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A Review paper on Experimental Validation of Nonlinear Dynamic Analysis for Damage Detection in RC Beams

Raahul S [a], Mohamed Salman Farsi M [a], Gowtham B [a], Lohit M [a], Subhika C [a], Dr. Vennila A [b]

[a] *First year M. E Student Structural Engineering, Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore 641049, India*
[b] *Assistant Professor, Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore 641049, India*

A B S T R A C T

Damage detection in reinforced concrete (RC) beams is crucial for ensuring structural safety and integrity, particularly in regions prone to seismic activity. This study focuses on the experimental investigation and analysis of nonlinear dynamic characteristics for effective damage detection in RC beams. The research distinguishes between linear elastic and nonlinear dynamic approaches, highlighting the inherent nonlinear behaviour of RC structures. While traditional methods primarily rely on linear dynamics, this study addresses the limitations by exploring the nonlinear response of RC beams. Experimental tests involving harmonic and impulsive excitations were conducted to obtain displacement amplitudes and frequencies at various loading levels. Time–frequency analysis (TFA) was employed to examine the relationship between structural stiffness variation over time and changes in natural vibration frequencies. The study also utilizes short-time Fourier transformation (STFT) to analyse displacement responses from impulsive excitation tests. The findings reveal significant correlations between nonlinear dynamic characteristics and the damage level of RC beams. By comparing amplitude and frequency curves before and after structural damage, this approach enables the accurate detection of damage in RC beams. The study contributes to advancing the understanding of nonlinear behaviour in RC structures and provides valuable insights into practical applications for structural health monitoring and damage assessment.

Keywords: Damage Detection, Concrete beams, Non-Linearity, Crack Formation, Dynamic Analysis.

Introduction

This review paper explores the evolution the classification of damage detection technology for structures into linear elastic and nonlinear dynamic approaches. Under linear elastic methods, there are two sub-categories: the modal method, which calculates natural frequencies and mode shapes using finite element software, and the wave motion method, which is gaining popularity due to its suitability for planar structures with multiple damages. While most research methods in damage detection are based on linear dynamics, reinforced concrete (RC) structures behave nonlinearly in nature. Various stiffness functions, such as the bilinear model, are available to depict this nonlinearity. However, there is limited literature on the nonlinear dynamic characteristics of RC beams. In an experimental–analytical study, the relationship between displacement amplitudes and frequencies was obtained from harmonic excitation tests. The window width for time– frequency analysis (TFA) was adjusted to ensure consistency with the results from harmonic excitation tests. By utilizing TFA with the chosen window width, the study obtained displacement response results from impulsive excitation tests using short-time Fourier transformation (STFT). The correlation between the nonlinear dynamic characteristics of an RC beam and its damage level was then examined using the obtained amplitude and frequency curves before and after structural damage at each loading level.

Damage detection of RC beams based on experiment and analysis of nonlinear dynamic characteristics

1.Beam Design and Material Properties:

A reinforced concrete (RC) beam with specific dimensions was designed to match the fundamental period of typical concrete bridges. The beam's properties, including dimensions, fundamental frequency, ultimate moment capacity, and concrete strength, were determined.

Table 1
Reinforcing steel of the RC beam.

	Bottom	Top	Shear
Reinforcing steel			
Diameter, d (mm)	12	8	6.5
Effective depth, h (mm)	154		
Yield strength, f_y (MPa)	436.45	279.5	210
Number of bars, N	3	2	44

Table 2
The concrete properties of the RC beam.

Cement	360 kg/m^3
Sand	736 kg/m^3
Gravel	1104 kg/m^3
Water	165 kg/m^3
f_{cu}	55.1 MPa

f_{cu} is the 28 day cubic strength of the concrete.

2. Test Setup:

The RC beam was supported by reinforced concrete piers on a laboratory basement shear wall. Accelerometers and displacement meters were strategically placed to monitor acceleration and displacement responses during testing. Various loading levels were applied to the beam to induce damage.

3. Testing Procedure:

: The experiments involved static loading tests up to ten levels, impulsive vibration tests after each static loading level, and harmonic excitation tests. These steps were repeated, and data on acceleration, displacement, and frequency responses were collected and analysed.

4. Experimental Method:

The static loading tests measured strain and observed crack development. Impulsive and harmonic excitation tests analysed acceleration and displacement responses to determine the relationship between amplitude and natural vibration frequency.

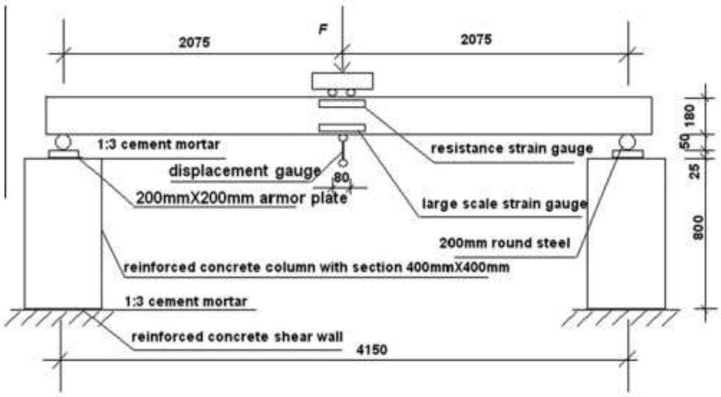


Fig. 1 - Dimensions, loading and measurement locations of testing beam

5. Nonlinear Dynamic Analysis:

Time-frequency analysis (TFA) was conducted using short time Fourier transformation (STFT) to examine how frequency spectrum varied with time. The TFA revealed the relationship between displacement amplitude and corresponding natural vibration frequency (DA-CNVF), showing nonlinear behaviour.

6. Discussion and Conclusions:

The analysis indicated that the nonlinear dynamic characteristics of the RC beam changed with increasing damage levels. The relationship between DA-CNVF was found to be nonlinear, with the degree of nonlinearity increasing initially and then gradually diminishing. The study concluded that the NDC of the RC beam could effectively detect low to moderate damage levels, making it suitable for structures with minor or invisible damage. However, caution was advised when detecting large-scale damage, as the NDC behaviour might not be monotonic. Overall, the study provided valuable insights into using nonlinear dynamic characteristics for damage detection in RC beams, with practical implications for structural health monitoring and maintenance.

EVALUATION OF THE NON-LINEAR DYNAMIC RESPONSE TO HARMONIC EXCITATION OF A BEAM WITH SEVERAL BREATHING CRACKS

The article discusses the analysis of a cantilever beam with multiple breathing cracks subjected to harmonic excitation. It builds upon previous research on beams with single cracks and extends the analysis to include the effects of multiple cracks and smoother crack closure transitions. The primary aim is to develop a method to evaluate the dynamic response of the beam efficiently while capturing the non-linear behaviour induced by the presence of breathing cracks.

1.Previous Studies:

A review of existing literature reveals research on beams with single cracks, primarily focusing on their dynamic response under harmonic excitation. Some studies have addressed the non-linear behaviour caused by breathing cracks, highlighting the importance of considering crack closure effects.

2.Project Scope:

The research aims to extend previous methods to analyze beams with multiple breathing cracks and incorporate smoother crack closure transitions. The method proposed utilizes harmonic balance techniques for rapid computation of the dynamic response, with numerical examples provided for validation.

3.Equation of Motion and Crack Function:

The article presents the equation of motion for a cantilever beam with multiple breathing cracks and describes the crack function representing the transition from closed to open cracks. The crack function is assumed to depend linearly on the curvature of the cracked element, allowing for partial crack openings.

4. Numerical Results:

Numerical simulations are conducted for beams with varying crack sizes and positions. The results demonstrate the effectiveness of the proposed method in approximating the dynamic response, with a significant reduction in computation time compared to direct numerical integration.

5. Conclusions:

The study concludes that breathing cracks induce non-linear dynamic behaviour in beams, leading to the generation of super harmonics in the response spectrum. The proposed method enables efficient evaluation of dynamic responses, offering potential applications in damage detection methods. Overall, the article provides a comprehensive approach to analysing the dynamic response of beams with multiple breathing cracks, emphasizing the importance of considering non-linear effects induced by crack presence.

Nonlinear Vibration Characteristics of Damaged Concrete Beams

The study investigated the nonlinear vibration characteristics of reinforced concrete beams to detect damage, particularly cracks, with potential applications in structural health monitoring. Here's a summary:

Experimental Setup:

1. Beam Specifications:

Laboratory-sized model beams were designed with a length of 3 meters and a simply supported span of 2.8 meters, providing a fundamental frequency of approximately 20 Hz.

2. Beam Dimensions:

The beams were 0.105 meters deep and 0.2 meters wide to prevent significant torsional vibration. They were reinforced with three 12-mm-diameter steel bars.

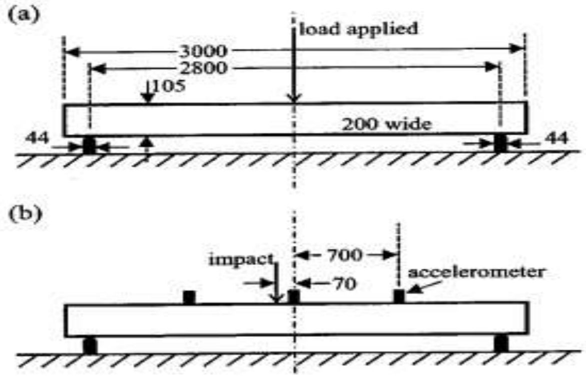


Fig. 2 - Beam dimensions and load and measurement locations

(a) Loading

(b) Impact excitation

test (not to scale)

Design properties	
Natural frequency	20 Hz
Failure moment	9.5 kN m
Midspan failure load	12.6 kN
Maximum shear force	7.1 kN
Beam dimensions	
Length	3 m
Span	2.8 m
Depth	0.105 m
Width	0.2 m
Shear reinforcement	
Orientation	vertical
Spacing	0.08 m
Bar diameter	4.8 mm
Concrete mix	
28 day cube strength (f_c)[a]	46 MPa
Water[b]	9.5%
Fine aggregate[b]	34.4%
Coarse aggregate[b]	37.3%
Cement[b]	18.8%
Reinforcing dimensions	
Bottom	
Type	Rebar
Effective depth	0.079 m
Bar diameter	12 mm
Number of bars	3
Yield strength	410 MPa
Rib spacing	10 mm
Top	
Type	Smooth bar
Effective depth	0.02 m
Bar diameter	6 mm
Number of bars	2
Yield strength	240 MPa

3. Support Conditions:

Solid steel supports on a concrete floor were used to minimize support movement during testing.

4. Test Procedure:

Two beams, denoted as A and B, were tested. Damage loading was performed incrementally up to failure, and at each load level, various tests including vibration response to impact excitation testing and cyclic static load testing were conducted.

Damage Loading:

1. Loading Method:

Damage was induced using three-point loading in steps of 1,500 N until failure.

2. Crack Monitoring:

Crack locations and lengths were monitored, with cracks initially appearing near shear reinforcing locations and later near the midspan.

Analysis of Vibration Test Data:

1. Support Conditions Assessment:

Preliminary tests compared impulse responses at the midspan and supports to assess support conditions.

2. Vibration Modes:

Filtering techniques were applied to analyse vibration modes, confirming that the vibration mainly consisted of the fundamental mode.

3. Time-Frequency Relationship:

The time-frequency distribution was estimated using the moving window Discrete Fourier Transform (DFT), showing changes in frequency with increasing damage levels.

4. Frequency-Amplitude Relationship:

The amplitude-frequency relationship was plotted to assess nonlinear behaviour with damage, revealing changes in frequency and amplitude.

Discussion and Conclusions:

1. Nonlinear Behaviour:

The study found that nonlinear vibration behaviour increased initially with damage up to a certain load level, after which it decreased slightly.

2. Potential for Damage Detection:

While the method showed potential for detecting low levels of cracking, it was less effective at distinguishing between low and high load levels, making it potentially suitable for special structures requiring high structural integrity.

Conclusions:

The investigation demonstrated the potential of nonlinear vibration characteristics for damage detection in reinforced concrete structures. Changes in frequency and amplitude were observed with increasing damage levels, providing insights into structural health monitoring. Further research is recommended to confirm and extend the findings, potentially enhancing the method's applicability in various structural assessment scenarios.

Simulation-based non-linear vibration model for damage detection in RC beams

The study you provided offers a comprehensive exploration of damage assessment in reinforced concrete (RC) beams using advanced computational and experimental techniques. Let's break down the key points and findings.

1. Constitutive Modelling:

The Concrete Damaged Plasticity model (CDPM) was employed to capture concrete behaviour, incorporating mechanisms for crushing under compression and cracking under tension. This model provided a realistic representation of concrete's response to loading.

2. FE Modelling of RC Beam:

Finite Element (FE) analysis was utilized to model an RC beam, considering both concrete and steel reinforcement. The modelling approach aimed to replicate real-world conditions, including non-symmetric support conditions, and accounted for both static and dynamic loading.

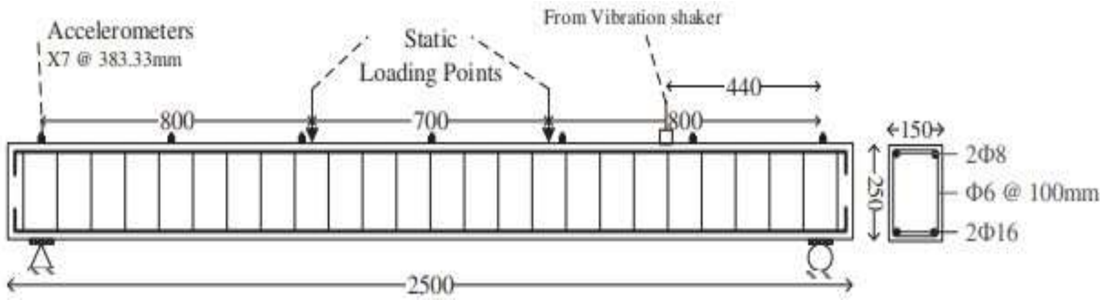


Fig. 3 - Schematic diagram of the beam geometry and test setup

3. Static Response:

The simulated beam's response under static loading was analysed, including load-deflection behaviour and crack formation. The simulation results aligned reasonably well with experimental data, demonstrating the model's capability to capture crack formation and structural behaviour.

4. Dynamic Response Modal Analysis:

Modal analysis and impact hammer testing were conducted to determine the beam's natural frequencies. Although there was a decrease in natural frequencies with damage, the reduction was not highly sensitive, making it less effective for damage detection compared to nonlinear responses.

Fig. 4 - Beam test setup for experimental investigation

5. Restoring Force Surfaces:

Analysis of restoring force-displacement relationships revealed changes in modal stiffness with increasing damage. This method proved efficient in identifying nonlinear behaviour, with the stiffness reduction being less pronounced compared to other studies due to the beam's stiffness characteristics.

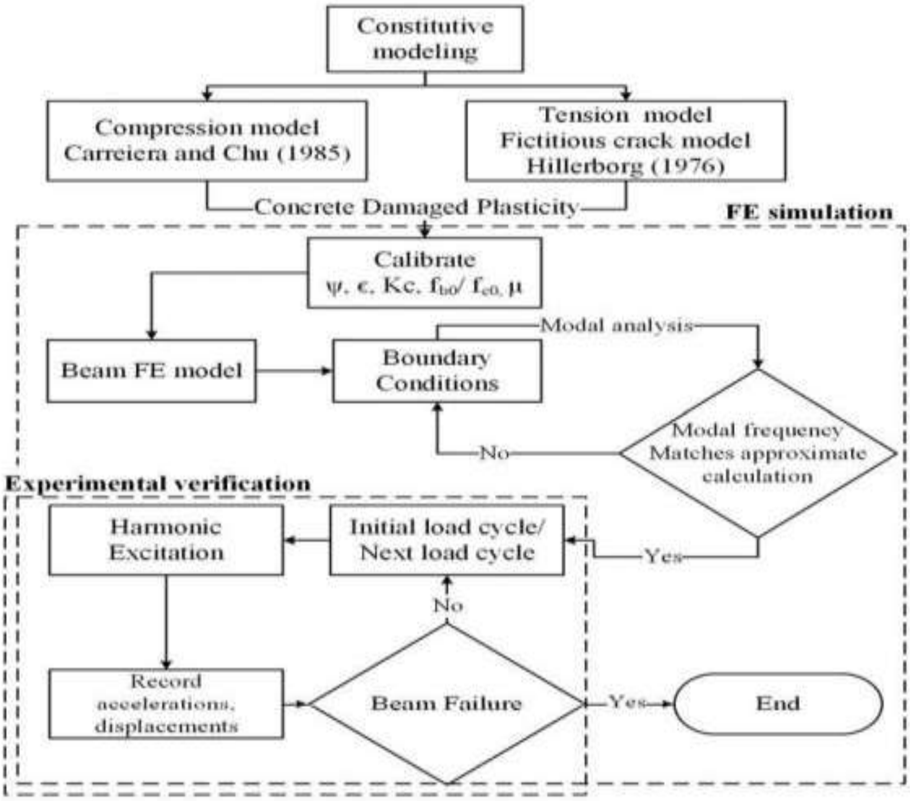


Fig. 5 - Flow chart of methodology

6. Formation of Super-harmonics:

Super-harmonics, observed through harmonic excitation, provided insights into nonlinear behaviour. The magnitude of super-harmonics increased with damage up to a certain point, indicating sensitivity to crack presence.

7. Damage Detection without Baseline Data:

A novel three-parameter relation (damage, nonlinearity, and excitation force) was proposed for damage detection, eliminating the need for baseline data. This method leveraged computational models to estimate damage levels based on observed non-linear behaviour and excitation force.

8. Conclusions:

The study concluded that nonlinear dynamic responses were more sensitive to damage compared to linear approaches. The proposed three-parameter relation offered an effective method for damage detection in RC beams, with implications for structural health monitoring without relying on baseline data. Overall, the investigation highlights the importance of advanced computational modelling techniques and experimental validation in assessing structural damage and developing reliable damage detection methods for civil infrastructure.

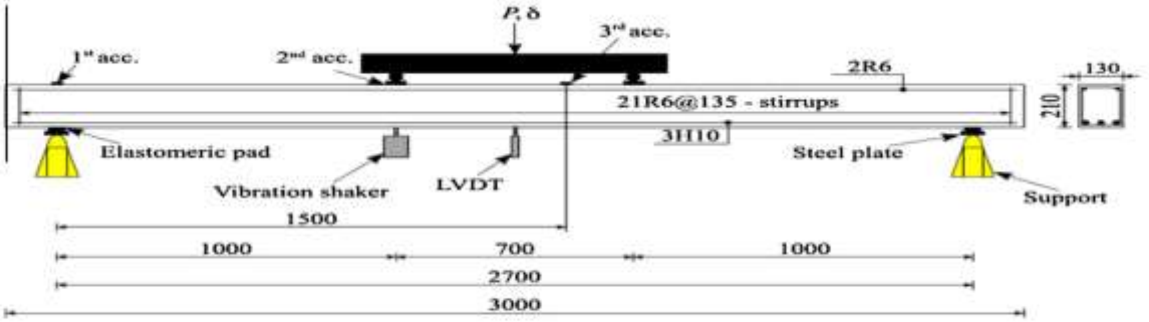
A new approach to estimate damage in concrete beams using non-linearity

The review paper has several aspects related to damage in concrete structures, constitutive relations, and finite element simulation. Here's a summary of the key points covered:

1. Damage in Concrete:

Concrete is strong in compression but weak in tension, often leading to crack initiation and propagation. Damage is defined as the condition of a structure when it is not operating ideally but is still serviceable. The study incorporates damage as a function of the maximum allowable load on the specimen to quantify damage as a percentage of the maximum load.

2.



Constitutive Relations:

The compressive model used translates the stress-strain behaviour of concrete, focusing on tensile concrete modelling. The Concrete Damaged Plasticity (CDP) model is used for compressive strength, capable of static and dynamic analysis of reinforced concrete members with embedded bars.

3. Steel Reinforcement:

Two types of steel reinforcement are used: plain bars with 6 mm diameter for top and transverse reinforcement, and 10 mm bars for main tension reinforcement.

4. Finite Element Simulation:

ABAQUS software is used for analysis, with reference data from recent research. Static and dynamic analyses are performed, with meshing details provided for both crack visualization and analysis. Modal dynamic analysis and dynamic implicit analysis are conducted to evaluate sensitivity to damage.

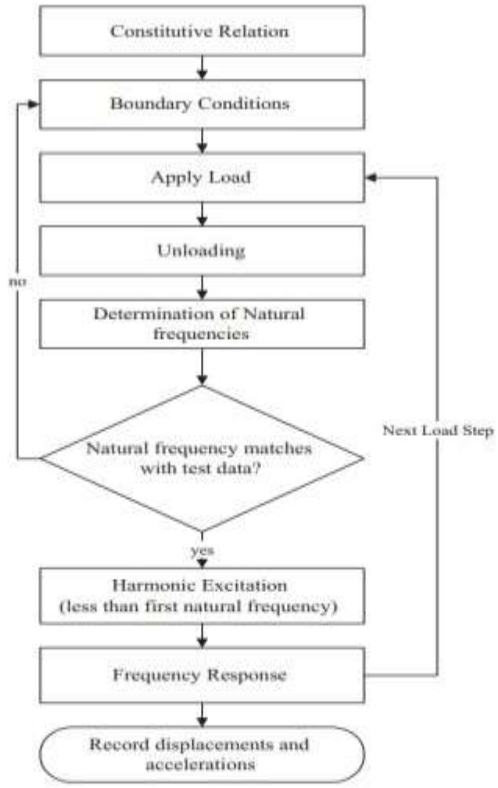


Fig. 6 - Flow chart of methodology

5. Results and Discussion:

Static simulation load deflection results show good agreement with experimental data. Crack propagation patterns are analysed to validate the capability of the study for mixed-mode crack formation. Sensitivity to damage is evaluated through modal frequency deterioration and dynamic analysis. Dynamic implicit analysis proves more sensitive to damage detection compared to modal dynamic analysis. The study offers insights into crack formation and provides a promising method for damage detection without the need for baseline structural data.

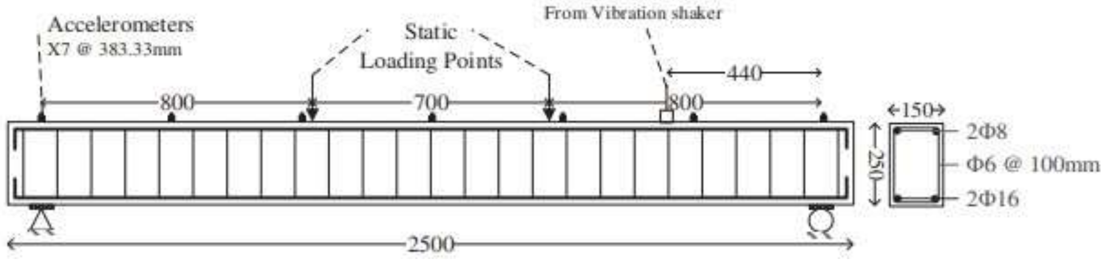


Fig. 7 - Schematic diagram of the beam geometry and test setup

6. Conclusions:

The Concrete Damaged Plasticity (CDP) model is effective in detecting damage without baseline structural data. Non-linear dynamic analysis is more sensitive to damage and less influenced by environmental conditions. The study provides insights into mixed-mode crack formation and offers a breakthrough in damage detection without baseline data. Overall, the study demonstrates an effective approach to detect damage in concrete structures, offering potential improvements for future damage detection methods.

Conclusion

In conclusion, this study emphasizes the critical importance of understanding and harnessing nonlinear dynamic characteristics for effective damage detection in reinforced concrete (RC) beams. By distinguishing between linear elastic and nonlinear dynamic approaches, the research addresses the inherent nonlinear behaviour of RC structures, particularly crucial in regions prone to seismic activity. Through experimental investigations involving harmonic and impulsive excitations, coupled with advanced analytical techniques such as time–frequency analysis (TFA) and short-time Fourier transformation (STFT), significant correlations between non-linear dynamic characteristics and damage levels in RC beams are unveiled. This approach enables the accurate detection of damage by comparing amplitude and frequency curves before and after structural damage, thereby enhancing structural safety and integrity. The literature reviews further reinforce the importance of nonlinear dynamic analysis in damage detection. Studies examining beams with multiple breathing cracks, nonlinear vibration characteristics of damaged concrete beams, and simulation-based non-linear vibration models underscore the effectiveness of nonlinear approaches in detecting damage without relying solely on linear methods. Moreover, the proposed three-parameter relation for damage detection offers a promising avenue for future research, eliminating the need for baseline data and providing insights into structural health monitoring without the constraints of traditional approaches. In summary, this research significantly advances the understanding of nonlinear behaviour in RC structures and offers valuable insights into practical applications for structural health monitoring and damage assessment. Moving forward, continued exploration of nonlinear dynamics promises further improvements in damage detection methodologies, ensuring the safety and resilience of RC structures in seismic-prone regions and beyond.

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