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Baseline-Free Damage Localization in Periodic Cable-Net Structures Using a Two-Dimensional Recursive Finite Element Method

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ABSTRACT: Large-span cable-net roof systems used in public infrastructure require efficient and reliable inspection or structural health monitoring because local prestress loss is frequently observed, which significantly affects structural safety and mechanical performance. To address the high computational cost of dynamic analysis and over-reliance on baseline in conventional methods, this study proposes a baseline-free damage localization framework for two-dimensional periodic cable-net structures by integrating periodic structural design, recursive finite element analysis, and frequency-response-based identification. First, a square periodic cable-net unit cell with crossed diagonal cables is established, and the two-dimensional dispersion curve considering initial pre-stress is derived based on the Floquet-Bloch theorem. Then, a pre-stressed dynamic model is established, and an efficient two-dimensional recursive finite element method is developed to construct the global dynamic stiffness matrix by recursively assembling a single unit cell, which can significantly reduce the computational degrees of freedom. Local damage is simulated by pre-stress loss in a single cable, and the structural dynamic response is obtained using the frequency response function. Numerical results show that the proposed method can efficiently capture local dynamic changes induced by damage. By comparing the energy variation of adjacent periodic cells within a characteristic frequency band, the damaged cell can be accurately localized without the damage-free baseline model. The proposed framework offers an efficient and promising approach to the online monitoring of large periodic cable-net structures.

KEYWORDS: Periodic cable-net; recursive finite element method; baseline-free damage detection; structural health monitoring

1 Introduction

Large-span cable-net structures have been extensively applied in public facilities such as stadiums, opera houses, and airport terminals due to their superior spanning ability, light self-weight, and flexible architectural form [1–3]. However, their low global stiffness and high flexibility also make them particularly vulnerable to local deterioration during long-term service. Under repeated loading, environmental corrosion, and other adverse service conditions, the pre-stress of cables may gradually decrease [4–6], significantly affecting structural safety and service performance. Therefore, the development of efficient and accurate structural health monitoring or inspection methods for the on-site, real-time, early detection and localization of damage in cable-net structures is very important and urgent for engineering application.

In the landscape of structural health monitoring techniques, vibration-based damage detection techniques show many merits over other methods because they offer global sensing capability and can be implemented without direct access to all structural components [7,8]. The corresponding principle is that local damage induces stiffness degradation, which can change the structural dynamic characteristics, including natural frequencies, mode shapes, and frequency response function (FRF) [6]. Nevertheless, the application of conventional vibration-based methods to large and complex cable-net structures still faces many challenges. First, cable-net systems typically have many degrees of freedom, and repeated FE dynamic analyses are computationally expensive. Second, the influence of environmental noise, temperature variation, and boundary-condition uncertainty may submerge the subtle variations in modal parameters caused by minor damage, thereby impairing the detection sensitivity [9–11]. Moreover, many conventional methods highly depend on an accurate baseline model representing the undamaged state, whereas the construction and verification of those models are difficult in practical engineering applications [12].

To overcome these limitations, some researchers have attempted to introduce the phononic crystal concept [13–15] with structural damage detection by utilizing the natural periodic configuration in the structure [16–18]. To this end, the structure is first divided into identical unit cells arranged regularly in space, and the Floquet-Bloch theorem is then employed to characterize the wave propagation behavior of the periodic system [16]. Based on this methodological framework, local dynamic characteristics less affected by structural boundaries can be extracted, which can provide a useful benchmark for damage-sensitive analysis. Moreover, efficient numerical approaches, such as the recursive finite element (RFE) method, can be applied to periodic systems [17–20]. So, only a single representative unit cell needs to be modeled, and the dynamic stiffness matrix of the entire structure can be obtained through recursive assembly. As a result, the computational cost associated with large-scale dynamic analysis can be greatly reduced. Several studies have successfully demonstrated the potential of integrating periodic design with efficient algorithms for structural damage detection. For example, Can et al. [18] applied this concept to a one-dimensional periodic steel truss system and combined it with a frequency-response-based strategy to achieve damage localization without requiring a baseline model. Koh and Yoon [19] developed a repetitive substructuring approach for large-scale dynamic problems, showing significant computational savings in periodic system analysis. Pei et al. [20] proposed a deep learning-based method utilizing multi-order frequency correlations for damage identification, achieving over 95% detection accuracy. Hussein et al. [13] provided a comprehensive review of phononic materials and periodic structures, highlighting their unique dynamic characteristics and potential applications in sensing and diagnostics. Wang et al. [14] investigated the generation of phononic band gaps in periodic structures using piezoelectric shunts, demonstrating the feasibility of controlling wave propagation for damage detection purposes. Kabir et al. [15] explored the use of phononic crystals to enhance acoustic emission detection of fatigue cracks, further validating the role of periodic design in damage sensing. These studies collectively demonstrate the strong potential of integrating periodic design with efficient computational algorithms for structural damage detection.

Despite these baseline-free methods making many advances, most existing studies have focused only on one-dimensional periodic members or assemblies, such as beams, bars, and trusses, whereas investigations of two-dimensional periodic cable-net systems remain limited. Extending periodic analysis and recursive algorithms from one-dimensional systems to two-dimensional cable-net involves both theoretical and computational challenges. On the one hand, a wave propagation framework suitable for two-dimensional planar periodic grids should be established first [12]. Second, the corresponding numerical methods that can efficiently handle two-dimensional recursive assembly need to be developed [17–19,21]. In addition, pre-stress loss is one of the most common forms of local damage in cable-net structures [21–25]. So, developing

a framework that can simultaneously exploit structural periodicity, enable efficient dynamic analysis, and support the sensitive localization of pre-stress loss damage remains an important unresolved problem.

Therefore, motivated by those challenges, this study extends the integrated framework of periodic design, efficient dynamic analysis, and baseline-free damage localization from one-dimensional periodic truss systems to two-dimensional periodic cable-net structures. The novelty lies in three aspects: (1) extending the recursive finite element method to bidirectional periodic assemblies; (2) establishing a baseline-free localization framework using adjacent-cell energy comparison; and (3) addressing pre-stress loss, a unique damage form in cable-nets. To this end, a recursive finite element method suitable for two-dimensional periodic grids is developed, and the corresponding assembly procedure enables efficient dynamic analysis of large cable-net systems. Local damage is simulated by pre-stress loss in a single cable, and a damage index based on dynamic-response differences between adjacent unit cells is used for localization. The study aims to provide a computationally efficient and baseline-free strategy for structural health monitoring of a large-span cable-net system.

2 Theory Model of Two-Dimensional Periodic Cable-Net

Fig. 1 illustrates the logical sequence of the theoretical derivation presented in this section. The framework begins with the definition of the overall periodic structure and its unit cell, followed by Floquet-Bloch wave analysis, derivation of the unit cell dynamic stiffness matrix, static condensation, two-dimensional block recursive assembly, and finally the formation of the global dynamic stiffness matrix for frequency response function (FRF) solution.

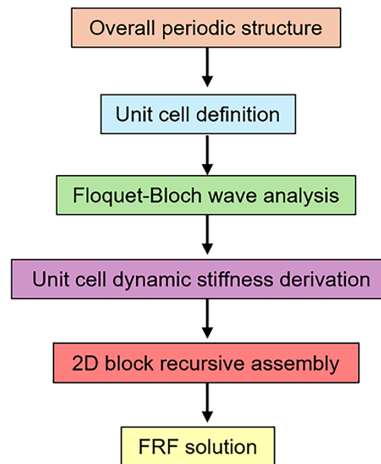


Figure 1: The overall theoretical framework.

2.1 Periodic Unit Cell and Structural Configuration

Large-span cable-net structures, including the roof of the speed skating arena (Fig. 2a), are typical three-dimensional spatial structures. For the purposes of dynamic analysis and damage detection, this structure is simplified into a two-dimensional periodic cable-net, which serves as the subject of this study, as shown in Fig. 2b. This infinite periodic configuration is composed of the repetitive arrangement of a fundamental unit cell along both x and y directions, with the detailed layout of a single unit cell illustrated in Fig. 2c. The unit cell has a square outer frame with side length a , consisting of four cable members. The interior contains two crossed diagonal cables. All nodes are considered as ideal hinged joints. In total, each unit cell contains eight cable members, which share identical material properties, namely, elastic modulus E ,

density ρ , and cross-sectional area A . In the initial state, each cable is subjected to an initial pre-stress force of magnitude T . For clarity in the subsequent theoretical derivation, a more general rectangular periodic case is first considered, with periodic lengths a and b along the x and y directions, respectively. In the numerical validation that follows, the unit cell will be specialized to a square shape ($a = b$).

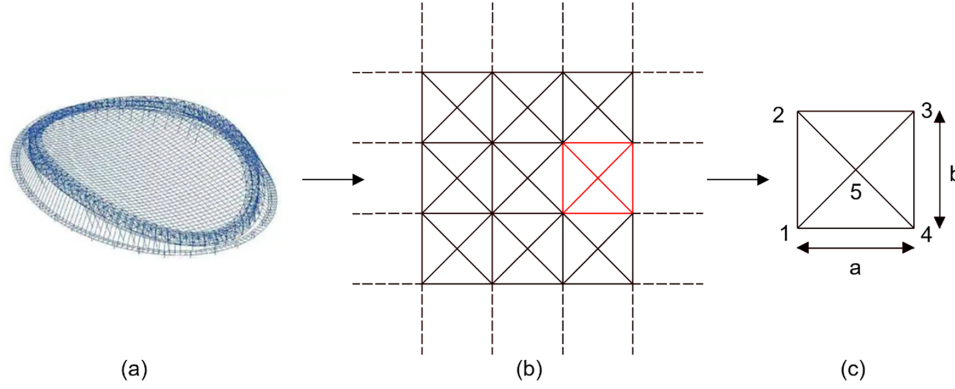


Figure 2: From engineering practice to theoretical model. (a) Three-dimensional cable-net structure; (b) assembly of the periodic unit cells; (c) periodic repeatability unit cell.

2.2 Dynamic Formulation of the Unit Cell with Initial Prestress

Spatial periodicity endows structures with distinctive dynamic behavior [9,10]. As established by Mead [11] and extended to two dimensions, the Floquet-Bloch theorem provides the theoretical foundation for analyzing wave propagation in planar periodic cable-nets, relating the dynamic states on adjacent unit cell boundaries through propagation constants. The “square-exterior, crossed-interior” cable-net unit cell shown in Fig. 2c is arranged periodically in the plane. Its periodic lengths are a and b in the x and y directions, respectively. For a square arrangement, a equals b . To analyze the dynamic behavior of the periodic cable-net, two different approaches are employed. The first method, grounded in the Floquet-Bloch theorem, imposes two-dimensional periodic boundary conditions on a single unit cell. This reduces the infinite system to a representative cell, from which wave propagation characteristics can be derived. The second method utilizes a RFE model tailored for two-dimensional grids.

2.2.1 Floquet–Bloch Analysis of Wave Propagation

When an elastic wave propagates in a two-dimensional periodic cable-net, its system solution exists. This solution follows the extension of the Floquet-Bloch principle [9] to two-dimensional space. This principle states that, in an infinite periodic system, the dynamic states (displacements and internal forces) on the corresponding boundaries of adjacent unit cells are not independent. Instead, they are related by a pair of frequency-dependent propagation constants λ_x and λ_y [12].

$$\mathbf{u}_L^n = \lambda_x \mathbf{u}_R^n, \mathbf{u}_T^n = \lambda_y \mathbf{u}_B^n \quad (1)$$

$$\mathbf{f}_L^n = -\lambda_x \mathbf{f}_R^n, \mathbf{f}_T^n = -\lambda_y \mathbf{f}_B^n \quad (2)$$

According to the Floquet-Bloch theorem [10,12], in an infinite periodic system, the dynamic states on the boundaries of adjacent unit cells are related by propagation constants. As a result, each unit cell exhibits an identical response that is independent of the boundary conditions imposed at the structure’s terminals. This phenomenon is applied to periodically assembled cable-net systems, meaning that the frequency response repeats from one cable-net unit cell to another.

2.2.2 Recursive Finite Element Formulation for Periodic Cable-Nets

The RFE method was proposed by Duhamel and Mencik [16]. Its purpose is to efficiently solve the FRF of periodic structures under harmonic excitation. The effectiveness of this method is rooted in the full use of structural periodicity [16–18]. Its core idea is as follows. For a structure formed by N identical unit cells arranged periodically in space, there is no need to mesh and solve the entire large-scale structure. Instead, a conventional finite element model is built for one representative unit cell. This model includes the stiffness matrix K , mass matrix M , and the damping matrix C . We carry out this numerical modeling via commercial finite element software, and on this basis, acquire the dynamic stiffness matrix d corresponding to the unit cell at frequency ω . The research object of this paper is a planar periodic cable-net. Its unit cell model is established in a three-dimensional global coordinate system. Each node has three translational degrees of freedom: u_x , u_y , and u_z . Therefore, in the global coordinate framework, the stiffness matrix K of the unit cell is constructed to account for six degrees of freedom. The geometric stiffness K_g , formed by the initial pre-stress, and the material's own elastic stiffness K_e are integrated into the total matrix K . Its calculation formula is

$$K = K_e + K_g = \begin{bmatrix} q & w & 0 & -q & -w & 0 \\ w & e & 0 & -w & -e & 0 \\ 0 & 0 & k_g & 0 & 0 & -k_g \\ -q & -w & 0 & q & w & 0 \\ -w & -e & 0 & w & e & 0 \\ 0 & 0 & -k_g & 0 & 0 & k_g \end{bmatrix} \quad (3)$$

here, $q = k_e l^2 + k_g m^2$, $w = l m (k_e - k_g)$, $e = k_e m^2 + k_g l^2$, $k_e = EA/L$, $k_g = T/L$, L is defined as the length of the cable element, calculated as $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$; parameters $l = (x_2 - x_1)/L$ and $m = (y_2 - y_1)/L$; where E represents Young's modulus and A corresponds to the cross-sectional area of the cable member. Subsequently, the global stiffness matrix of the element is assembled, and the mass matrix is defined in the form of a concentrated mass.

For the two-dimensional planar cable-net structure investigated in this study, the RFE technique is employed to streamline the computational modeling process. Under a harmonic load with frequency ω , the dynamic stiffness matrix d of the unit cell can be constructed as follows: $d = K - i\omega C - \omega^2 M$. Here, K represents the comprehensive stiffness matrix of the unit cell, which integrates both the material-based elastic stiffness and the stiffness induced by initial pretension, C denotes the damping matrix, while M corresponds to the mass matrix. By multiplying this matrix with the nodal displacement vector u , the discrete dynamic equilibrium equation for the unit cell is derived: $f = d \cdot u$, where f stands for the external load vector applied to the unit cell.

Within the framework of two-dimensional block recursion, the dynamic degrees of freedom (DoFs) for each periodic unit cell are categorized into two parts. These include the internal DoFs q_I and the boundary DoFs q_B associated with the four periodic edges. The boundary degrees of freedom include nodes on the left, right, top, and bottom edges. The internal DoFs are subsequently eliminated through static condensation. This procedure leads to a condensed dynamic stiffness matrix d_C that solely retains the boundary degrees of freedom: $d_C = d_{BB} - d_{BI}d_{II}d_{IB}$.

When assembling four adjacent substructures (denoted as A, B, C, and D, forming a 2×2 block) into a larger supercell, the cohesion matrices of each substructure are placed along the diagonal. The shared interfaces become the new internal boundaries: the right side of A and the left side of B, the right side of C and the left side of D, the bottom of A and the top of C, the bottom of B and the top of D, as well as the

four internal corner nodes. Compatibility of displacements and equilibrium of forces at these interfaces are enforced by assembling the corresponding DoFs into a set of internal interface DoFs q_I . The resulting system is then condensed again by eliminating q_I , yielding a new condensed dynamic stiffness matrix d_n that has the same dimensions as d_c of a unit cell, retaining only the outer boundary DoFs of the larger super unit cell.

The core step of the block recursion is assembling the dynamic stiffness matrices of four adjacent 2×2 identical substructures. These four matrices are assembled into a larger super unit cell of the next level. During this assembly, the common boundary degrees of freedom between the four blocks become new internal interfaces. These interfaces are eliminated again through static condensation. The result is a condensed dynamic stiffness matrix. This new matrix has the same dimensions as the condensed matrix of the original unit cell. It only retains the new outer boundary degrees of freedom. In other words, each level of recursion merges a 2×2 block of substructures at the current scale. This forms a new super unit cell with doubled dimensions. Its condensed matrix is then updated. This process is repeated (as shown in Fig. 3). For a two-dimensional periodic lattice composed of $N \times N$ unit cells (with $N = 2^p$), this block merging process is repeated $\log_2 N$ times, after which the global dynamic stiffness matrix for the full structure is subsequently derived. For cases where the total number of units N is not a power of 2, express N in binary form and then assemble the matrix bit by bit. For example, a 7×7 grid can first be viewed as having 7 units in one dimension; the binary representation of 7 is 111_2 , meaning $7 = 4 + 2 + 1$. The assembly process is as follows: First, use recursion to compute the matrix a consisting of 4 cells, then compute the matrix b consisting of 2 cells. Finally, combine these with the single-cell matrix c to obtain the 7-cell matrix. For a two-dimensional 7×7 grid, the one-dimensional binary assembly described above is applied independently to the x direction and the y direction, and the overall matrix is then obtained through two-dimensional block assembly.

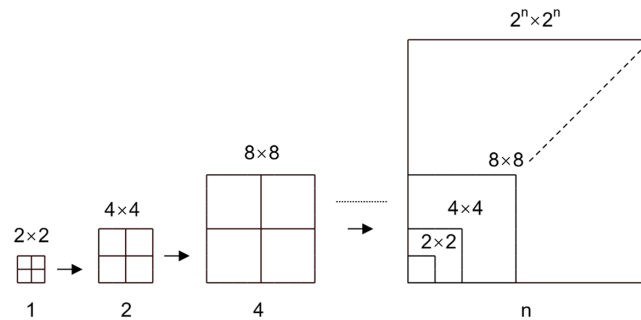


Figure 3: Block-based recursive process.

The recursive finite element method can handle harmonic loads at any location. Its standard procedure is as follows. The structure is divided into two independent periodic substructures at the load application point. These two parts are the left and right parts (or the top and bottom parts). The dynamic stiffness matrices of these substructures are synthesized recursively. Then, these matrices are assembled. Finally, the applied load and boundary conditions are incorporated to resolve the resulting system of equations. The FRF methodology adopted in this work is tantamount to computing the harmonic response behavior of the structure under broadband frequency excitations within the frequency domain. Therefore, this method is fully applicable to the RFE framework described above. This lays the foundation for efficiently predicting the frequency response of periodic cable-nets and extracting damage indicators in subsequent steps.

After solving the condensed global system for the boundary displacement vector q_B^g under harmonic excitation, the interior displacements q_I of any desired unit cell can be reconstructed using the stored

condensation relations. During each static condensation step, the relation $q_I = -D_{II}^{-1}D_{IB}q_B^c$ is established and stored for every substructure. Starting from the top-level super cell, the boundary displacements of its child substructures are extracted, and the interior displacements of each child are computed via the stored matrices. This back-substitution proceeds recursively down to the original unit cells, where the displacements (and thus accelerations) of interior nodes, such as the central node of each cell, are fully recovered. The additional computational cost of this recovery is negligible compared to the recursive assembly and solution.

3 Validation of Periodic Behavior in Finite Cable-Net Models

The theoretical framework of periodic structural analysis rests on the fundamental premise of an infinitely extended periodic system. In practice, both physical cable-net structures and their corresponding numerical models are constructed from a finite quantity of repeating unit cells. Consequently, it is essential to assess whether the dynamic response of a finite-scale cable-net structure aligns with the idealized periodic behavior predicted by the theoretical model. This evaluation is a key prerequisite for ensuring the effectiveness of the subsequent recursive finite element method and damage detection strategy. This section aims to investigate, through numerical simulation, whether the local dynamic responses in the inner region of a planar cable-net converge as its size changes. The goal is to determine the minimum practical size that can be approximately considered to satisfy the “approximately infinite periodic” boundary condition.

To achieve this goal, four distinct finite element models of two-dimensional periodic cable-nets are established within the COMSOL finite element analysis platform. Their total numbers of unit cells are 7×7 , 15×15 , 35×35 , and 55×55 . In each model, a 3×3 array of unit cells at the geometric center is selected as the observation region, as illustrated in Fig. 4, respectively. All models employ the same unit cell topology, material properties, and boundary conditions, as described below. The basic repeating cell features a square structure with side lengths $a = b = 3$ m, as shown in Fig. 2c. Each cell consists of four outer frame cables and two intersecting diagonal cables. All cable members are modeled as truss elements, with all nodes connected via hinged joints. For the entire cable-network model, all nodes on the outer boundary are fixed. The cable material is steel. The material properties of the cable-net model are detailed in Table 1. Every cable adopts a circular cross-sectional shape, with a diameter of $d = 18$ mm, corresponding to a cross-sectional area $A = \pi d^2/4$. A uniform pre-stress force $T = 18000$ N is applied to each cable in the initial state to simulate the actual prestressed condition. All nodes on the outer boundary of the entire cable network model are fixed. No additional constraints are applied to internal nodes. Damping effects are incorporated via the complex Young's modulus formulation $E(1 + i\eta_s)$, in which the structural loss factor $\eta_s = 0.008$.

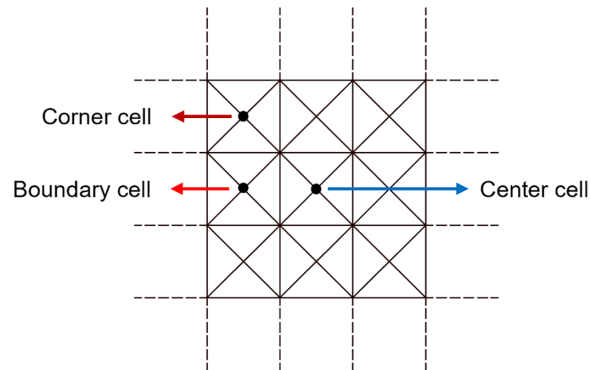


Figure 4: Schematic of a periodic cable-net model showing the central 3×3 observation region and three representative unit cells.

Table 1: Material and geometric properties of the cable.

Parameter	Value
Density	7850 kg/m ³
Young's modulus	200 GPa
Poisson's ratio	0.3
Pre-stress	18,000 N
Diameter	18 mm
Cross-sectional area	2.545×10^{-4} m ²

To eliminate the interference of boundary effects and focus on the core periodic behavior, all analyses are conducted in the central region of the structure. In each model, a 3×3 array of unit cells at the geometric center is selected as the observation region. Due to the symmetry of the cable-net unit cells, only three representative unit cells need to be observed. These are the center unit cell, the edge unit cell, and the corner unit cell. The FRF is used as the key indicator for evaluating periodic behavior. A unit harmonic force is applied at the central node of each of these three unit cells. The out-of-plane (z -direction) acceleration frequency responses at the corresponding nodes of these three unit cells in the 3×3 array are calculated. By comparing the degree of coincidence of these three frequency response curves, it is possible to intuitively judge whether the central region exhibits consistent dynamic characteristics for a given grid size.

Fig. 5 shows the comparison results. For a small grid dimension (7×7 unit cell), the frequency response profiles of the three unit cell elements exhibit obvious dispersion within the studied frequency range (0–20 Hz), this observation reveals that boundary constraints exert a pronounced influence on the central region of the structure, which fails to display stable periodic characteristics. Nevertheless, the acceleration responses of the three unit cells at 11.19 Hz are highly consistent. The frequency response curves around this peak frequency also show good agreement. At this frequency, the structure meets the minimum practical unit cell size requirement for “infinite periodicity”. This provides a basis for the subsequent damage detection study. When the number of unit cells increases to 15×15 , the frequency response curves become much more consistent, especially in the high-frequency range. With a further increase in the number of unit cells, the three curves nearly overlap over the whole analyzed frequency band. Moreover, the improvement in curve consistency gradually becomes less pronounced as the number of unit cells continues to increase. This suggests that, at this scale, the dynamic response in the central region shows a high level of consistency. Therefore, the influence of boundary effects can be considered negligible.

4 Validation of the Two-Dimensional Recursive Finite Element Method

To assess the accuracy and computational efficiency of the two-dimensional RFE method proposed in this study, it is implemented for the two-dimensional periodic cable-net model established herein. Subsequently, the obtained results are compared with those calculated using the commercial finite element software COMSOL Multiphysics, following the validation procedure adopted in previous studies [16–18].

The numerical model is constructed in strict accordance with the theoretical framework presented in Chapter 2. The cable mechanical parameters are the same as those listed in Table 1, and all cable elements are modeled with circular cross sections. Damping is characterized by the form of complex Young's modulus, expressed as $E(1 + i\eta_s)$, with the loss factor η_s assigned a fixed value of 0.008.

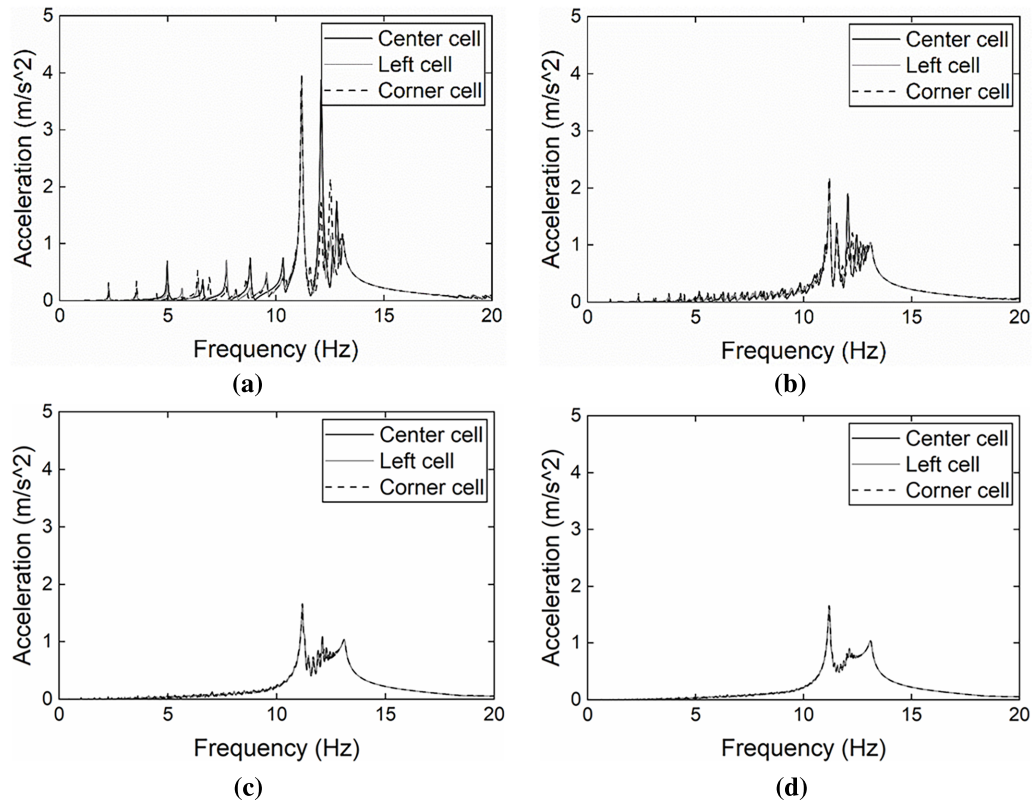


Figure 5: Comparison of acceleration frequency response functions of representative unit cells for cable-net models with different grid sizes: (a) 7×7 ; (b) 15×15 ; (c) 35×35 ; (d) 55×55 .

For validation, two periodic cable-net models with different sizes are established, namely a 16×16 unit-cell grid and a 32×32 unit-cell grid. A self-developed MATLAB program is used to implement the two-dimensional RFE algorithm. First, the stiffness matrix K and mass matrix M of a single “square-exterior, crossed-interior” cable-net unit cell are formulated using standard finite element expressions. Finally, a harmonic concentrated load with an amplitude of 1 N is applied at the central node of the structure. Using the RFE method, the frequency response function of the z-direction displacement at the same excitation point can be obtained efficiently. For comparison, an identical global finite element model is also established in COMSOL Multiphysics. In COMSOL, the “Structural Mechanics Module” together with a “Frequency Domain” study is employed to obtain the displacement frequency response at the same excitation location.

Fig. 6 compares the displacement frequency responses at the excitation point obtained by the RFE method and by direct COMSOL analysis for two different model sizes. It can be seen that the results obtained from the two approaches are in close agreement. Moreover, the agreement becomes more evident for the model containing more unit cells than for the smaller model. There are two main reasons for this: in larger grids, the central region is farther from the boundary, so the influence of the boundary on it is reduced, which makes the internal region more closely resemble the ideal state of an infinitely periodic structure. On the other hand, the number of iterations in the recursive finite element method was increased from 4 to 5. The additional recursive merging allowed the internal degrees of freedom to be more fully consolidated, bringing the model’s dynamic stiffness matrix closer to the theoretical value for an approximately infinitely periodic structure. The combined effect of these two factors resulted in the 32×32 model exhibiting superior frequency response consistency compared to the 16×16 model. In addition, for the unit-cell topology

adopted here, the number of independent boundary degrees of freedom is much smaller than the number of internal degrees of freedom. Through recursive assembly, the RFE method finally solves a condensed system involving only these boundary degrees of freedom. Taking 16×16 and 32×32 unit cell grid as examples, as shown in Table 2, the effective number of degrees of freedom solved by the RFE method depends only on the boundary degrees of freedom of a single unit cell. This quantity is only on the order of several hundred. In comparison, the conventional finite element method in COMSOL requires solving the complete system containing all three translational degrees of freedom for every node, leading to a degree-of-freedom count exceeding the order of 10^4 . This large difference in magnitude gives the RFE method clear advantages in both computational time and memory usage. This confirms the reliability of using the RFE method in the subsequent damage-detection analysis.

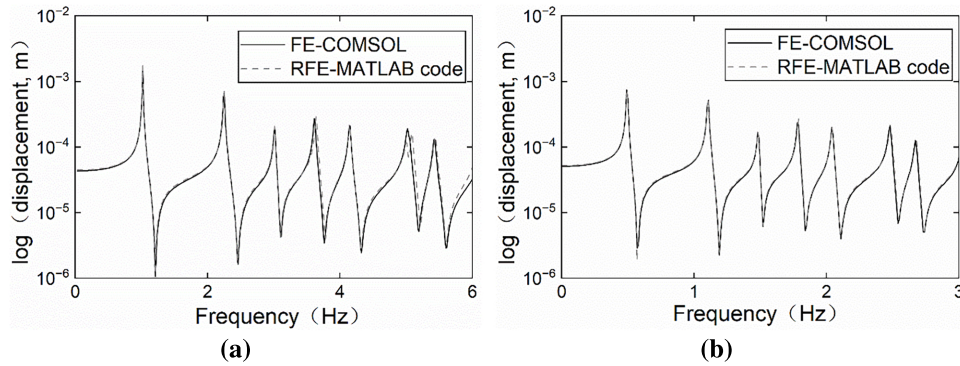


Figure 6: Comparison of displacement frequency response functions obtained by the recursive finite element method and COMSOL for cable-net models with different sizes: (a) 16×16 ; (b) 32×32 .

Table 2: Comparison of computational performance between COMSOL and RFE.

Model Size	Method	Total DoFs	Retained DoFs	Time Per Freq. Point (s)	Peak Memory (GB)
16×16	COMSOL	1635	N. A.	0.24	5.49
	RFE	1635	192	0.048	0.52
32×32	COMSOL	6339	N. A.	1.15	10.46
	RFE	6339	384	0.17	0.45

5 Frequency-Response-Based Damage Localization in Periodic Cable-Net Structures

To validate the efficacy of the newly proposed frequency-response-based damage identification approach for two-dimensional periodic cable networks, numerical simulations are performed using COMSOL Multiphysics. The model is a 7×7 unit cell grid. Although Section 3 shows that the 7×7 model exhibits boundary effects over the full frequency range, the central 3×3 observation region demonstrates sufficient dynamic consistency within the characteristic frequency band (10.4–11.5 Hz) around 11.19 Hz (Fig. 5a), justifying its use for damage localization. Each unit cell has a “square-exterior, crossed-interior” configuration. The material parameters employed are consistent with those presented in Table 1. A single unit cell has dimensions of $a = b = 3$ m, resulting in an overall cable-net size of $21 \text{ m} \times 21 \text{ m}$. All cable members have a circular cross-section. Their cross-sectional area is calculated as $A = \pi d^2/4$. All nodes in the cable-net plane are hinged connections. All boundary nodes are fixed to simulate actual boundary conditions, as

shown in Fig. 7. Damping is considered in the form of a complex Young's modulus. The loss factor is set to 0.008.

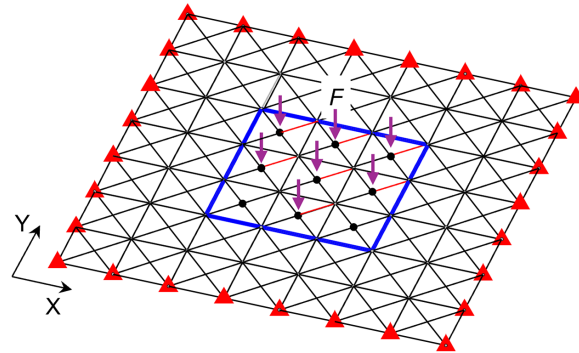


Figure 7: Cable-net model with the central 3×3 observation area.

The selection method employed in this paper follows the “adjacent cell comparison” strategy demonstrated in one-dimensional truss systems [15] to achieve damage detection. At the same time, due to the symmetry of the cable-net unit cells, a 3×3 unit cell grid region at the center of the structure is selected as the observation region. Since the first row (or column) and the third row (or column) in the observation region are equivalent, unit cells in the first row and the second row (or equivalent columns) are chosen for focused analysis. This selection method forms a group of unit cell pairs that are spatially close to each other. This perfectly fits the principle of locating anomalies by comparing the dynamic consistency of adjacent unit cells. At the same time, it makes full use of the structural symmetry to avoid redundant calculations. For the convenience of subsequent analysis, the unit cells in the first row (or column) are named Cell A1, Cell A2, and Cell A3, respectively. The unit cells in the second row (or column) are named Cell B1, Cell B2, and Cell B3, respectively.

Through frequency response analysis of the undamaged model, a peak is found at 11.19 Hz. This peak is sensitive to local damage, and the responses of adjacent unit cells at this frequency show high consistency. Therefore, a narrow frequency band centered at this peak (10.4–11.5 Hz) is selected as the characteristic frequency band. This bandwidth is sufficient to cover the peak shifts caused by damage, while not being so wide as to introduce energy contributions from other peak frequencies. This band is used for subsequent energy calculations and damage index construction.

Damage is simulated by reducing the pre-stress in a specific cable within a particular unit cell. Three damage levels are set: 10%, 25%, and 40% loss. The red cables in the figures indicate the specific target members where damage is introduced. First, damage is simulated within unit cell 1 located at the first row. As illustrated in Fig. 8, the frequency response characteristics of the three adjacent unit cells exhibit distinct deviations compared to the undamaged condition. This discrepancy becomes increasingly pronounced as the magnitude of damage intensifies. Conversely, the dynamic response of Unit Cell 3, which is geographically and structurally distant from the damaged zone, maintains a high degree of similarity to its initial intact state. Next, damage is introduced into unit cell 2. The dynamic responses of the three unit cells under this scenario are recorded and presented in Fig. 9. The analysis reveals that the most significant alterations in frequency response are confined to the unit cell that has undergone damage. Following this, damage is induced in Unit Cell 3, with the corresponding response data depicted in Fig. 10, similar conclusions are obtained. Subsequently, the above process is applied to the three unit cells of the second row. Their response diagrams are shown in Figs. 11–13, respectively. The same conclusions as above are also obtained.

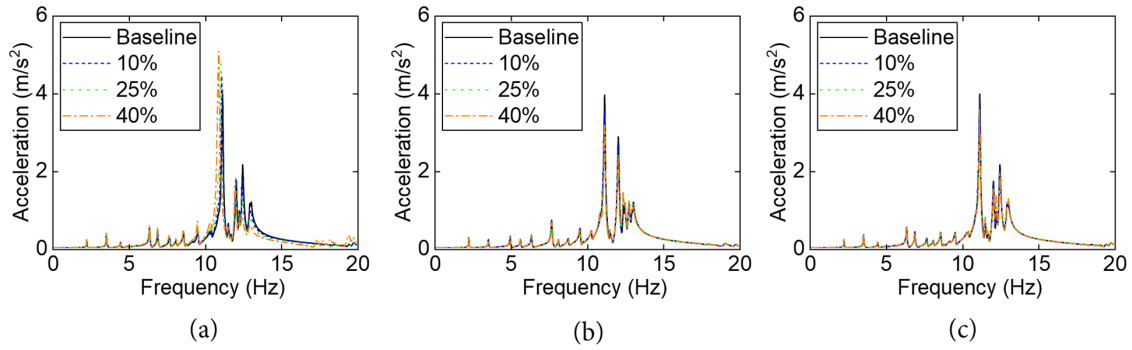


Figure 8: Frequency response of 1st row unit cells with damage in A1: (a) damaged unit cell A1; (b) undamaged unit cell A2; (c) undamaged unit cell A3.

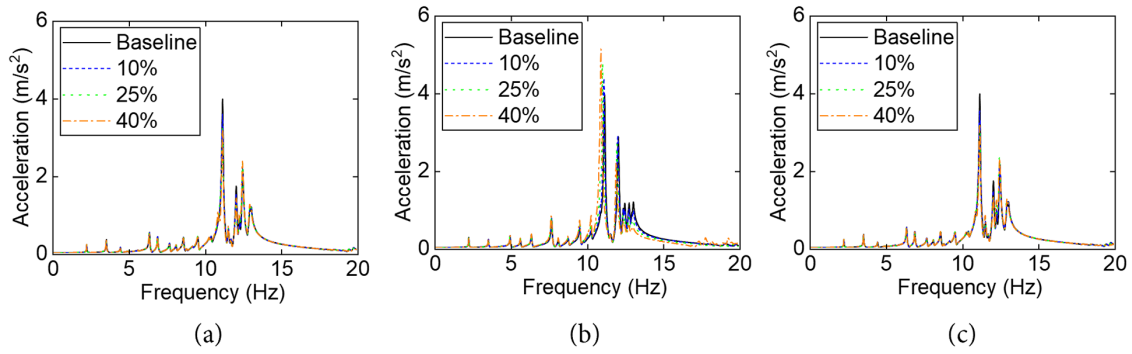


Figure 9: Frequency response of 1st row unit cells with damage in A2: (a) undamaged unit cell A1; (b) damaged unit cell A2; (c) undamaged unit cell A3.

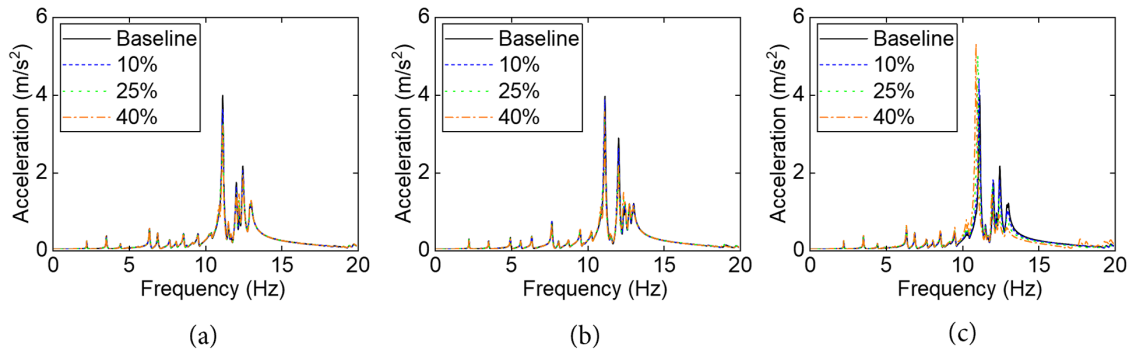


Figure 10: Frequency response of 1st row unit cells with damage in A3: (a) undamaged unit cell A1; (b) undamaged unit cell A2; (c) damaged unit cell A3.

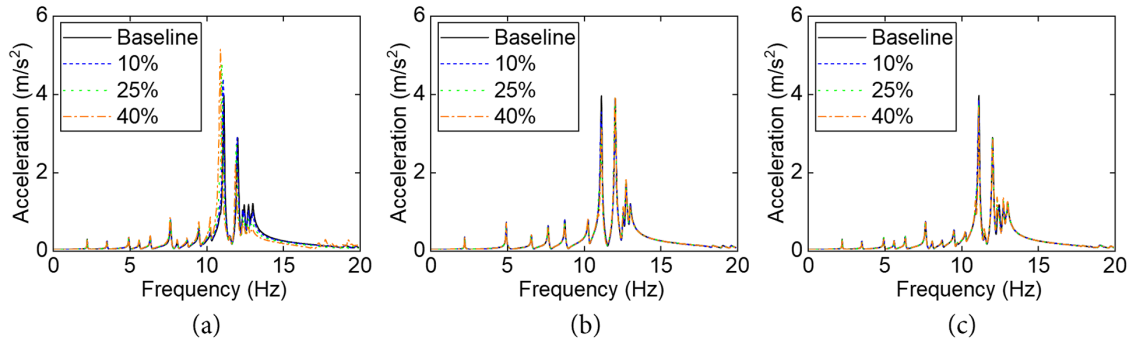


Figure 11: Frequency response of 2nd row unit cells with damage in B1: (a) damaged unit cell B1; (b) undamaged unit cell B2; (c) undamaged unit cell B3.

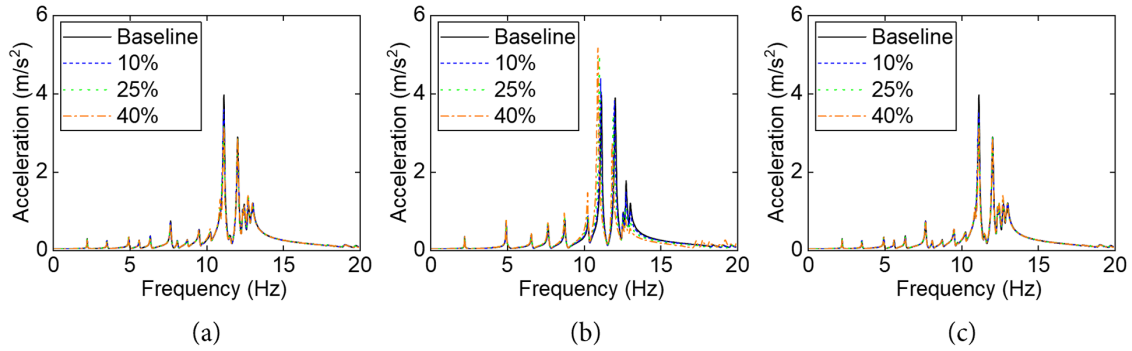


Figure 12: Frequency response of 2nd row unit cells with damage in B2: (a) undamaged unit cell B1; (b) damaged unit cell B2; (c) undamaged unit cell B3.

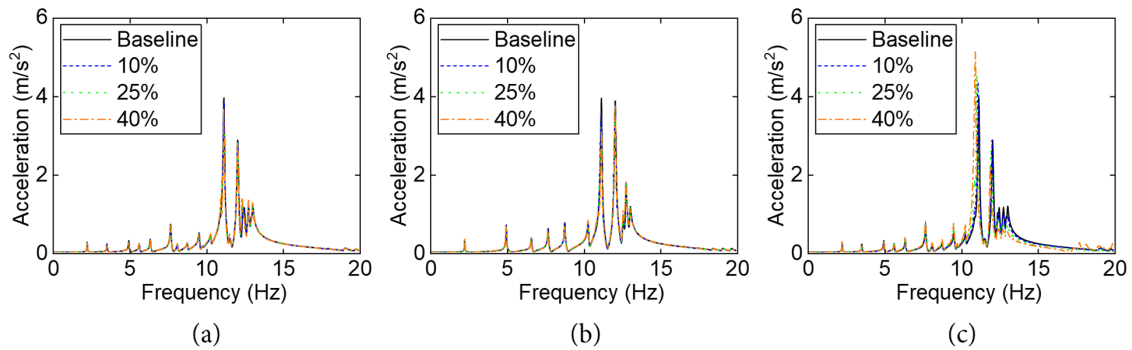


Figure 13: Frequency response of 2nd row unit cells with damage in B3: (a) undamaged unit cell B1; (b) undamaged unit cell B2; (c) damaged unit cell B3.

To quantify this effect, the energy E of each unit cell within the characteristic frequency band (10.4–11.5 Hz) is calculated. It is worth noting that although this characteristic frequency band is selected from an undamaged model, in practice, it can be directly determined based on any measured response of the structure, even when the structure is in a damaged state. Compared to undamaged elements, damaged elements exhibit increased peak amplitudes and slight frequency shifts; however, this has no impact on the selection of the frequency band. It follows that the frequency bandwidth can be determined solely from the

frequency responses of adjacent elements and used for subsequent energy calculations, without the need for baseline data from the undamaged state. The peak energy $E(m, p)$ of the m th horizontal and p th vertical unit cell is defined as

$$E(m, p) = \int_{f_1}^{f_n} A_f df \quad (4)$$

here, A_f is the response amplitude at frequency f , f_1 and f_n are the boundary frequencies of the frequency band, where df is the frequency differential. Figs. 14 and 15 show the changes in unit cell energy when damage is located at different positions. Regardless of which row the damage is in, the energy change is highly concentrated in the damaged unit cell. The energy of unit cells in adjacent rows remains stable. This verifies the local nature of the damage effect. On the other hand, this result provides strong evidence for the equivalence between different rows of the periodic structure and the universality of the proposed energy metric across different spatial locations.

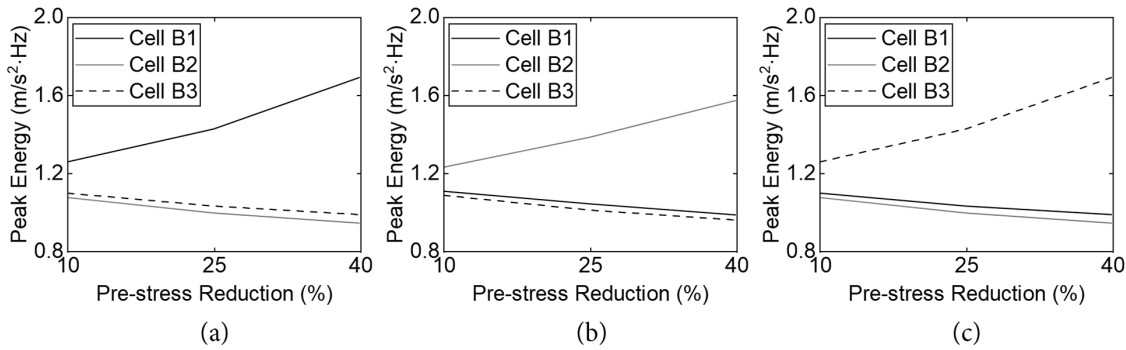


Figure 14: Variation in unit-cell response energy for damage located in 1st row cells: (a) damage located in unit cell A1; (b) damage located in unit cell A2; (c) damage located in unit cell A3.

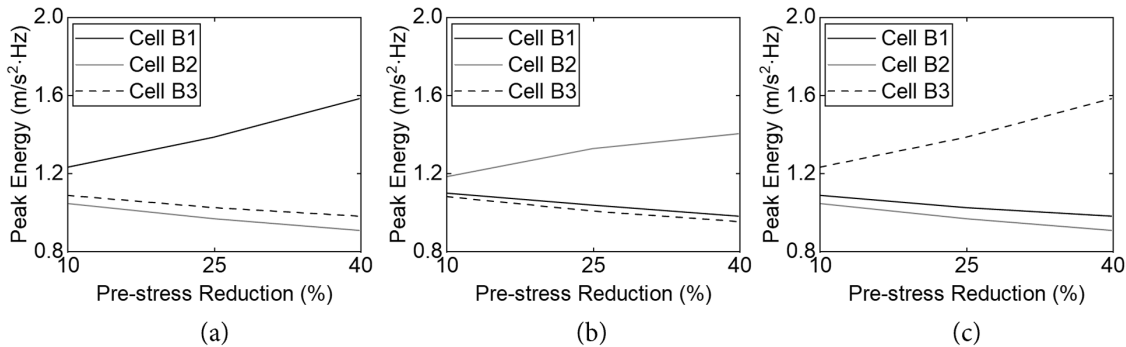


Figure 15: Variation in unit-cell response energy for damage located in 2nd row cells: (a) damage located in unit cell B1; (b) damage located in unit cell B2; (c) damage located in unit cell B3.

For one-dimensional periodic truss structures, the damage index is established by comparing the FRF energy of adjacent unit cells within a selected frequency range. For two-dimensional periodic cable-net structures, each interior unit cell has four neighboring cells, namely the top, bottom, left, and right cells, excluding those located on the boundary. In this study, the damage-index scheme originally developed for one-dimensional systems is extended to the two-dimensional case.

$$DI_{(m,p)} = \frac{1}{n} \sum_{d \in \{\text{adjacent}\}} \left| \frac{E_{(m,p)} - E_d}{E_{\min}} \right| \quad (5)$$

here, n is the number of selected adjacent unit cells used to calculate the damage index. The value of n ranges from 1 to 4. For the row of unit cells under evaluation, the damage index is determined from the energy difference between the left and right neighboring unit cells. In this case, $n = 1$. $E(m, p)$ is the peak energy of the target unit cell, and E_d is the energy of its adjacent unit cells. $E_{\min}$ is the minimum peak energy in the measurement step. The damage index is evaluated for unit cell 2 in each row, that is, by comparing it with the adjacent unit cells 1 and 3. Figs. 16 and 17 present the comparison results for the first row and the second row, respectively. When the damage is introduced into unit cell 1, the DI from unit cell 1 to unit cell 2 increases compared to the DI from unit cell 2 to unit cell 3. When the damage is introduced into unit cell 2, both the DI from unit cell 1 to unit cell 2 and from unit cell 2 to unit cell 3 increase as the stiffness reduction increases. When the damage is introduced into unit cell 3, the DI from unit cell 2 to unit cell 3 increases compared to the DI from unit cell 1 to unit cell 2. This demonstrates that the response pattern in the first and second rows is consistent, which further confirms the validity of the proposed method. For an observation region composed of a 3×3 unit-cell grid, all cells within the region can be used for damage identification by means of the aforementioned method. Therefore, the energy comparison between adjacent unit cells can be employed for local damage identification in two-dimensional periodic cable-net structures.

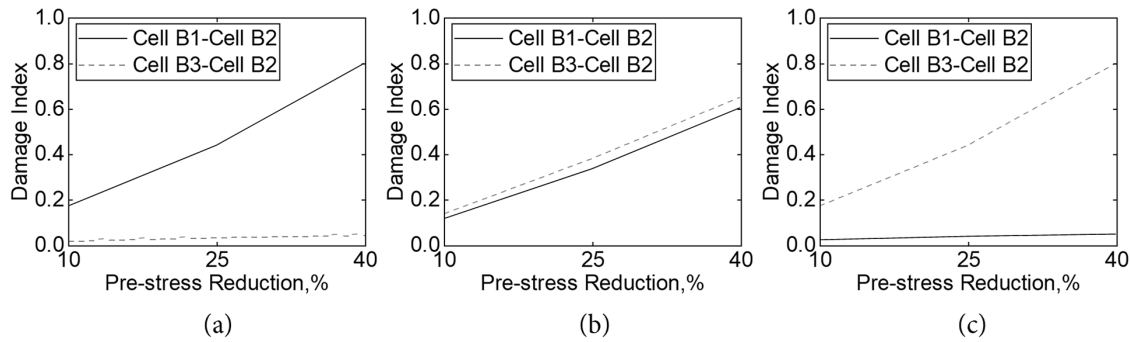


Figure 16: Damage-index comparison using A2 as the target unit cell: (a) damage located in unit cell A1; (b) damage located in unit cell A2; (c) damage located in unit cell A3.

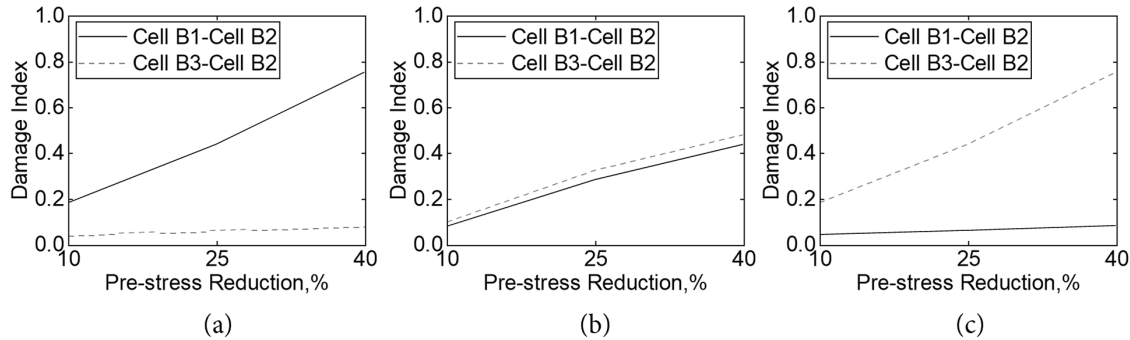


Figure 17: Damage-index comparison using B2 as the target unit cell: (a) damage located in unit cell B1; (b) damage located in unit cell B2; (c) damage located in unit cell B3.

When $n = 4$, the central unit cells of the 3×3 observation region and the four adjacent unit cells (upper, bottom, left, and right) are selected as the subjects of study. Fig. 7 shows the specific damage locations of the central unit's cables. It can be observed that the left unit cell is symmetrical with respect to the down, up, and right unit cells. Since the frequency response curves for the left, up, and right unit cells have already been presented, the frequency response plots for the corresponding unit cells (including the down unit cell) are not shown here. In this case, the corresponding data are substituted into Eqs. (4) and (5). The results are shown in Figs. 18 and 19. Fig. 18 depicts the energy changes of the five cells under three damage states. As the damage severity of the central cell gradually increases, its energy also gradually increases, while the energy of the four adjacent unit cells to the central cell gradually decreases. At the same time, the data in the bar charts clearly show that the energy of the left and bottom unit cells, as well as that of the top and right unit cells, is consistent, which verifies the symmetry relationship mentioned earlier. Fig. 19 shows the two-dimensional damage index of the central unit cell when $n = 4$. It can be clearly observed that the damage index of the central unit cell increases as its own damage severity deepens. This result indicates that damage modeling is also feasible in two-dimensional configurations.

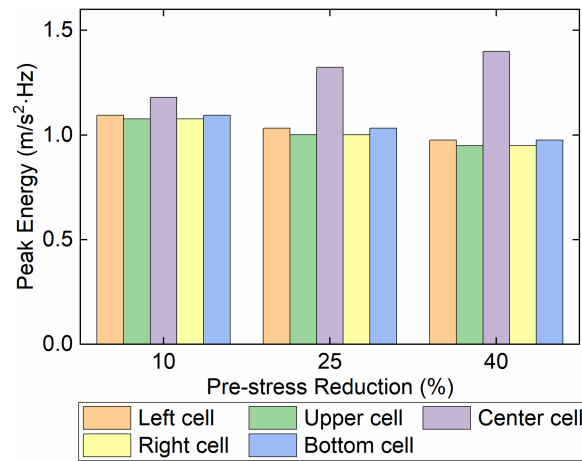


Figure 18: The peak energy of the central unit cell and its four adjacent unit cells within the characteristic frequency band (10.4–11.5 Hz).

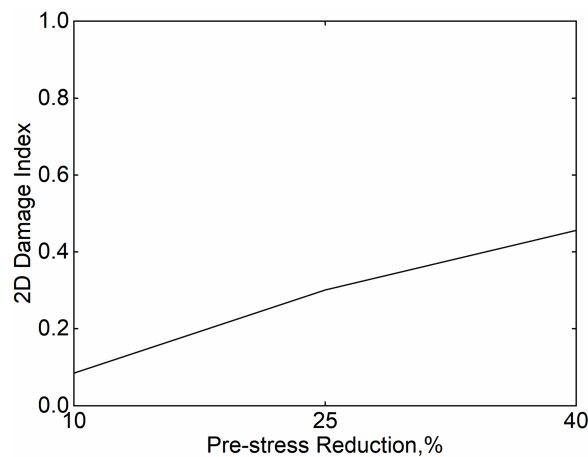


Figure 19: The relationship between the two-dimensional damage index of the center unit cell and the level of prestress loss.

To evaluate the minimum damage level that the proposed method can reliably detect, the DI was calculated for the central cell and its adjacent cells across a range of prestress loss from 1% to 10%. The results are summarized in Table 3. The DI value for the intact state is 0.0345. A conservative detection threshold was set at 1.5 times the DI value for the undamaged state (i.e., 0.05175) to ensure that changes caused by damage clearly exceed the noise level observed in the baseline. As shown in Table 2, the DI value at 6% damage is 0.0394 (below the threshold), while at 7% damage it reaches 0.0528 (above the threshold). Therefore, under ideal noise-free conditions, the minimum distinguishable prestress loss is estimated to be 7%. It should be noted that damage levels below 3% result in a DI value lower than that of the intact state, which is attributed to numerical noise and frequency discretization; such minor losses are considered unreliable to detect.

Table 3: Damage index for pre-stress loss levels (1%–10%).

Loss	DI	Loss	DI
0%	0.0345	6%	0.0394
1%	0.0226	7%	0.0528
2%	0.0107	8%	0.0665
3%	0.0014	9%	0.0805
4%	0.0137	10%	0.0949
5%	0.0263		

6 Conclusions

This study generalizes the concept of periodic-structure-based damage identification from one-dimensional systems to two-dimensional cable-net structures. A combined theoretical and numerical framework is established by integrating Floquet-Bloch analysis, recursive finite element modeling, and frequency-response-based damage localization. For the structural health monitoring of large-span cable-net structures, this framework addresses issues such as high computational cost and strong dependence on baseline data. The key outcomes of this study are outlined below:

- (1) The results show that the proposed two-dimensional recursive finite element approach can accurately reproduce the dynamic behavior of periodic cable-net structures while significantly reducing the computational cost. For the 32×32 model, the effective degree-of-freedom count is decreased from over 10^4 to several hundred.
- (2) A baseline-free damage localization method relies on the frequency-response energy differences between adjacent unit cells is further proposed. Numerical results demonstrate that local prestress-loss damage can be effectively identified within the selected observation region. However, the current method can only locate damage at the cell level; it cannot identify which specific cable within a damaged cell has been affected.

To sum up, the proposed approach provides an efficient and promising strategy for structural health monitoring of large-span periodic cable-net structures. This approach holds significant promise for practical engineering applications, such as stadiums, opera houses, and airport terminals, where early detection of cable prestress loss is crucial for ensuring structural safety and serviceability. Although the method is demonstrated under ideal harmonic excitation, future research will extend it to output-only scenarios (e.g., ambient wind) using transmissibility-based features. The present study focuses on demonstrating the feasibility of the method using relatively large damage levels (10%–40%). Future work will investigate the minimum detectable pre-stress loss through finer parametric studies. Although the present study assumes clamped boundaries for simplicity, the proposed adjacent-cell comparison method is expected to be robust to

realistic compliant edge conditions because it relies on relative energy differences within the interior region. Future work will quantify the influence of elastic boundary supports. The current study is limited to noise-free numerical simulations; future research will systematically investigate the robustness of the method under various noise levels and environmental disturbances. However, this study is limited to numerical validation, and experimental verification will be conducted in future work.

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References

1. Kong X, Liu Z, Liu H, Hu J, Deng L. Recent advances on inspection, monitoring, and assessment of bridge cables. *Autom Constr.* 2024;168(10):105767. doi:10.1016/j.autcon.2024.105767.
2. Fan Z, Tang X, Chen Y, Ren Y, Deng C, Wang Z, et al. Review of anomaly detection in large span bridges: available methods, recent advancements and future trends. *Adv Bridge Eng.* 2024;5(1):2. doi:10.1186/s43251-024-00113-9.
3. Shao S, Yuan Y, Xue Z, Feng X, Qiao Y, Huang B. Research status and prospects of health monitoring methods and applications for large-span structures. *Discov Appl Sci.* 2025;7(9):1021. doi:10.1007/s42452-025-07679-7.
4. Chen X, Zhang H, Liu H, Wang J, Zhang Y, Guo L, et al. Mechanical behavior and performance degradation of structural cables in buildings: a comprehensive review. *Materials.* 2025;18(24):5502. doi:10.3390/ma18245502.
5. Avci O, Abdeljaber O, Kiranyaz S, Hussein M, Gabbouj M, Inman DJ. A review of vibration-based damage detection in civil structures: from traditional methods to machine learning and deep learning applications. *Mech Syst Signal Process.* 2021;147(2):107077. doi:10.1016/j.ymssp.2020.107077.
6. Cuadrado Sanguino M, Pernas Sánchez J, Artero Guerrero JA, Varas Doval D. Detection of barely visible multi-impact damage on carbon/epoxy composite plates using frequency response function correlation analysis. *Measurement.* 2022;196(9):111194. doi:10.1016/j.measurement.2022.111194.
7. Ganguly S, Roy K. Baseline-free localization and quantification of structural damage using spectral response. *Appl Math Model.* 2025;142(4):115967. doi:10.1016/j.apm.2025.115967.
8. Esu OE, Wang Y, Chryssanthopoulos MK. A baseline-free method for damage identification in pipes from local vibration mode pair frequencies. *Struct Health Monit.* 2022;21(5):2152–89. doi:10.1177/14759217211052335.
9. Mead DJ. Wave propagation and natural modes in periodic systems: I. Mono-coupled systems. *J Sound Vib.* 1975;40(1):1–18. doi:10.1016/S0022-460X(75)80227-6.
10. Mead DJ. Wave propagation and natural modes in periodic systems: II. Multi-coupled systems, with and without damping. *J Sound Vib.* 1975;40(1):19–39. doi:10.1016/S0022-460X(75)80228-8.
11. Mead DJ. A general theory of harmonic wave propagation in linear periodic systems with multiple coupling. *J Sound Vib.* 1973;27(2):235–60. doi:10.1016/0022-460X(73)90064-3.

12. Duhamel D. A recursive approach for the finite element computation of waveguides. *J Sound Vib.* 2009;323(1–2):163–72. doi:10.1016/j.jsv.2008.12.012.
13. Hussein MI, Leamy MJ, Ruzzene M. Dynamics of phononic materials and structures: historical origins, recent progress, and future outlook. *Appl Mech Rev.* 2014;66(4):040802. doi:10.1115/1.4026911.
14. Wang Y, Xu X, Li L. Advances in tunable bandgaps of piezoelectric phononic crystals. *Materials.* 2023;16(18):6285. doi:10.3390/ma16186285.
15. Kabir M, Mostavi A, Ozevin D. Noise isolation with phononic crystals to enhance fatigue crack growth detection using acoustic emission. *J Civ Struct Health Monit.* 2018;8(3):529–42. doi:10.1007/s13349-018-0291-6.
16. Duhamel D, Mencik JM. Reduced-order modeling for time domain analysis of finite periodic structures with absorbing boundary conditions. *J Sound Vib.* 2024;590(3):118576. doi:10.1016/j.jsv.2024.118576.
17. Yassine R, Salman F, Al Shaer A, Hammoud M, Duhamel D. Application of the recursive finite element approach on 2D periodic structures under harmonic vibrations. *Computation.* 2017;5(1):1. doi:10.3390/computation5010001.
18. Can O, Kabir M, Ozevin D. Periodic assembly of steel truss systems for efficient analyses and early detection of localized damage using impulse response method. *J Struct Eng.* 2018;144(5):04018032. doi:10.1061/(asce)st.1943-541x.0002018.
19. Koh HS, Yoon GH. Large-scale topology optimization for dynamic problems using a repetitive substructuring approach. *Struct Multidiscip Optim.* 2024;67(3):33. doi:10.1007/s00158-024-03759-1.
20. Pei XY, Hou Y, Huang HB, Zheng JX. A deep learning-based structural damage identification method integrating CNN-BiLSTM-attention for multi-order frequency data analysis. *Buildings.* 2025;15(5):763. doi:10.3390/buildings15050763.
21. Xu W, Zheng X, Fu W, Chen Y, Xu X, Shen Y. Construction-phase monitoring for large-span prestressed cable-net structure: system implementation and data analysis. *J Build Eng.* 2025;113:113926. doi:10.1016/j.jobe.2025.113926.
22. Nguyen TT, Ho DD, Huynh TC. Electromechanical impedance-based prestress force prediction method using resonant frequency shifts and finite element modelling. *Dev Built Environ.* 2022;12:100089. doi:10.1016/j.dibe.2022.100089.
23. Farhadi S, Corrado M, Borla O, Ventura G. Prestressing wire breakage monitoring using sound event detection. *Comput Aided Civ Infrastruct Eng.* 2024;39(2):186–202. doi:10.1111/mice.13079.
24. Ou T, Zhu W, Lan C, Bai B, Bai S, Qiu Y, et al. Development and engineering application of fiber Bragg grating intelligent cable in large-span hyperbolic parabolic spatial cable network. *Structures.* 2024;68:107196. doi:10.1016/j.istruc.2024.107196.
25. Zhang L, Qiu G, Chen Z. Structural health monitoring methods of cables in cable-stayed bridge: a review. *Measurement.* 2021;168:108343. doi:10.1016/j.measurement.2020.108343.