of periodic pressures and the structure's intrinsic frequency [7]. Essential data for structural health monitoring, including FE model updates and damage identification, can be gleaned from the detected measured vibration responses [8]. The research argues that the FEM's robustness and reliability as a technique for structural damage identification could be improved by verifying and updating the model by optimising its parameters. Better agreement between numerical modelling and parameter optimisation requires verifying and updating the numerical model parameters with the experimental results. The potential benefits of SHM for lowering consequential damage can be diminished if SHM is applied without first verifying and updating the analytical model's parameters to account for changes in the actual environment.

This study aims to improve the outcome of the FE model dynamic performance of the UHPC beam by comparing the analytical parameter of numerical modelling to the experimental results and making any necessary adjustments. FE models are used to analyse internal forces, stresses, displacements, and structural dynamic factors; therefore, reducing uncertainty in those analyses is essential [9]. The modal parameters are determined by doing a FE model analysis in ANSYS software on a control model of an undamaged UHPC beam. Before the UHPC beam is fractured and damaged, its initial dynamic properties are compared to those acquired from the FE model. These initial dynamic characteristics include natural frequencies and mode shapes. Nonetheless, the scope of this study is restricted to updating and verifying UHPC beam modal parameters for SHM.

This study aims to compare the experimental results with the FE model's dynamic features to identify the structural failure caused by the loss of structural stiffness in the UHPC beam. Direct optimisation in ANSYS is used to check the integrity of the undamaged analytical UHPC beam against experimental data. In addition, the FE model is updated in this study to eliminate the inconsistencies in the conceptual description. Natural frequency and structural stiffness are two examples of the UHPC beam parameters examined and compared to obtain more robust and accurate results for structural evaluation under varying conditions. Verifying the original, undamaged parameters of the UHPC beam with ANSYS direct optimisation is one way to increase the reliability of FEM results. It is also important to compare its theoretical results with its analytical outcomes. This study evaluates the UHPC's dynamic performance by checking and updating the FE model's analytical dynamic properties, such as its mode shapes and natural frequencies, to reduce the value of the discrepancy between the two. Furthermore, this research establishes the potentially damaged dynamic parameters of the UHPC beam for structural health monitoring.

The best structural monitoring and evaluation can only be provided if the modelling efforts yield accurate findings. Validating and updating the FE model with the experimental results is necessary to reduce discrepancies between the represented and actual models. The stiffness study also provides a means of contrasting undamaged, cracked, and damaged materials. It could generate more reliable SHM application results in a safer environment than other vibration tests because of its high-performance characteristics, such as not requiring any known artificial excitation.

2. Methodology

Due to its precision and reliability, the FEM is becoming increasingly used for structural health monitoring. Software like ANSYS contains useful tools for estimating the durability of structural components. FEM is reliable in previous studies in terms of delivering realistic structural conditions and its dynamic response [9]. Several crucial aspects, including the FEM's creation process, must be precisely established and solved to acquire the most accurate data. This process includes assigning structural attributes, boundary setup, meshing, and analysis. Damage location and severity can be reliably assessed using FEM using the resulting changes in the stiffness of the affected part.

The pre-processing step is where vital geometric attributes and boundary constraints are set. Next, meshing is crucial to FEM since it develops partial differential equations. The post-processing phase defines the model's inherent frequency spectrum and mode structure. ANSYS 2022 R1 is the primary FE software used for modelling and analysis. In this study, a 500 mm × 100 mm × 100 mm UHPC beam was modelled in three-dimensional (3D). The meshing approach was based on 8-node elements of solid hexahedral elements. Input parameters based on the technical attributes provided by DURA Technology Sdn Bhd (see Table 1) were used to generate the physical properties of the UHPC beam in ANSYS. This is a critical stage of modal analysis that requires pinpoint accuracy. This data must be assigned to the model during the material's phase to be further assessed.

Table 1 - Technical characteristics of UHPC beam [10]

Mechanical Properties	Value
Cylinder Compressive (MPa)	140 – 160
Cube Compressive (MPa)	160 – 180
Flexural Bending (MPa)	25 – 35
Young’s Modulus (GPa)	45 – 50
Density (kg/m^3)	2400 – 2500

A fundamental part of FEM is establishing boundary conditions. Due to its availability in the experimental facilities at Universiti Teknologi MARA Shah Alam, the UHPC beam model is subjected to two pinned supports in this investigation. Fig. 1 represents the structure bounded at both ends in the same manner.

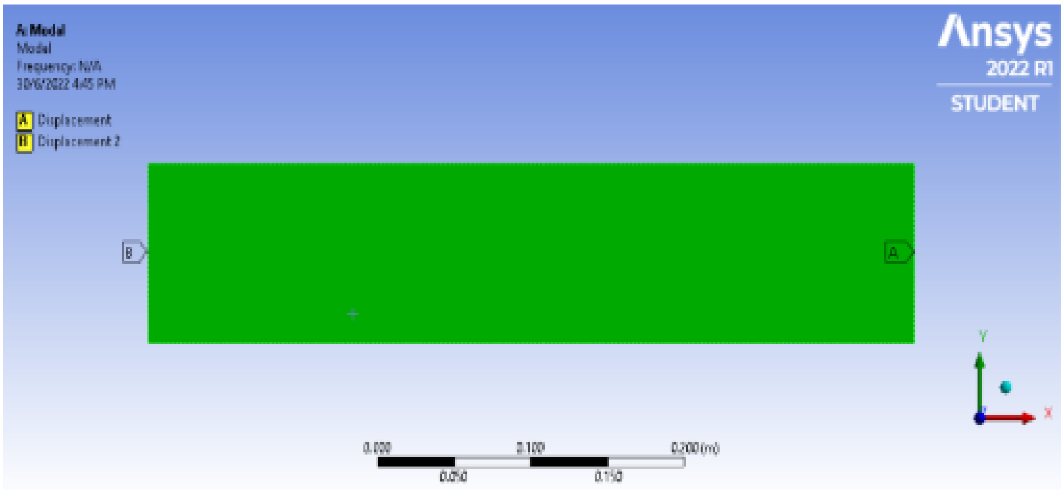


Fig. 1 - Pinned support at both ends

Analysing using **implicit methods** necessitates using mesh sensitivity analysis. In this research, accurate findings are obtained using **a tiny mesh size of 0.02 m** to provide the best possible computational efficiency. Before moving on to the fine mesh setting, the coarse mesh has been compared to ensure minimal variance in results. As a result, the setting is adjusted to the finer sizing of the meshing. Non-destructive testing (NDT) is used in the experiments to acquire the true dynamic properties of a structure through the damage characterised by the modification of signal propagation through the structure [11]. Parameters, such as the undamaged modal parameters of UHPC, can be optimised directly to reduce the discrepancy between experimental and analytical results. This step is crucial for validating the FE model's likeness to the physical structure. Direct optimisation is the FEM verification approach from ANSYS. The initial step in direct optimisation in ANSYS is selecting verification parameters. Parameters for this investigation are the 1^{st}, 2^{nd}, and 3^{rd} flexural bending natural frequencies of an undamaged UHPC beam. Then, before starting the procedure, goals and restrictions were established regarding the experimental data for each parameter to prove that the beam had passed verification.

Over the past few years, some reliable techniques have been developed to assess the stability of structures over time [12]. For structural health monitoring, modifications to the structure's vibration characteristics can reveal how the structure's behaviour has changed over time [9]. The first cracked and damaged dynamic parameters of UHPC can be optimised directly to reduce discrepancies between experimental and analytical results, allowing for a more accurate simulation of the real structure. The beam underwent a second bending, often known as a double flexural bending.

3. Results and Discussion

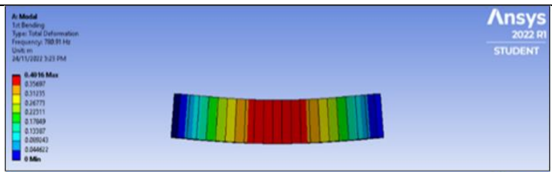
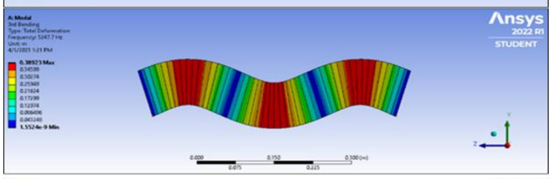
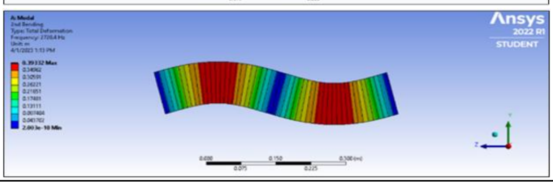
The findings from the modelling, FEM update and optimisation, and UHPC beam stiffness analysis were addressed after the study methodology was accomplished. The theoretical and numerical results of the modal analysis were compared to perform a more reliable and robust SHM of the UHPC beam.

The FEM investigation results can be seen in the mode shape visualisation and the natural frequency. Table 2 displays the frequency of the first flexural bending (780.91 Hz) of the UHPC beam model. First flexural bending occurs when the member bends in only one direction. The frequency of 2728.4 Hz produces the 2^{nd} mode form. The beam underwent a second bending, often known as a double flexural bending [9].

Furthermore, the beam model's colour spectrum reflects how much the beam has been deformed. The amount of distortion at its smallest is 0 mm, represented by blue. Meanwhile, the depth of red indicates the greatest amount of distortion. There is evidence of 3^{rd} flexural mode form in the third mode shape. At a frequency of 5247.7 Hz, 3^{rd} flexural bends were observed in the beams, hence referred to as third flexural bending. A tested component's ability to withstand flexure indicates its stiffness qualities and abilities. Flexural testing can determine the maximum flexural capacity, also known as the deformation point. This highlights the significance of a structure's Young's modulus when analysing its durability.

Table 2 shows the ANSYS-analysed UHPC beam model result. This research unequivocally demonstrates that flexural bending is a significant deformation encountered by the UHPC beam. It is further revealed that the beam's mode forms will alter with frequency, resulting in a rich spectrum of possible modes. It is observed that the frequency of the UHPC beam correlates with its degree of deformation. The beam distortion grows worse with increasing frequency. Modal analysis and investigation are thus vital for SHM to guarantee the security of structural components or civil structures.

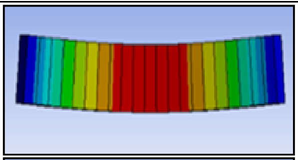
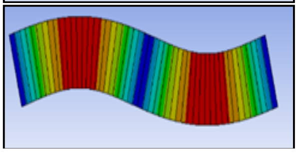
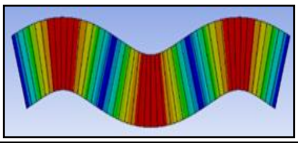
Table 2 - Summary of output tabulation from ANSYS analysis

Name	Frequency (Hz)	Mode Shape
First flexural bending	780.91	
Second flexural bending	2728.40	
Third flexural bending	5247.70	

3.1 FE Model Verification of Undamaged UHPC Beam Through ANSYS Direct Optimization

Table 3 exhibits the discrepancy between the initial FEM and experimental frequencies for all three modes. This indicates that there are inconsistencies that weaken the FE analysis's reliability. The verification was completed using the direct optimisation feature of ANSYS software to minimise the differences between the actual structure and the FE model. The FE model's natural frequency for each mode must be close to the corresponding value for the real structure, as the FE model is meant to represent the real structure.

Table 3 - Frequency parameter of verified undamaged UHPC beam (modal analysis)

Bending Mode	Frequency			Error, Δf (%)	Mode Shape
	Experimental, f_{exp} (Hz)	Initial FEM, f (Hz)	Verified FEM, $f_{fem,vrfd}$ (Hz)		
1st	786.62	780.91	783.11	0.45	
2nd	3183.59	2725.5	3192.25	0.27	
3rd	7151.93	5247.7	7186.06	0.48	

Note: $\Delta f = (f_{exp} - f_{fem,vrfd})/(f_{exp}) \times 100$ (%)

The natural frequency value from the FE model is shown to be approximative to reflect the genuine UHPC beam through error calculation. The inaccuracy in the 1st flexural bending mode decreased to 0.45% after validation. There was an increase from 780.91 Hz to 783.11 Hz in the natural frequency. Meanwhile, the 2nd flexural bending mode has demonstrated a sufficient rise in frequency from 2725.5 Hz to 3192.25 Hz, with an inaccuracy of only 0.27% from the experimental natural frequency. The natural frequency inaccuracy of the 3rd flexural bending has also been lowered to 0.48%. Following validation, the approximative gap between the experimental result of 5247.7 Hz and the FE model value of 7186.06 Hz.

Table 4 shows that after the FE model has been verified, its dimensions and moment of inertia remain unchanged. The constant values demonstrated that no attempt was made to accurately depict the actual structure in the FE model or the geometry of the UHPC beam sample used in the verification process. Therefore, there has been a change between the original and current values of Young's modulus. The desired experimental natural frequencies of the real structure have been attained by increasing the starting Young's modulus of the 1st, 2nd and 3rd bending modes to 53 GPa, 69 GPa, and 94 GPa, respectively.

Table 4 - Stiffness properties of verified undamaged UHPC beam (modal analysis)

Bending Mode	Young's Modulus		Breadth h, (m)	Width, b (m)	Moment of Inertia, I (m^4)	Stiffness, K
	Initial, E (GPa)	Updated, E (GPa)				
1st	50	53	0.1	0.1	8.33×10^{-6}	4.19×10^{-5}
2nd	50	69	0.1	0.1	8.33×10^{-6}	5.72×10^{-5}
3rd	50	94	0.1	0.1	8.33×10^{-6}	7.81×10^{-5}

Table 5 - Theoretical frequency validation of verified undamaged UHPC beam

Bending Mode	Frequency		Error, Δf (%)
	Theoretical, f_{analyt} (Hz)	Updated FEM, $f_{fem,updt}$ (Hz)	
1st	783.11	780.91	0.3
2nd	3311.67	3192.25	3.6
3rd	7451.26	7186.06	3.6

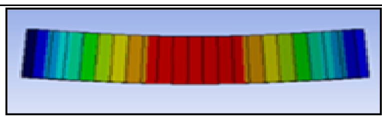
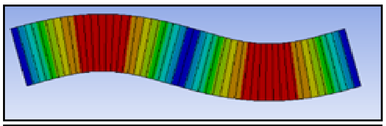
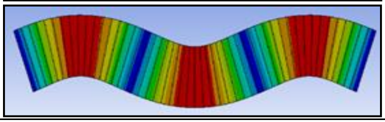
Note: $\Delta f = (f_{analyt} - f_{fem,updt})/(f_{analy}) \times 100$ (%)

The increase in Young's modulus value is due to the increase in natural frequency associated with each mode. The natural frequency predicted by the FE model is lower than the experimental data (see Table 5). Table 4 further exhibits that the stiffness of the 1st, 2nd and 3rd bending modes has exponentially grown with Young's modulus. This is due to a direct relationship between Young's modulus and the model's stiffness.

3.2 First Cracked UHPC Beam FE Model Updating Through ANSYS Direct Optimization

Table 6 displays the results of a comparison between the revised FEM frequency and the experimental frequency for all three modes. Nevertheless, the variation across the 1st, 2nd, and 3rd bending modes is still within acceptable limits (5%). This indicates good cooperation between the FE model and the real model. Hence, a FE model update is necessary to depict the real structure's first cracked condition based on modal parameters. Direct optimisation inside ANSYS has been used to update the model, and this process is being carried out to reduce the gap between the actual structure and the FE model as much as possible. The FE model's natural frequency for each mode at the first cracked condition must resemble the real structure's natural frequency.

Table 6 - Frequency parameter of updated first cracked UHPC beam (modal analysis)

Bending Mode	Frequency		Error, Δf (%)	Mode Shape
	Experimental, f_{exp} (Hz)	Updated FEM, $f_{fem,updt}$ (Hz)		
1st	708.35	689.33	2.7	
2nd	3007.81	2922.27	2.8	
3rd	6209.75	6146.6	1.02	

Note: $\Delta f = (f_{exp} - f_{fem,updt})/(f_{exp}) \times 100$ (%)

The natural frequency value from the FE model is shown to be close to reflecting the genuine UHPC beam through error calculation. The validation procedure resulted in a 2.7% reduction in error for the initial flexural bending mode. The experimental result of 689.33 Hz is quite close to the value obtained from studying the natural frequency. Furthermore, the second flexural bending mode has shown an adequate approximation of frequency, with a value of 2922.7 Hz, offering just a 2.8% difference from the actual value of 3007.81 Hz. Table 6 further shows that the natural frequency inaccuracy of the third flexural bending has been brought down to 1.02%. After the revision procedure, the updated value of 6146.6 Hz in both the experimental and FE model is comparable to the actual structure.

Table 7 - Stiffness properties of updated first cracked UHPC beam

Bending Mode	Updated Young's Modulus, E (GPa)	Breadth, b (m)	Width, h (m)	Moment of inertia, I (m^4)	Stiffness, K
1st	39	0.036	0.044	2.56×10^{-7}	9.97×10^{-6}
2nd	57	0.098	0.032	2.68×10^{-7}	1.53×10^{-5}
3rd	69	0.01	0.03	2.25×10^{-8}	1.55×10^{-6}

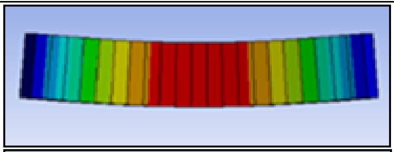
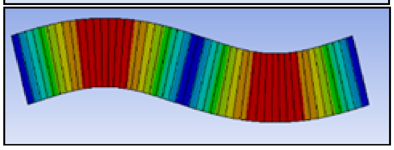
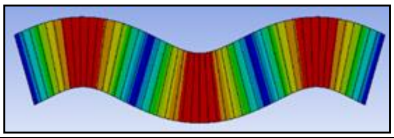
Based on Table 7, the updated Young's modulus of the FE model shows a decrease in values after the update. The geometrical characteristics of the UHPC model beam have also decreased, affecting its moment of inertia. With the reduction of the model's area, each mode's moment of inertia has been given the values of 2.56×10^{-7} m^4, 2.68×10^{-7} m^4, and 2.25×10^{-8} m^4, accordingly. The drop in values proved that during the updating process, the condition of the FE model is targeted to represent the real structure as the first cracked condition of the UHPC real beam, affecting Young's modulus reduction. Hence, the initial and updated Young's modulus have shown alteration. The initial Young's modulus of the 1st, 2nd and 3rd bending modes have dropped from 53 GPa, 69 GPa, and 94 GPa to 39 Hz, 57 Hz and 69 Hz consecutively. The experimental natural frequencies of the real structure are intended to be represented by Young's modulus of the FE model.

Young's modulus decreases as the natural frequency of each mode decreases. Table 7 displays the results of a comparison between the natural frequencies predicted by the FE model and the experimental values. The table also reveals an exponential decrease in stiffness across the 1st, 2nd, and 3rd bending modes when Young's modulus decreases. Therefore, it is demonstrated that Young's modulus is proportional to model stiffness.

3.3 Damaged UHPC Beam FE Model Updating Through ANSYS Direct Optimization

Table 8 highlights that there is just a slight difference between the experimental frequency and the updated FEM frequency for the UHPC-damaged condition across all three modes. However, the variation between the 1st, 2nd and 3rd bending modes is tolerable, between 5% and 6%. This implies good cooperation between the FE model and the actual model. Consequently, it has been established that updating the FE model is essential to accurately portray the deteriorated state of the actual structure using modal parameters. Direct optimisation within ANSYS software has been used for the update process to reduce the gap between the actual structure and the FE model to an acceptable level. Given that the FE model is meant to represent the real structure in its damaged state, its natural frequency for each mode should be close to the value for the real design.

Table 8 - Frequency parameter of updated damaged UHPC beam (modal analysis)

Bending Mode	Frequency		Error, Δf (%)	Mode Shape
	Experimental, f_{exp} (Hz)	Updated FEM, $f_{fem,updt}$ (Hz)		
1st	544.74	542.67	0.38	
2nd	2549.15	2405.9	5.6	
3rd	5195.36	5251.69	1.07	

Note: $\Delta f = (f_{exp} - f_{fem,updt})/(f_{exp})\times100$ (%)

The natural frequency value from the FE model appears to be approximative to reflect the genuine UHPC beam through error calculation. The validation approach resulted in a 0.38% reduction in error for the 1st mode of flexural bending. The experimental value of 543.75 Hz is quite close to the value obtained from the natural frequency. In addition, the frequency of 2405.9 Hz demonstrated by the 2nd flexural bending mode is a good approximation of the 2549.15 Hz of the actual model, with an error of only 5.6%. Even better, the natural frequency inaccuracy of the 3rd flexural bending has decreased to only 1.07%. Following the update, the experimental and FE model values are closer to the actual structure at 5251.69 Hz.

Table 9 - Stiffness properties of updated damaged UHPC beam

Bending Mode	Updated Young's Modulus, *E* (GPa)	Breadth, *b* (m)	Width, *h* (m)	Moment of inertia, *I* (m^4)	Stiffness, *K*
1st	24	0.028	0.043	1.86×10^{-7}	4.45×10^{-6}
2nd	39	0.036	0.044	2.56×10^{-7}	9.97×10^{-6}
3rd	50	0.030	0.011	3.33×10^{-9}	2.30×10^{-7}

Table 9 shows that the revised value for Young's modulus of the UHPC beam has decreased. Reducing the UHPC model beam's geometrical properties also decreases its moment of inertia. Moments of inertia for each mode have been calculated, and their values are as follows: 1.86×10^{7} m^4, 2.56×10^{7} m^4, and 3.33×10^{9} m^4 as the model's area shrunk. The reduction in values demonstrated that the condition of the FE model was intended to replicate the real structure during the updating process, as the damaged state of the UHPC real beam affected the reduction in its Young's modulus. Therefore, there has been a change between the original and current values of Young's modulus. From an initial value of

53 GPa, 69 GPa, and 94 GPa, Young's modulus of the 1st, 2nd and 3rd bending modes decreases to 24 Hz, 39 Hz, and 50 Hz, respectively. The FE model's Young's modulus is designed to resemble the real structure's experimental natural frequencies.

Young's modulus decreases as the natural frequency of each mode decreases. The table also compares the natural frequencies predicted by the FE model and the experimental values. The findings further reveal that as Young's modulus decreases, the stiffness of the 1st, 2nd and 3rd bending modes decreases exponentially. Therefore, it established that Young's modulus is proportional to model stiffness.

3.4 Frequency Parameter of Updated Undamaged, First Cracked, and Damaged UHPC Beam

The UHPC beam modal analysis allows the experimental and analytical study of several characteristics, one of which is frequency. Maintaining the integrity of the FEM analysis necessitates regular updating of the FE model. This is because FE models accurately represent the monitored structure, allowing for more accurate structural health assessments.

Table 10 demonstrates that distinct values have been generated by the updated undamaged, first cracked, and damaged frequencies. The first fractured and damaged UHPC beam is measured against its original, undamaged frequency. In all cases, the frequency of each mode has decreased, revealing that the state of the UHPC beam affects the frequency of the beam itself.

Table 10 - Frequency parameter of updated undamaged, first cracked, and damaged UHPC beam

Bending Mode	Frequency		
	Undamaged, f_{udam} (Hz)	1st Cracked, f_{crack} (Hz)	Damaged, f_{dam} (Hz)
1st	783.110	689.330	542.670
2nd	3192.24	2922.27	2405.89
3rd	7186.06	6146.60	5251.69

3.5 Stiffness Properties of Updated Undamaged, First Cracked and Damaged UHPC Beam

The flexural stiffness of a structure is a measure of its rigidity. The UHPC beam's stiffness is a measurable property that can be analysed and whose variations may be observed in experiments. Keeping the FE model up-to-date is crucial for ensuring the FEM analysis representation is valid when calculating each mode's stiffness under varying situations. Verifying the existence of structural damage involves determining the stiffness parameter of each mode under varying conditions.

Table 11 displays the results of three distinct tests measuring the stiffness of the updated undamaged, first cracked, and damaged versions of the material. As the stiffness of each mode has decreased in every condition, the undamaged frequency of the UHPC beam serves as a reference for the changes in the state of the cracked and damaged UHPC beam, proving that the condition of the UHPC beam affects its stiffness. There is also a clear downward tendency in the structural stiffness of each mode under varying conditions.

Table 11 - Stiffness properties of updated undamaged, first cracked and damaged UHPC beam with the corresponding modes

Bending Mode	Stiffness		
	Undamaged, K_{udam} (10^{-5} Nm^2)	Cracked, K_{crack} (10^{-5} Nm^2)	Damaged, K_{dam} (10^{-5} Nm^2)
1st	4.19	0.997	0.445
2nd	5.72	1.530	0.997
3rd	7.81	0.155	0.023

Table 12 shows that as damage increases, so does the percentage by which Young's modulus has been reduced. Additionally, the 1st mode's moment of inertia has decreased under various conditions. The rate is down to 96.93% for the first cracked state from 100% for the undamaged one. Young's modulus is affected by the state of the UHPC beam, as evidenced by the 92.7% decrease from the first crack to the damaged condition. A reduction in Young's modulus value for the first cracked and damaged beam may indicate a loss in structural integrity. Examining the declining trend of Young's modulus from 26.42 to 38.46% aids in predicting the structural integrity of a material.

Table 12 - Updated Young's modulus and moment of inertia (1st bending mode)

Condition	Young's Modulus		Moment of Inertia	
	E (GPa)	Reduction *E* (%)	*I* (10^{-6} m^4)	Reduction *I* (%)
Undamaged	53	0	8.33	0
First Cracked	39	26	0.256	96.93
Damaged	24	38.46	0.0186	92.7

As shown in Table 13, the percentage by which Young's modulus is reduced rises with the severity of the damage. Additionally, the second mode's moment of inertia has decreased under varying conditions. From a perfect state, it has depreciated to a mere 99.68% for the first cracked condition. The Young's modulus of the UHPC beam was proven to be affected by its state by the 4.48% decrease from the initial cracked condition to the damaged condition. A reduction in Young's modulus value for the first cracked and damaged beam may indicate a loss in structural integrity. Reviewing the declining trend of Young's modulus value from 17.39% to 31.58% allows for the prediction of structural integrity.

Table 13 - Updated Young's modulus and moment of inertia (2nd bending mode)

Condition	Young's Modulus		Moment of Inertia	
	E (GPa)	Reduction *E* (%)	*I* (10^{-6} m^4)	Reduction *I* (%)
Undamaged	69	0	8.33	0
First Cracked	57	17.39	0.00225	99.68
Damaged	39	31.58	0.0256	4.48

Table 14 also shows a similar pattern where the percentage by which Young's modulus is reduced grows with the severity of the damage. Additionally, the third mode's moment of inertia has decreased under varying conditions. From a perfect state, it has depreciated to a mere 99.68% for the first cracked condition. The Young's modulus of the UHPC beam was proven to be affected by its state by the reduction of 98.77% from the initial cracked condition to the damaged condition. A decrease in Young's modulus value for the first cracked and damaged beam may indicate a loss in structural integrity. Predictions of structural integrity can be established by looking at Young's modulus value's declining trend from 26.6% to 27.5%.

Table 14 - Updated Young's modulus and moment of inertia (3rd bending mode)

Condition	Young's Modulus		Moment of Inertia	
	E (GPa)	Reduction *E* (%)	*I* (10^{-6} m^4)	Reduction *I* (%)
Undamaged	94	0	8.33	0
First Cracked	69	26.6	0.0268	99.68
Damaged	50	27.5	0.00033	98.77

3.6 Relationship Between the Structural Stiffness and Natural Frequency of the Updated Undamaged, First Cracked and Damaged UHPC Beam

The natural frequency of a system should be virtually represented as it directly correlates with the degree of harm that an excessive amount of vibration could bring on. This is the most important quality of a system that needs to be virtually represented. A structure's functionality, performance, and lifespan can all be assessed by meticulously tracking its inherent frequency and stiffness.

Structural health monitoring requires the investigation of many factors, including structural parameters like rigidity, which can theoretically be affected by damage and degradation. Its rigidity and integrity will suffer irreparable losses due to structural deterioration. The modal analysis determined the natural frequency and other dynamic parameters of an undamaged, first cracked, and damaged UHPC beam. This shows that the natural frequency is directly related to structural rigidity [13], as the loss of natural frequency would disintegrate the structure.

Natural frequency and structural stiffness are intertwined in that their values fluctuate as one shifts or the other does. Structural stiffness must be enhanced to increase its natural frequency. Table 15 displays the approximate relationship between the reduction ratio of structural stiffness and the natural frequency of the first bending mode for the first cracked and damaged UHPC beam circumstances. It is possible to differentiate damage incidence in the sample by examining the relationship between structural stiffness and natural frequency, which provides an approximate value of the reduction ratio.

Table 15 - Relationship between the structural stiffness and natural frequency of the updated undamaged, 1st cracked and damaged UHPC beam (1st bending mode)

Condition	Stiffness		Natural Frequency		Reduction Ratio
	K (Nm^2)	Reduction *K* (%)	*f* (Hz)	Reduction *f* (%)	(*f*/K)
Undamaged	4.19 x10^{-5}	0	783.11	0	0
1st Cracked	0.997x10^{-5}	22.43	689.33	11.98	0.53
Damaged	0.445x10^{-5}	37.85	542.67	21.28	0.56

Table 16 shows that under the first cracked and damaged UHPC beam conditions, the reduction ratio of structural stiffness and the natural frequency of the second bending mode is approximately proportionate. This relationship implies that as the structural stiffness decreases due to cracking and damage in the UHPC beam, there is a corresponding reduction in the natural frequency of the second bending mode. This correlation indicates the structural response to damage, highlighting the interconnectedness of stiffness and dynamic characteristics in the beam's condition.

Table 16 - Relationship between the structural stiffness and natural frequency of the updated undamaged, 1st cracked and damaged UHPC beam (2nd bending mode)

Condition	Stiffness		Natural Frequency		Reduction Ratio
	K (Nm^2)	Reduction *K* (%)	*f* (Hz)	Reduction *f* (%)	(*f*/K)
Undamaged	5.72 $x10^{-5}$	0	3192.25	0	0
1st Cracked	1.53$x10^{-5}$	73.25	2922.27	8.46	0.12
Damaged	0.997$x10^{-5}$	34.84	2405.9	17.67	0.51

Table 17 shows that under the first set of cracked and damaged UHPC beam circumstances, the reduction ratio of structural stiffness and natural frequency of the third bending mode equals 0.54, suggesting that these two quantities are related. The reduction ratio is a quantitative indicator of the proportional decrease in structural stiffness and the natural frequency of the third bending mode under specified circumstances. This observation underscores the interconnected nature of stiffness and dynamic characteristics.

Table 17 - Relationship between the structural stiffness and natural frequency of the updated undamaged, 1st cracked and damaged UHPC beam (3rd bending mode)

Condition	Stiffness		Natural Frequency		Reduction Ratio
	K (Nm^2)	Reduction *K* (%)	*f* (Hz)	Reduction *f* (%)	(*f*/K)
Undamaged	7.81 $x10^{-5}$	0	7186.06	0	0
1st Cracked	0.155$x10^{-5}$	98.02	6146.6	14.46	0.15
Damaged	0.023$x10^{-5}$	85.16	5251.69	14.56	0.17

3.7 Conclusion

This research used ANSYS for FEM, modal analysis, verification of the undamaged state of UHPC beam parameterisation, and updating dynamic parameters for both cracked and damaged UHPC beam situations. The study reveals the need to correctly identify and assign UHPC features and geometrical shapes if precise results are desired. The FEM should be employed with a meshing size of 0.002 m at the fine setting for accurate results. The large discrepancy between the first cracked, damaged, and undamaged parameters allows for an experimental test to be conducted to reduce the difference. Furthermore, it helps reduce the disparity between FEM and empirical findings. According to ANSYS numerical analysis, the structural stiffness of a UHPC beam varies widely depending on its natural frequency. As a result, ANSYS must be checked and updated with experimental data to ensure the accuracy of the damaged and undamaged dynamic properties. The software, however, has a flaw in that it can only perform a linear analysis of the FE model. The reduction ratio has been used to examine the effects of changing the structural stiffness and the natural frequency of the UHPC beam, demonstrating the correlation between the two. Consequently, this allows for precise and reliable structural health monitoring by identifying any damage or deterioration to the UHPC beam.

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