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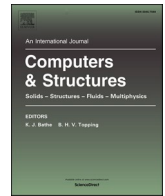
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Integrating computer vision techniques with finite element phase field damage analysis

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ABSTRACT

Realistic and accurate finite element (FE) models are crucial for understanding and predicting the health, performance, and safety of deteriorated structures. Accordingly, this paper presents a novel approach that integrates computer vision techniques and a phase field method to enhance FE damage analyses. Computer vision techniques are employed to analyze the visual inspection or monitoring data and to extract the geometric features of a structure and its damage, while the phase field method provides a robust numerical solution for representing the damage and simulating its progression. The integration of these methods allows for automated and precise updates of damage information in the FE model, improving model accuracy and reducing manual intervention. Case studies on a paper board and a steel cross beam of a bridge demonstrate the applicability and effectiveness of the proposed approach, highlighting its feasibility for monitoring and assessment in real-world engineering applications.

1. Introduction

The fields of civil and mechanical engineering have undergone remarkable progress driven by rapid advancements in sensing technology [1–3], numerical simulation methodologies [4,5], and structural health monitoring (SHM) techniques [6–10]. These developments have led to the emergence of digital twins (DT) [11–13], an innovative concept that offers a powerful solution for mirroring the operational status and predicting future performance in various scenarios. DTs facilitate the synchronization of physical system behaviors with corresponding digital models, enabling comprehensive analyses and accurate predictions that hold immense promise in enhancing engineering practices.

For civil and mechanical engineering projects, finite element (FE) models have been widely adopted as digital representations [14–21], owing to their ability to estimate the current work capacity and to predict the performance degradation of physical structures from mechanical aspects in particular. Currently, successfully using FE models as structural digital twins (SDTs) urgently needs algorithms for the connectivity which enhances the communication and interaction between the physical structures and the corresponding FE models. Standard FE methods are primarily characterized by their deterministic nature and

offline operational approach. The closed computational framework restricts their capacity to be engaged dynamically with streaming sensor data acquired from physical systems during FE analysis. As a result, SDTs may fail to interact effectively with corresponding physical structures, leading to inaccurate and delayed simulation results. To address this challenge, SDTs need to be continuously updated based on the developing engineering and structural situations, or changes in the surrounding environment.

In the context of using finite element digital twins (FEDTs) for managing and maintaining existing structures, continuously synchronizing and updating the possible degradation of the physical structure with the corresponding numerical model is essential. This process provides insights into the current state of structural health and enables predictive analysis of the remaining load-bearing capacity. To address this challenge, a digital twinning method for structural dynamics [22] has been developed using sparse pointwise local motion data. This method aims to synchronize and reproduce the dynamic behavior of structures. Meanwhile, several methods have been proposed for updating damage information [23,24] by directly introducing discontinuities into the finite element models based on visual information gathered from monitoring systems on the physical structure. However, these damage updating methods rely on directly introducing mesh

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discontinuities into finite element models and do not provide specific damage descriptors, such as the phase field, which are essential for computational approaches that simulate and predict damage evolution. Such computational approaches include phase field modeling [25–31], nonlocal damage models [32,33], and the extended finite element method (XFEM) [34–36]. The methods presented in references [23,24] are more suitable for damage representation and related further analysis, but they rely on direct geometric modifications to the FE mesh, introducing sharp mesh discontinuities to represent damage. For modeling damage evolution, they require substantial preprocessing and re-meshing at each step, which can significantly impact computational efficiency. In contrast, computational approaches like the phase field method update the damage phase field as a continuous process governed by energy minimization principles, ensuring a more stable and accurate simulation of crack progression, without requiring re-meshing.

Consequently, the methods in articles [23,24] are limited in their ability to predict damage progression directly, which hinders the rapid assessment of structural performance degradation. Meanwhile, damage evolution is a nonlinear dynamic process that is challenging to accurately predict in real-world engineering structures due to uncertainties arising from factors such as inhomogeneous material properties, manufacturing imperfections, and undetected micro-defects. To address this challenge, there is a need for an effective damage update method that is directly compatible with computational methods dealing with damage evolution which can enable continuous damage updating. Such a method would enable seamless communication between FE models and physical structures, while integrating streaming sensor data in the FE simulation.

To address the above challenge, this article presents a damage update method that leverages computer vision techniques and the phase field modeling approach to enhance crack propagation synchronization and evolution prediction within FEDT systems. By incorporating monitoring visual data, the proposed approach updates the damage phase field of digital simulations based on the geometric features of the actual damage, resulting in more accurate crack evolution predictions, as well as facilitating rapid updates and analysis when new damage growth is detected. Meanwhile, the dynamic integration of monitoring data and FE methods establishes a robust computational framework for simulating, updating, and synchronizing crack evolution in FEDT systems, effectively bridging the gap between physical structures and their digital physics-based models. In the following sections, the proposed damage update method is discussed in detail in Section 2. Section 3 presents an experiment on a paperboard, followed by Section 4, which validates the method through an experiment on a steel cross beam of a bridge. Finally, Section 5 concludes the article with some key insights. Overall, the

integers to describe damage areas) and the phase field method (introducing a field ranging from 0 to 1 to indicate local health states, where 0 denotes intact and 1 denotes fully damaged), the proposed method bridges these approaches into a unified solution for damage updating. This method is targeted at facilitating the automation of FEDT systems.

2.1. Overview of the proposed method

Fig. 1 illustrates the detailed workflow of the proposed damage update method. Initially, an intact (or relatively intact) FE model and an image containing damage information are required. Through a sequence of image processing steps such as segmentation, contour detection, contour simplification, and perspective transformation, geometric features of the structure and the damage are extracted from the image. This extracted information enables conversions of the contours in the segmented image into polygons that represent the damage and the structure. Subsequently, these polygons and the intact FE model are embedded into a shared coordinate space, aligning their corresponding parts. Then, geometric analysis identifies the nodes requiring a phase update. These nodes are then assigned new phase values of 1, reflecting the extracted damage information from the image data. With the completion of these updates, the FE model is capable of further downstream analysis to assess the performance of the damaged structure.

2.2. Standard phase field method (as background knowledge)

The phase field method is a fairly modern numerical approach [25,30] for simulating crack propagation in materials and structures [37–43]. It introduces a new continuous scale field to the structure as the phase field ϕ to represent the presence or absence of a crack. The phase field smoothly varies between 0 and 1, where $\phi = 0$ indicates intact material and $\phi = 1$ indicates a fully damaged material, i.e., a fully developed crack. The phase field ϕ evolves over time to simulate the initialization and growth of the crack, and the energy associated with the crack propagation is expressed in terms of the gradient of the phase field. The phase field method considers crack propagation from an energy perspective. According to the Griffith theory [44], the total potential energy of a system $\mathcal{E}$ is defined as

$$E := \Psi_s + \Psi_c - P. \quad (1)$$

The first term Ψ_s is the stored strain energy in the object, the second term Ψ_c is the fracture surface energy, and the third term $\mathcal{P}$ is the external work, like body force and tractions. The total potential energy $\mathcal{E}$ can be expressed with displacement field $\mathbf{u}(\mathbf{x})$ and phase field $\phi(\mathbf{x})$ as

$$E(\mathbf{u}, \phi) = \int_{\Omega} \psi(\epsilon(\mathbf{u}), \phi) dV + \int_{\Omega} G_c \gamma(\phi(\mathbf{x}); |\nabla \phi(\mathbf{x})|) dV - \int_{\Omega} \mathbf{b} \cdot \mathbf{u} dV - \int_{\partial\Omega_t} \mathbf{t} \cdot \mathbf{u} dA, \quad (2)$$

proposed method strengthens the connection between FE models, physical systems, and SHM systems, and has the potential to become a significant milestone in the field of DT engineering.

2. Methodology

The proposed damage update method integrates a series of computer vision techniques and the phase field method in a structural FE environment. This approach enhances the automation of extracting damage information from real structures and synchronizing it with FE models, thereby advancing the analysis of the structural performance of structures with updated damage information.

Inspired by the damage representation in segmented images (using

in which, ψ is the stored strain energy density, $\mathbf{u}$ means displacement field, $\epsilon(\mathbf{u})$ indicates elastic strain energy, G_c is critical energy release rate, γ indicates the crack density function, $\mathbf{b}$ means the body force tensor, and $\mathbf{t}$ is the traction vector. The first two terms in Eq. (2), forming the internal energy $\Psi(\phi, \mathbf{u})$, can also be described by using ϕ and $\mathbf{u}$ as

$$\Psi(\phi, \mathbf{u}) = \int_{\Omega} \left\{ \left[(1 - \phi)^2 + k \right] \psi_0(\epsilon) + G_c \left[\frac{1}{2\ell} \phi^2 + \frac{\ell}{2} |\nabla \phi|^2 \right] \right\} dV. \quad (3)$$

In this equation, the stored strain energy density $\psi_0(\epsilon)$ corresponds to the undamaged material state. The phase field damage variable ϕ characterizes the progressive fracture process, with values ranging from 0 (intact) to 1 (fully broken). To avoid numerical singularities when $\phi \approx 0$, a small regularization parameter k is introduced. The phase field

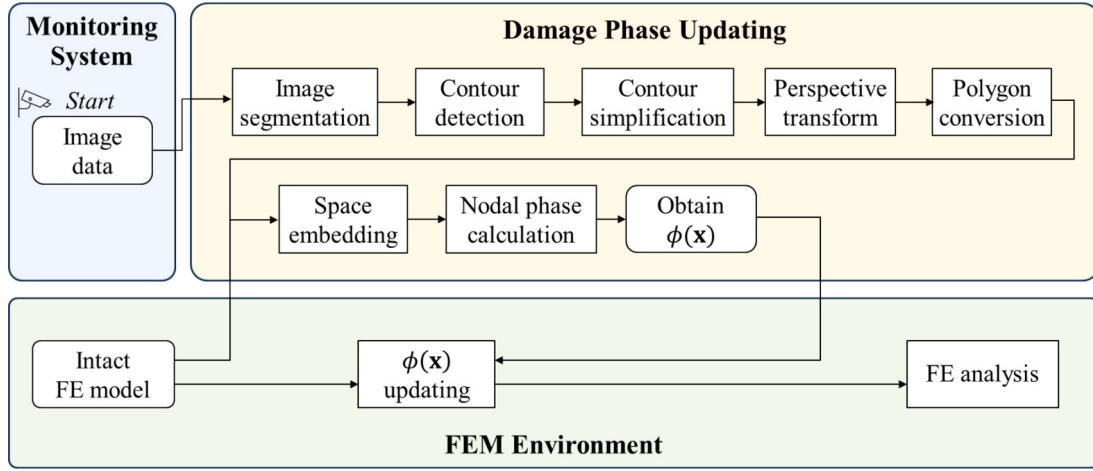


Fig. 1. Workflow of the proposed damage update method.

length scale ℓ determines the width of the diffused crack representation, influencing numerical accuracy together with the element size. The gradient term $|\nabla\phi|^2$ ensures a smooth transition between damaged and undamaged regions. The integral is evaluated over the computational domain Ω , defining the total internal energy of the system. Based on the above fact, Francfort and Marigo [45] and Bourdin et al. [46] considered brittle fracture as an energy minimization problem, which can be formally expressed as

$$(\mathbf{u}(\mathbf{x}), \phi(\mathbf{x})) = \text{Arg}\{\min \mathcal{E}(\mathbf{u}, \phi)\} \text{ subjected to } \dot{\phi} \geq 0, \phi \in [0, 1] \quad (4)$$

The equilibrium of external and internal virtual works is expressed as the quasi-static process

$$\partial W_{\text{int}} - \partial W_{\text{ext}} = 0, \quad (5)$$

which can be further expanded to

$$\int_{\Omega} \left\{ -[\text{Div}[\boldsymbol{\sigma}] + \mathbf{b}] \cdot \delta \mathbf{u} - \left[2(1 - \phi)\psi_0(\epsilon) - G_c \left[\frac{1}{\ell} \phi - \text{Div}[\ell \nabla \phi] \right] \right] \delta \phi \right\} dV + \int_{\partial\Omega_h} [\boldsymbol{\sigma} \cdot \mathbf{n} - \mathbf{h}] \cdot \delta \mathbf{u} dA + \int_{\partial\Omega} [G_c \ell \nabla \phi \cdot \mathbf{n}] \delta \phi dA = 0, \quad (6)$$

which represents the weak form of the coupled mechanical equilibrium and phase field evolution equations in the phase field fracture model. The Cauchy stress tensor $\boldsymbol{\sigma}$ balances the body force vector $\mathbf{b}$ and the prescribed traction force $\mathbf{h}$ on the boundary $\partial\Omega_h$. The divergence of the phase field gradient $\text{Div}[\boldsymbol{\sigma}]$ enforces a smooth distribution of the damage variable, avoiding discontinuities in the numerical solution. The weak form formulation includes integrals over the domain Ω and its boundary $\partial\Omega$, where $\mathbf{n}$ is the outward normal vector. The boundary term $\int_{\partial\Omega} [G_c \ell \nabla \phi \cdot \mathbf{n}] \delta \phi dA$ ensures proper enforcement of phase field boundary conditions, while the integral $\int_{\partial\Omega_h} [\boldsymbol{\sigma} \cdot \mathbf{n} - \mathbf{h}] \cdot \delta \mathbf{u} dA$ accounts for traction equilibrium on the external boundary. Together, these terms define the balance of mechanical forces and the phase field evolution, ensuring a physically consistent representation of fracture propagation within the finite element model. Then the strong form of governing equations of the coupled problem can be described as

$$\begin{cases} \text{Div}[\boldsymbol{\sigma}] + \mathbf{b} = 0 \\ G_c \left[\frac{1}{\ell} \phi - \ell \Delta \phi \right] - 2(1 - \phi)\psi_0(\epsilon) = 0 \end{cases} \quad (7)$$

with the following Neumann-type boundary conditions

$$\begin{cases} \boldsymbol{\sigma} \cdot \mathbf{n} = \mathbf{h} \text{ on } \partial\Omega_h \\ \nabla \phi \cdot \mathbf{n} = 0 \text{ on } \partial\Omega. \end{cases} \quad (8)$$

To solve the partial differential equations in Eq. (13), the finite element method with the corresponding weak form

$$\begin{cases} \int_{\Omega} \boldsymbol{\sigma} \delta \boldsymbol{\epsilon} - \mathbf{b} \cdot \delta \mathbf{u} dV + \int_{\partial\Omega_h} \mathbf{t} \cdot \delta \mathbf{u} dA = 0 \\ \int_{\Omega} \left\{ -2(1 - \phi) \delta \phi \psi_0(\epsilon) + G_c \left[\frac{1}{\ell} \phi \delta \phi + \ell \nabla \phi \cdot \nabla \delta \phi \right] \right\} dV = 0 \end{cases} \quad (9)$$

are used, where the displacement field $\mathbf{u}$ and the phase field ϕ are discretized by using the nodal values and shape functions. To solve the governing equations detailed in Equation (9), FE discretization was performed, incorporating weak form derivation, shape function definitions, strain-displacement matrices, and residual formulations. Subsequently, the tangent stiffness matrices are constructed and the numerical solution for the coupled displacement and phase field are calculated. To improve numerical stability, the staggered solution approach is applied, solving the phase field and displacement field equations sequentially rather than simultaneously. More details of the phase field method have been introduced in articles [30,47,48]. Note that the simulation is conducted iteratively, as illustrated in Fig. 2 as an example, where the phase field ϕ and displacement field $\mathbf{u}$ are calculated and updated at each iteration by using a segregated strategy.

2.3. Identification of monitored phase values from image

Fig. 3 shows the workflow for the identification of the monitored phase from image data. First, a crack can be segmented from the image data by using CV techniques, for instance, color filters, segmentation networks like U-Net [49], U-Net++ [50], FCN [51], Vision Transformers [52], Segment Anything [53], etc. Such an operation can output a

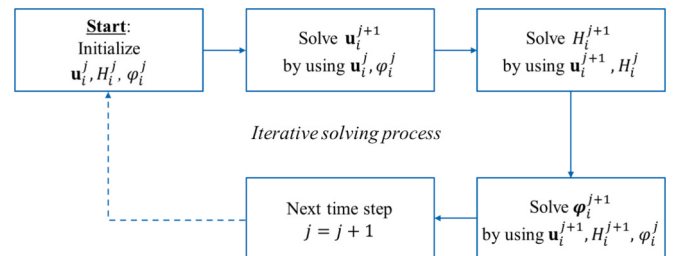


Fig. 2. Workflow of a segregated solver in phase field method.

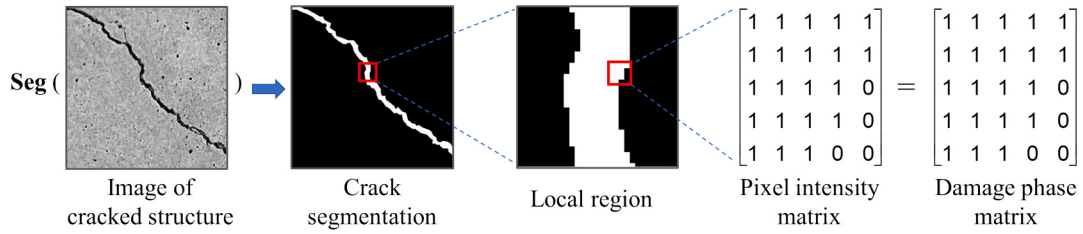


Fig. 3. Translation from segmentation result to discrete phase values.

segmented image which indicates the crack pixel-wise. Using a binary image as an example, in the segmented image, the pixel intensities of the pixels that represent the identified crack can be represented as 1, while those of the non-cracked places can be 0. As the development of the phase field method is inspired by image segmentation, the pixel intensity values in the binary image can be directly translated into the damage phase values.

The segmentation step directly determines the geometric representation of the damage, making it the most critical factor influencing model accuracy. If the segmentation underestimates the damage region, the corresponding damage representation in the FE model will be smaller than the actual damage, leading to underprediction of structural degradation. Conversely, over-segmentation may introduce artificially enlarged damage zones, affecting the accuracy of damage evolution predictions. The proposed workflow is flexible, allowing users to integrate different segmentation techniques, including future advancement of deep-learning-based models, to enhance accuracy.

2.4. Processing of image data

The image data requests a series of processing before being used for phase field updating, and the workflow is shown in Fig. 4. As the shapes of the monitored structures in the acquired image data are generally distorted owing to the perspectives and locations of cameras, it is necessary to perform perspective transformation and image scaling to recover the original geometry of the structure in the segmented image data, which is requested for the interaction between the monitoring data and the FE analysis. Those two pre-processing operations unify the co-ordination systems in the FE model and the image data. Then contour detection and contour simplification are performed to further convert the structure and damage in the image into polygons. These polygons enable the embedding of the monitored information into the FE model. To avoid duplication in this article to our previous work [23], the detailed introductions of CV processing algorithms, e.g., perspective transformation, scaling operation, contour detection, and contour simplification are omitted. Finally, the perspective-transformed image data can be converted into polygons which will be used for phase field updating, as the polygons include the geometric information of the damage in different regions of the structure.

In the proposed workflow shown in Fig. 4, most of the CV techniques, such as contour detection, contour simplification, perspective transformation, are well-established standard methods. These techniques follow deterministic algorithms and are widely used in research and industry. As such, their impact on accuracy is minimal, provided that the input image quality is sufficient. Their primary role is to process and refine the damage and structural information extracted in earlier steps, and they do not introduce significant variability in results.

Image segmentation is the only step where the choice of technique directly affects accuracy, as it significantly affects the extracted geometries of both the structure and the damaged regions. The segmentation method dictates how precisely the damaged area is identified, which in turn influences the accuracy of the phase field damage update in the FE model. Inadequate segmentation may lead to incomplete or imprecise damage representation, affecting subsequent simulations. Different segmentation techniques offer varying levels of accuracy and computational requirements. Traditional non-learning-based methods (e.g., color filtering, thresholding) provide quick and simple solutions but may struggle in complex environments. Deep learning-based methods (e.g., U-Net [49], U-Net++ [50], FCN [51], Vision Transformers [52], and Segment Anything [53]) generally achieve higher accuracy but require a large and labeled dataset for training and significant computational resources. The choice between these approaches depends on the complexity of the case study and available resources. Since damage segmentation is just one step within the proposed workflow, the proposed workflow remains flexible and can integrate any segmentation technique, including future advancements. The impact of segmentation accuracy can be mitigated by selecting an appropriate method based on specific case study requirements.

In addition, the accuracy of damage extraction depends on the clarity and resolution of the input images. Poor image quality, such as low resolution, noise, or uneven lighting, may lead to inaccurate segmentation of the damage region, which in turn affects the accuracy of the phase field update. However, standard image processing techniques, such as denoising filters and contrast adjustments, can mitigate these effects and improve robustness.

2.5. Extraction of nodal phase values from embedding space

Once the geometric features of the structure and damage are converted into polygons, they are used to interact with the FE model to identify the nodes that need their nodal phase values updated. The detailed workflow for phase updating is illustrated in Fig. 5. Initially, the polygons representing the structure and damage and the FE model are aligned and embedded within a shared space. Next, each node is checked to determine whether it lies within or touches the polygons of the damage. For nodes within the damage polygons, the nodal phase values are set to 1, as shown in Fig. 5(a). If no node is found within or touching the damage polygons, it indicates that the damage is too narrow relative to the mesh size, meaning that cracks or imperfections are smaller than the element scale. In this case, a modified phase updating workflow is applied, as shown in Fig. 5(b). The FE elements are first converted into polygons. These element polygons are then checked to determine whether they intersect or touch the damage polygons. If an element polygon intersects with or touches a damage polygon, all its

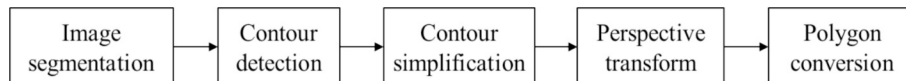
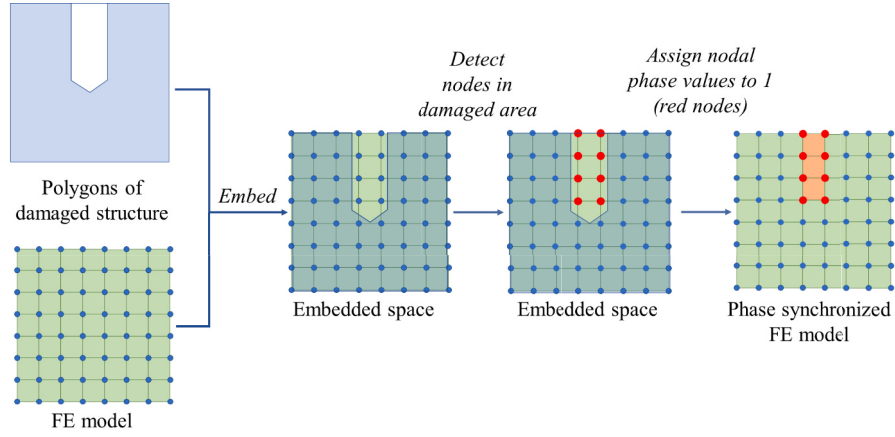
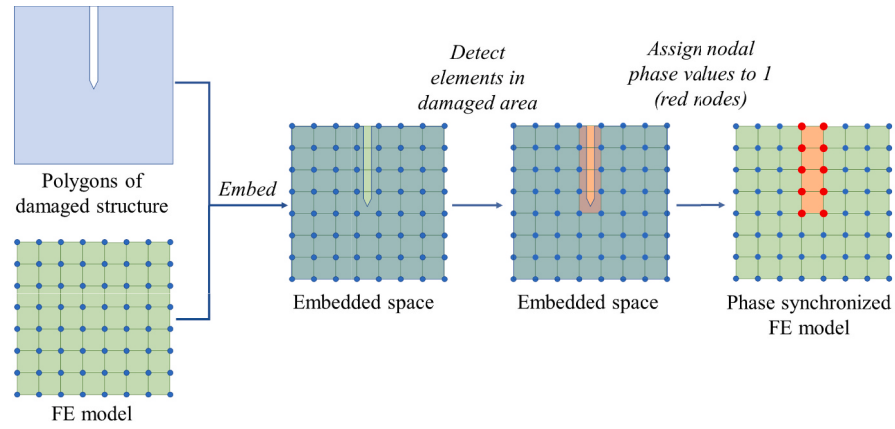


Fig. 4. Workflow of image processing to calculate the polygons.



(a)



(b)

Fig. 5. Illustration of synchronization of nodal phase values: (a) normal cases, and (b) cases with narrow crack(s).

associated nodal phase values are set to 1. This alternative approach ensures that even narrow cracks, which do not align with individual nodes, are incorporated into the phase field update by considering element-level intersections instead of direct node-damage interactions. The entire workflow is outlined as pseudo-code in Algorithm 1, providing a clear and computationally efficient method for updating phases. As an additional option, one could consider adding a (local) mesh refinement into the algorithm to be able to apply the case depicted in Fig. 5(a).

Algorithm 1: Phase Updating in FE Model

Input: FE_Model, Structure_Polygons, Damage_Polygons

Output: Updated Nodal Phase Values

Align and embed Structure_Polygons and Damage_Polygons with FE_Model.

for each Node in FE_Model:

if there is Node within or touches a Damage_Polygon:

Set Nodal_Phase_Value(Node) = 1.

Else: (if no Nodes are found within or touching any Damage_Polygon)

For each Element in FE_Model:

Convert Element to Element_Polygon.

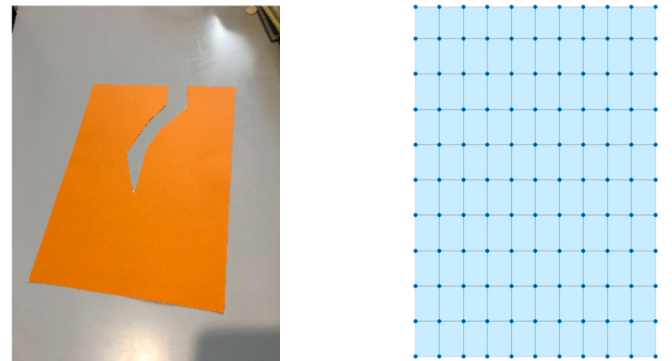
if Element_Polygon intersects or touches a Damage_Polygon:

for each Node in Element:

Set Nodal_Phase_Value(Node) = 1.

end Algorithm

The choice of mesh size affects the spatial resolution of the phase field representation of damage. A coarse mesh may not capture intricate damage details, potentially leading to less precise phase field updates.



(a)

(b)

Fig. 6. Damaged paper board and corresponding intact FE model.

However, since the proposed method directly assigns phase values without requiring mesh modification, it maintains numerical stability across different mesh sizes. Using a finer mesh improves accuracy but increases computational cost. A balance must be achieved between computational efficiency and accuracy, which depends on the structural complexity and available computational resources.

3. Experiment on a paper board

3.1. Experimental setups

To validate the proposed phase updating method, a case study was conducted on a damaged paperboard, as shown in Fig. 6(a), which was also utilized in our previous study [23]. The board measures 297 mm in length, 210 mm in width, and 0.2 mm in thickness. A crack is visible from the upper edge to the center of the paperboard.

The corresponding intact FE model, presented in our earlier work [23], is also employed in this study, as shown in Fig. 6(b). The FE model comprises 121 nodes and 100 quadrilateral shell elements. In this experiment, the paperboard was horizontally extended after updating its damage state. The left edge of the paperboard is fixed, while an outward-distributed load with a time increment of 0.01 mm over 300 steps is applied along the right edge. These boundary conditions replicate the real-world mechanical behavior of paperboard under tensile loading. As this study aims solely to demonstrate the feasibility of the proposed damage update method, setting material properties within practical ranges does not influence the study's conclusions. Accordingly, the following material properties are assigned: a Young's modulus of 2.5 GPa, a Poisson's ratio of 0.2, and a critical energy release rate of 0.1 N/mm. For the phase field method implementation, the parameters include a characteristic length l of 0.1 mm and a time increment of 0.01 s over 300 steps.

All computations, including image processing, geometric analysis, phase updating, and FE analysis, were carried out in a Python 3.8 environment. The Python library OpenCV [44] was used for image processing, while another Python library Shapely [45] was employed for geometric analysis.

3.2. Results

Using the computer vision techniques described in Sections 2.3-2.5, the geometric features of both the structure and the damage are extracted and converted into polygons, as illustrated in Fig. 7. The process begins with the application of a color filter to segment the structure from the background, making the relevant portions of the image are isolated. Next, contour detection and simplification algorithms are employed to accurately detect the edges and corners of the paperboard. These corners serve as key reference points for performing a perspective transformation, enabling a precise alignment of the damaged structure with the original model. This transformation corrects the distortions caused by camera angles or irregularities in the image capture process. The CV techniques used to extract polygons for the damage and structural features are consistent with the procedures detailed in reference [23]. To avoid redundancy, detailed parameter settings and implementation specifics can be found in reference [23].

Subsequently, the polygons representing the structure and the damage are generated. These polygons are then used to map the geometric features of the paperboard onto the FE model. The intact FE model, as depicted in Fig. 6(b), is overlaid with the polygons

corresponding to the damaged structure and the damage itself. The alignment of these two parts in a shared space, as shown in Fig. 8(a), is crucial for ensuring that the damage is accurately mapped onto the model for further analysis. By applying the proposed method detailed in Fig. 5 and Algorithm 1, the specific nodes of the FE model that require phase updating are identified. These nodes, which lie within the boundaries of the polygon of damage, are highlighted in red to indicate the affected areas. The precise identification of these nodes allows for accurately updating the damage within the structure. Finally, the nodal phase values of the identified nodes are updated to 1, representing fully damaged areas, as visualized in Fig. 8(b). Consequently, the phase fields within the elements containing the updated nodes are automatically interpolated and updated using shape functions. This method not only accurately represents the initial damage but also sets the stage for further simulations, such as crack propagation or structural failure analysis, enabling a comprehensive understanding of the structural behavior under various damage conditions.

The above result demonstrates that the proposed method provides an efficient approach for integrating damage information into the phase field model, while eliminating the need for re-meshing. By directly updating the phase field values based on extracted damage features, the method ensures seamless damage evolution modeling, making it particularly suitable for large-scale or automated structural simulations. Comparing the proposed method to the method presented in reference [23], the latter generates explicit geometric representations of damage by using computer vision techniques, which can be used to define explicit mesh discontinuities for pre-cracks. This approach could be integrated with phase field modeling, even with assigned initial phase values, to predict further damage propagation. Explicit mesh discontinuities provide the advantage of capturing localized stress concentrations and crack behavior with higher accuracy, particularly in complex geometries. However, incorporating meshing editing process into the phase field framework significantly increases computational complexity. Moreover, the phase field method is inherently designed for continuous damage representation, avoiding the need for re-meshing. Maintaining a continuous damage field allows for a more seamless numerical implementation while preserving computational efficiency. In contrast, the additional computational cost and implementation effort required for integrating explicit mesh discontinuities may reduce the scalability of the combined approach, making it less practical for automated workflows or large-scale structural models. Given the above considerations, the proposed method follows a simplified workflow that prioritizes computational efficiency and automation. It is particularly suitable for scenarios where damage updating needs to be performed efficiently and automatically without the overhead of mesh modifications.

After updating the damage in the FE model, a virtual experiment was conducted, as shown in Fig. 9. The detailed settings, which serve as the initial state for the FE analysis, are described in Section 3.1. Subsequently, a standard phase field method was applied to simulate crack propagation across the paperboard.

The simulation results are presented in Fig. 10. The first row depicts

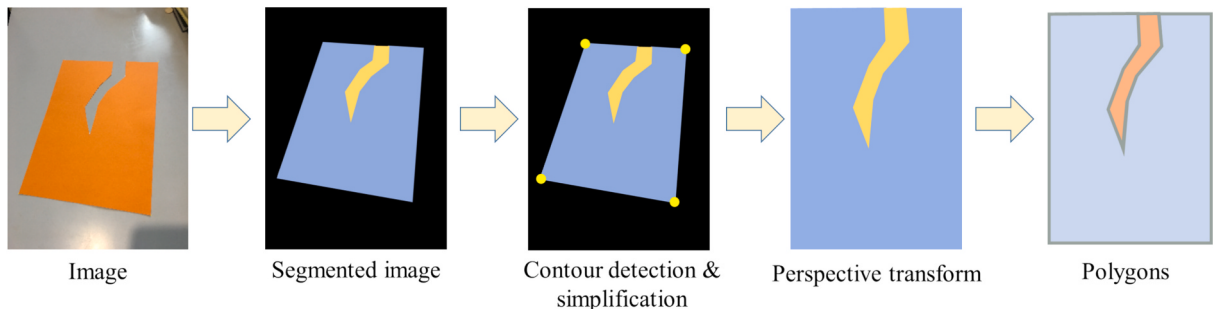


Fig. 7. Perspective transform.

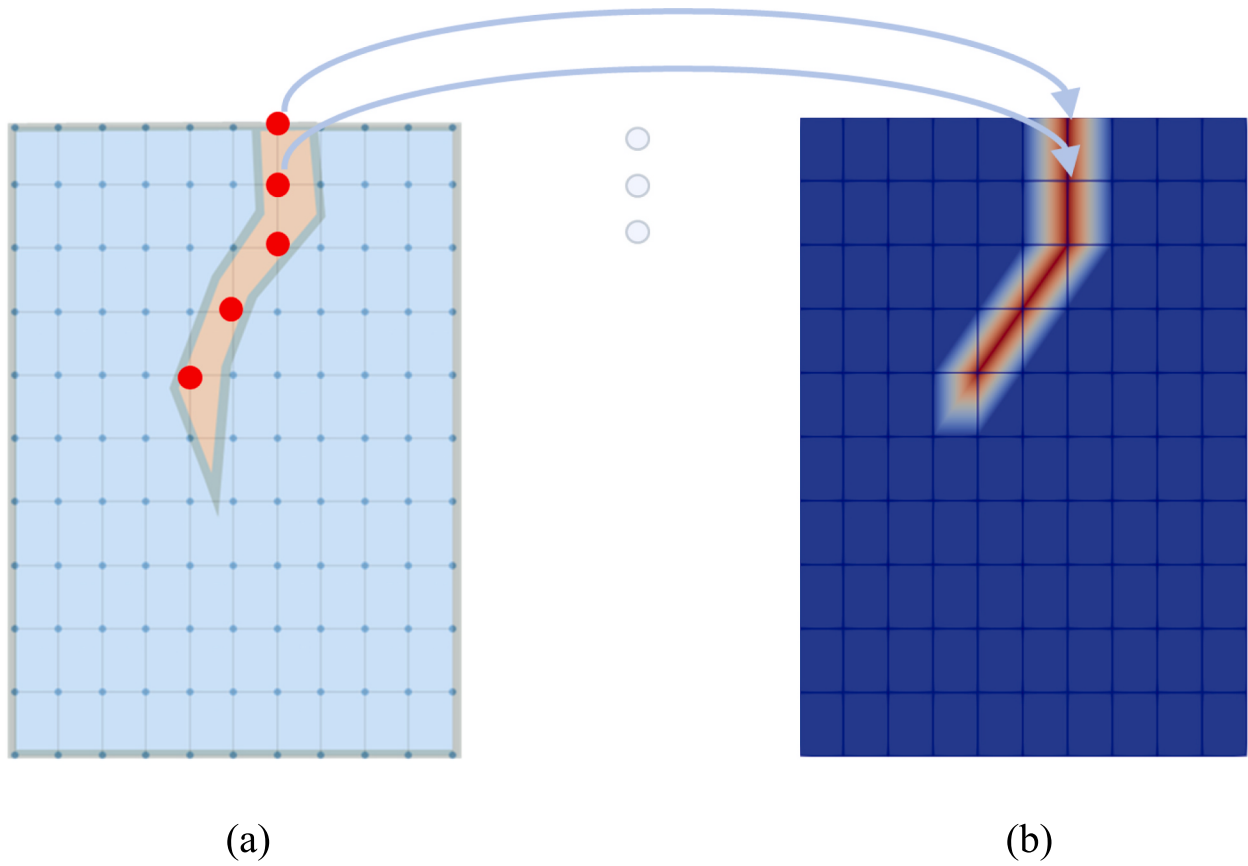


Fig. 8. Results of phase updating on the damaged paperboard: (a) node identification, and (b) phase-updated FE model.

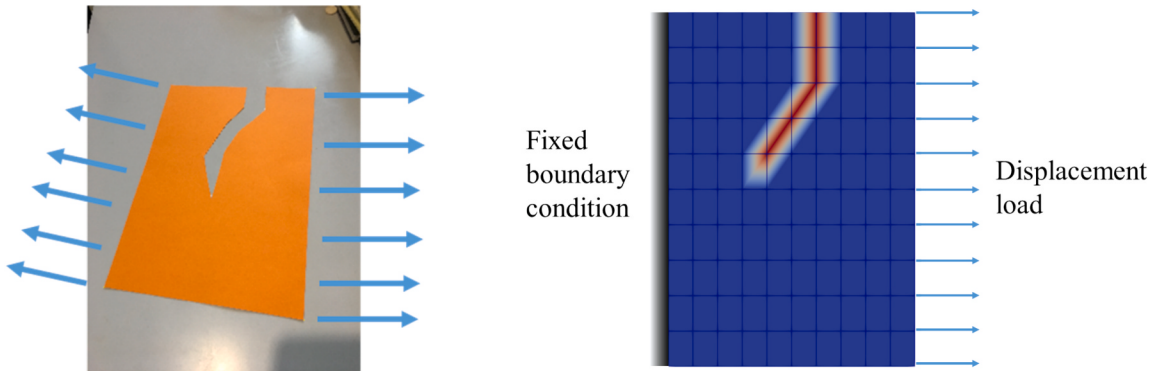


Fig. 9. Illustration of the horizontal extension load on the board.

the evolution of the phase field over time, while the second row shows the development of the displacement field. As observed in Fig. 10, the crack propagates along a physically accurate path, beginning from the center of the paperboard and extending downwards until the material is torn. This crack trajectory closely aligns with real fracture patterns. Simultaneously, the displacement field behaves logically, with the fixed left side of the paperboard remaining stationary, while the displacement on the right side increases gradually as the load intensifies over time. The model accurately captures the gradual deformation of the right side of the board. The consistency between the phase field evolution and the displacement field further demonstrates the capability of the proposed damage update method which successfully incorporates the existing damage with the corresponding intact FE model for predicting further damage growth, providing valuable insights for understanding and predicting failure processes.

4. Experiment on a steel cross beam

4.1. Experimental setups

In this section, a case study is conducted on a real-world civil structure to further demonstrate the effectiveness of the proposed damage update method. Fig. 11 shows a photograph of a damaged cross beam of a bridge, which has been referenced in [23]. The dimensions align with the description provided in [23]. The web height is set at 300 mm, the flange width at 100 mm, and the thickness at 10 mm. These dimensions are used to establish the scale of the FE model. The corresponding FE model in its intact state is presented in Fig. 3.

The damage visible in the cross beam is primarily due to fatigue stress accumulated over time. This type of damage is common in aging civil structures and poses significant risks to structural integrity. The

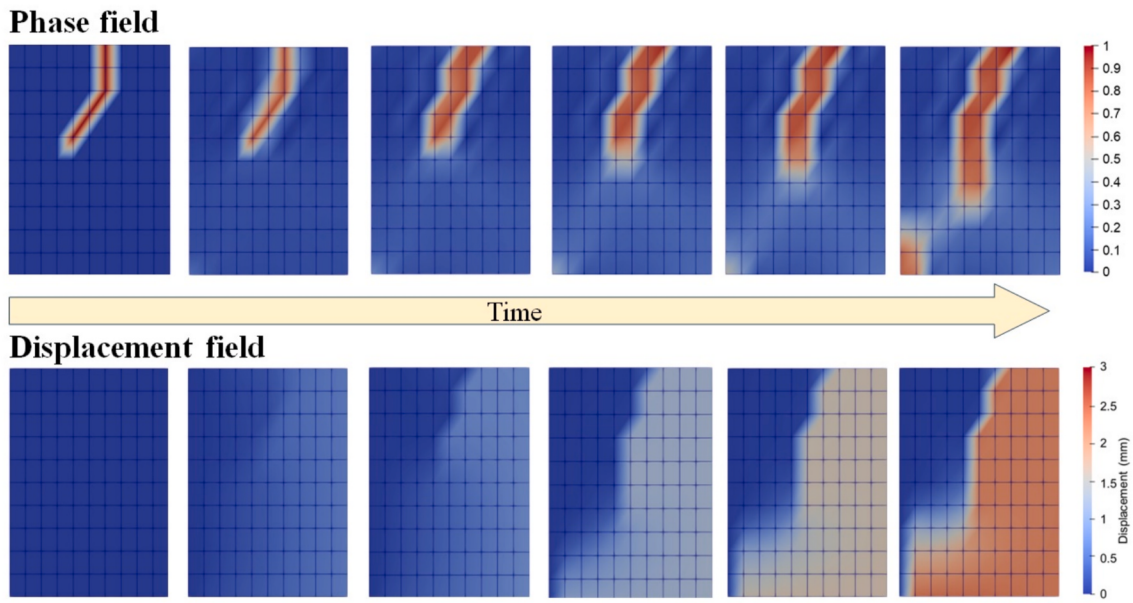


Fig. 10. Result of phase field analysis for simulating damage evolution on the paper board.



Fig. 11. Photo of a damaged cross beam of a bridge [30].

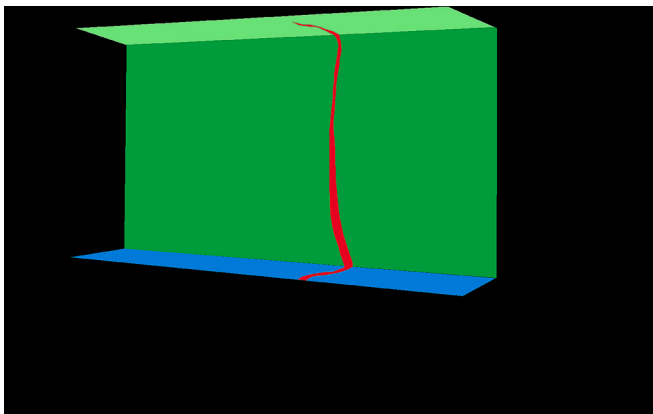


Fig. 12. A segmented image of the damaged area presented in article [23].

existing damage on the beam makes it a suitable specimen for testing the effectiveness of the proposed method. The corresponding image segmentation results of Fig. 11, detailed in [23], were obtained through computer vision techniques and are directly utilized for extracting the

geometric features of the structure. These features are then converted into polygons, as illustrated in Fig. 12, representing critical structural components such as the upper flange, web, lower flange, and the area of damage, as well as the surrounding background. By accurately identifying and isolating these different areas, the method allows for a precise extraction of the structure and the damage on it. The detailed procedure of polygon conversion can refer to article [23], thus it is omitted here to avoid duplication.

Although the bridge cross beam is a part of a larger 3D structure, it can be decomposed into several 2D sub-members for analysis. Since these sub-members, like the upper flange, web, lower flange, and damage region, are all essentially planar surfaces, the proposed damage update methods, initially developed for 2D structures, remain fully applicable. The process involves analyzing each 2D sub-member independently, updating the damage information, and subsequently combining the results to provide a complete 3D picture. In other words, after each sub-member is analyzed, the individual results are integrated to deliver a comprehensive assessment of the entire structure. The proposed approach highlights a key strength of the proposed method: its versatility in handling some complex 3D structures which consists of planar components.

Additionally, modeling the damage and simulating its propagation by using only a Python code for 3D structures can be time-consuming due to the increased complexity and coding effort compared to 2D simulations. In such scenarios of 3D structures, integrating the proposed damage update method with commercial finite element analysis (FEA) software presents a more practical and efficient solution. Therefore, in this study, the proposed computer-vision-based damage update method is combined with a commercial finite element software, COMSOL Multiphysics, to synchronize and represent the damage within a phase field. The phase field method, which is highly beneficial and valuable for engineering projects, has been implemented into COMSOL Multiphysics as a dedicated module. This module allows for precise control over the damage simulation, enabling users to easily assign initial phase values to selected regions within the model, reflecting areas of pre-existing damage. The ability to define these initial conditions is crucial for accurate phase field analysis, as it provides a realistic starting point for simulating crack initiation and growth. In other words, the phase field module in COMSOL Multiphysics allows integration with the proposed damage update method for further prediction of damage propagation. The integration not only reduces the coding effort but also accelerates

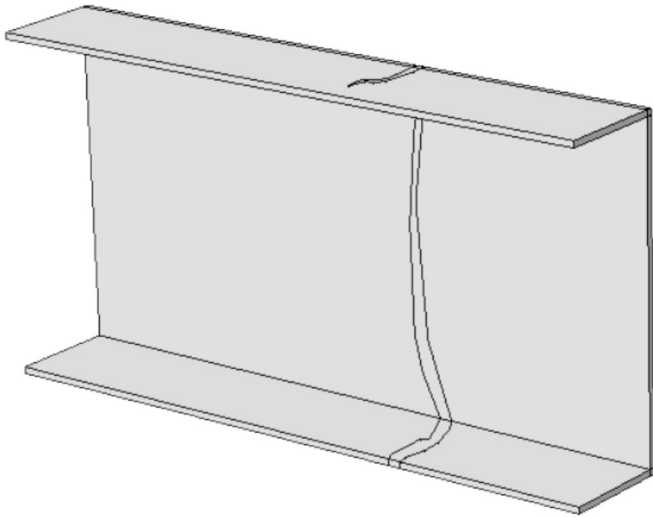


Fig. 13. Geometry of damage-updated model in COMSOL Multiphysics.

the computation time, making it feasible to handle larger and more detailed scenarios.

Based on the above fact, the geometric features of the damaged cross beam obtained from the polygons can be directly imported into COMSOL Multiphysics, as shown in Fig. 13 which highlights the damage on the cross beam. The crack spans the entire width of the lower flange, reaches the full height of the web, and affects a significant portion of the upper flange.

Solid elements are used to model the beam. The left side of the beam is fixed, and vertical or horizontal displacement load is applied on the right end of the beam corresponding to the load cases subjected to shear and axial forces with a time increment of 0.12 mm over 150 steps. For the phase field method implementation, the parameters include a characteristic length l of 0.5 mm and a time increment of 0.12 s over 150 steps. In actual scenarios, cross beams are subjected to various types of forces due to the loads they carry and the overall design of the bridge, including shear force, bending moment, axial force, torsion, etc. To refrain from repeating similar results, only the load actions of shear force and axial force are presented. The detailed mesh, loads and boundary conditions, shown in Fig. 15, are applied in the FE model, respectively.

Considering the practical limitations, the accurate material properties cannot be measured from the field tests. As this study is only to

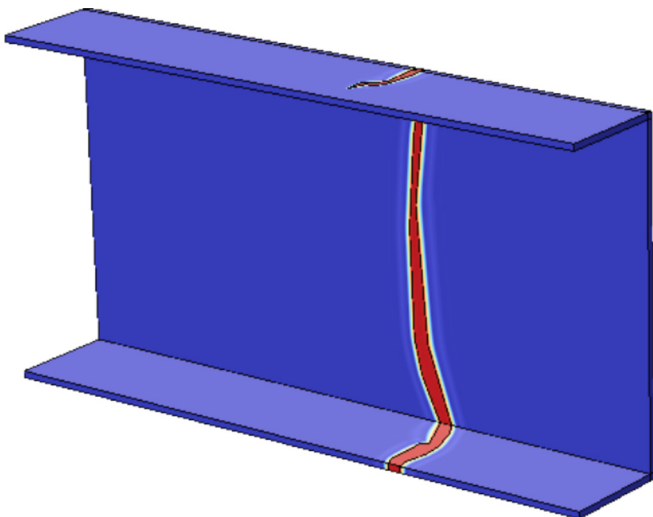


Fig. 14. Damage-updated model in COMSOL Multiphysics.

demonstrate the feasibility of the proposed damage update method, setting the material properties in practical ranges does not affect the conclusions of this study. Therefore, the following material properties are set: density of 7850 kg/m³, Young's modulus of 210 GPa, Poisson's ratio of 0.3, and critical energy release rate of 20 N/mm.

4.2. Results

Given that the precise geometry and boundaries of the damage have already been incorporated into the model, the initial phase field in the damaged area can be set to 1, while the remaining areas retain the default initial phase value of 0, indicating the intact state. At this point, the damage depicted in the image has been successfully updated within the FE model in COMSOL Multiphysics, as shown in Fig. 14, enabling analysis to simulate the progression of the existing damage on the structure.

Fig. 16 depicts the damage evolution over time within the structure in both the shear force load case and the axial force load case. In each case, the top row describes the phase field of damage, while the bottom row illustrates the displacement field within the beam as the damage propagates. In both load cases, as time evolves, the damage extends from the initial crack, propagating outward on the upper flange till the structure is fully damaged. The red area represents the region of full damage, while the blue areas represent undamaged portions of the beam. For the displacement fields, the red regions indicate areas of high vertical or horizontal displacement on the right side of the structure, while the blue regions show areas of low displacement. In both cases, damage-displacement correspondence can also be observed: as the damage propagates, the displacement field responds accordingly. High displacements initially develop around the end of the crack, but over time, these areas dissipate as the structure is separated into two pieces. The evolutions in both the phase field and the displacement field also present how energy dissipation occurs due to the damage evolution, leading to a reduction in the structural integrity of the beam. The results convincingly demonstrate the effectiveness of the proposed computer-vision-based damage update method. The model effectively predicts the crack propagation and corresponding displacement responses, showcasing its applicability in simulating the degradation of the structural integrity of real-world damaged structures.

The results demonstrate that: the key advantage of the proposed FE damage updating method is that it provides a more efficient and structured workflow for extracting, transforming, and mapping damage geometry and location information into the phase field model. The method significantly reduces the workload associated with traditional damage modeling approaches by digitizing and streamlining the process of extraction geometric information of damage and FE model updating. Comparing with traditional approaches, the proposed method utilizes computer vision techniques to extract damage geometry and assists in mapping the extracted damage to the phase field representation in the FE model. While some manual parameter adjustments (e.g., image processing parameters) may still be needed, the method reduces the manual effort compared to traditional approaches. In contrast, traditional damage updating methods require fully manual measurement of damage geometry, making the process more labor-intensive and time-consuming.

Meanwhile, by using the proposed workflow, the FE geometry and mesh remain unchanged, and the damage is incorporated by updating nodal phase field values instead of modifying the mesh structure. This helps to maintain numerical stability and avoids the computational overhead of re-design and re-meshing. On the contrary, traditional damage updating methods typically require manual re-design and re-meshing to accommodate complex or irregular damage geometries, which increases computational cost and can lead to numerical instability issues. Furthermore, the computational cost of the proposed damage updating method primarily arises from image processing as well as damage detection and setting, which is significantly less time-

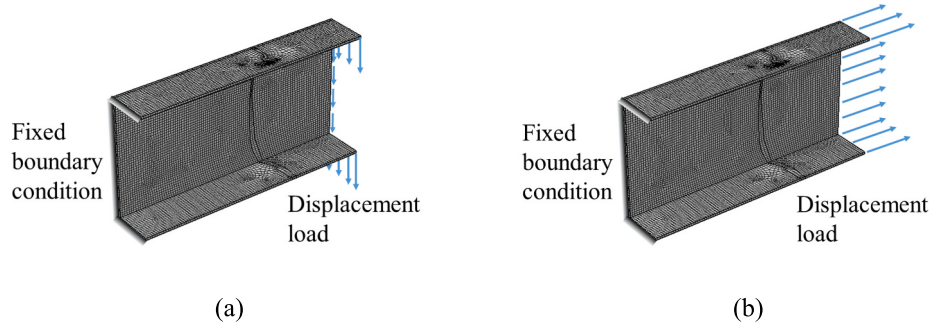


Fig. 15. Mesh, boundary conditions, and displacement loads of the FE model for the damaged cross beam: (a) case of shear force load, and (b) case of axial force load.

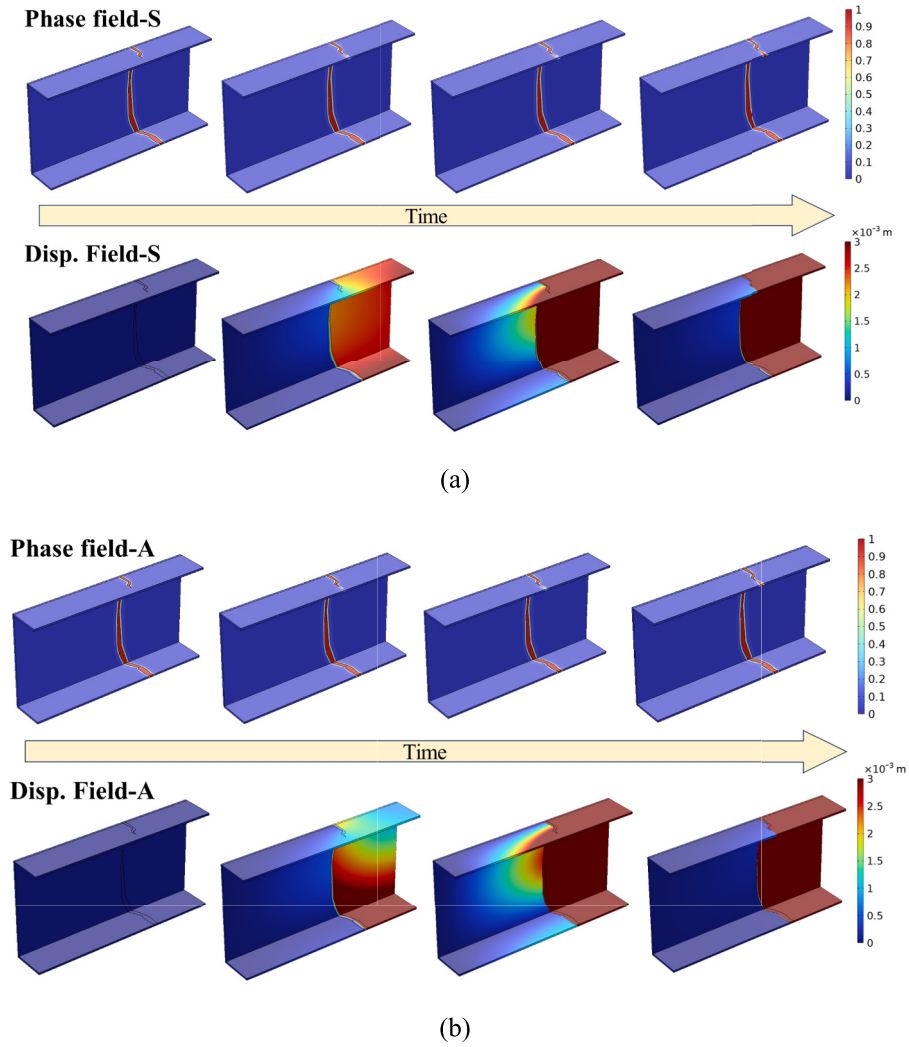


Fig. 16. Results of the simulation of damage propagation in both phase field and displacement field in the cross beam: (a) case of shear force load, and (b) case of axial force load.

consuming than re-design and re-meshing. By contrast, the most computationally expensive steps of the traditional damage updating methods: involve manual re-design, re-meshing and mesh refinement, especially in 3D models, leading to higher preprocessing time.

5. Conclusions

This paper presents a novel damage update method that integrates computer vision techniques with the phase field method. The proposed

integrated method enhances the rapid understanding of structural integrity degradation in existing structures. It also forms a foundation for developing computational engines for damage updating within structural digital twin systems. The key observations are outlined as follows:

First, the feasibility of the proposed damage update method was successfully demonstrated through two experiments conducted on a paperboard and a steel cross beam. These experiments confirmed the ability of the proposed method to update the damage phase field within

FE models in alignment with the damage observed in physical structures, facilitating rapid simulations of damage evolution by reducing the reliance on manual damage modeling.

Second, the proposed method proves to be effective for both 2D planar structures and 3D structures that can be decomposed into planar components. This flexibility broadens the applicability of the method to a wide range of real-world engineering scenarios.

This study demonstrates the feasibility of integrating CV-based damage identification with phase field modeling for damage evolution prediction. However, it still needs more quantitative experimental and analytical validation. The current validation approach is qualitative, relying on case studies to assess the method's applicability and effectiveness. To ensure a more comprehensive evaluation, future work will focus on experimental validation through controlled laboratory tests where observed damage patterns can be compared with numerical predictions. This step will be crucial in further refining the method and expanding its applicability to real-world structural health monitoring scenarios. Future research will focus on extending the damage update method to fully 3D for the damage types of concrete spalling, corrosion, etc. By expanding the capability to model and update solid 3D damage states, the proposed method will significantly enhance its applicability to a broader range of engineering scenarios. The scalability of the proposed method to larger and more complex 3D structures represents a promising avenue for future research. While the current study primarily focuses on 2D planar structures or 3D structures decomposable into 2D components, the methodology can be extended to fully 3D domains. Advanced image segmentation methods can be used to extract damage features from 3D imaging data (e.g., LiDAR or 3D point clouds), and these features can be integrated directly into FE models. However, challenges such as handling intricate geometries in large-scale models will need to be addressed. The integration of this method with commercial FE software, as demonstrated in the steel cross-beam case study, provides a practical pathway for scaling up the approach, as these platforms can efficiently handle large-scale simulations. Overall, extending the method to larger 3D structures would enhance its applicability to a broader range of real-world engineering problems, such as bridges, buildings, and industrial facilities.

The integration of computer vision techniques with the phase field method represents a significant step in bridging the gap between SHM systems and computational simulations. This novel approach allows for rapid updating of damage states in FEDT systems, providing engineers with unprecedented predictive power to assess the remaining life of critical infrastructure. As a result, this method not only facilitates more accurate predictive simulations but also enables proactive maintenance strategies, potentially extending the lifespan of aging structures.

CRedit authorship contribution statement

Youqi Zhang: Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Jarkko Niiranen:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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