Incorporating cracks into the structural analysis of concrete walls using full-dimensional update of point clouds

Honghong Song[1], Haijiang Li[2*], Gang Yang[1*], Tian Zhang[1], Xiaofeng Zhu[2], Yan Gao[2]
[1] Dalian Maritime University, China; [2] Cardiff University, Cardiff
Songh19@cardiff.ac.uk (Honghong Song)

Abstract. Some cracks in concrete structures following severe disasters such as earthquakes may exceed the specified limits. In addition to aesthetics and durability, cracks may affect the strength of the structure. However, it is difficult to quantify the effect of cracks on structures in current assessment methods. This article presents a method based on a digital twin framework to incorporate pre-existing cracks from scan data into a finite element model (FEM) and to perform structural analysis. Firstly, the coordinates and point cloud data of the cracks are obtained via Terrestrial Laser Scanning (TLS), and the skeleton configuration of the cracks are extracted and captured through pre-processing and cropping of 3D point cloud model. Then, the point cloud model coordinates and finite elements coordinates of the cracks are used as input to complete the mapping of the crack model based on Python and generate an ANSYS readable APDL command. Finally, the method is validated with a case study of concrete wall crack updates, illustrating that the method can accurately map full-dimensional crack shapes from a point cloud model to a FE model and effectively incorporate them into the structural analysis.

Keywords: Crack updating, Point cloud, Finite element model updating, Digital Twin

1. Introduction

Cracking is the most common damage to concrete structures, and many structures are designed to allow cracking under service loads (*EN 1992-1-1: Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings*, 2004). However, it is necessary to ensure the safety of the structure and the residual capacity of the cracked concrete structure needs to be determined (Wang et al., 2013), with particular attention to large cracks that result after natural disasters such as earthquakes. Finite element (FE) methods are widely used to simulate the condition of concrete structures and to model crack expansion. However, FE models based on design parameters no longer reflect the real state of the structure and therefore existing cracks should be incorporated into the initial FE model for more accurate structural analysis and decision making.

One advanced method is a digital twin (DT), which is devoted to the interaction and updating of multiple models to achieve a more accurate representation of physical entities (Honghong et al., 2023; Saback et al., 2022). The DT framework integrates four models for different purposes: a structural analysis model, a 3D geometric model to reflect the structure surface state, a surrogate model to predict the future performance of the structure, and a knowledge model for information management. Therefore, in the framework of the DT, breaking down the data barriers between models and facilitating model interaction is of paramount importance. This paper will work on the interaction between the surface geometry model and the structural analysis model, enabling the mapping of cracks from point cloud model to FE model and incorporating crack into the structural analysis.

The construction of surface models in the DT framework relies on point cloud scanning-based surface reconstruction techniques. This method allows for the acquisition of overall geometric and surface damage information of the structure e.g., cracks, spalling, etc (Hosamo and Hosamo, 2022; Jiang et al., 2021; Stojanovic et al., 2018). Most of the work is concerned with the transformation of a point cloud model to a structural model based on a global scanning. For example, Yu et al.(Yu et al., 2021) proposed an automated approach to generate nonlinear FE models of the beam. Yan et al.(Yan et al., 2017) investigated an automatic approach of using spatial data from laser scanning along with computer vision techniques for creating high-fidelity FE models automatically. However, there are four main challenges to global scan updating. Firstly, it is time-consuming and labor-intensive to process the large amount of point cloud data generated by the global scan, such as the removal of vegetation, vehicles and other things not related to the structure. Secondly, point cloud data-based component identification and semantic segmentation methods are still immature. Most of the research so far has been carried out on simple structure which is implemented in a laboratory environment. For complex structures, the accuracy of component recognition is difficult to guarantee. Moreover, after the point cloud model has turned into a geometrical model, there are many issues to consider such as the connection of components and structural constraints, as well as the addition of material properties and the meshing of the structural model. Finally, capturing structure surface damage in an overall scan places high demands on scanning accuracy and point cloud density.

Considering the challenges of the FE model surface damage updating based on global scanning inverse modeling, local surface damage in FE model update has been proposed to incorporate cracks into the finite element analysis. For example, Zhang et al. (Zhang et al., 2022) proposed a registration algorithm to project onto 3D models, for the automatic generation of FE models, in this study, cracks are extracted in 2D images. However, this method can only consider the crack length and width, not the crack depth. Kong et al. (Kong et al., 2023) present a vision-aided framework to achieve 3D concrete damage quantification and FE model geometric updating for RC structures. To extract damage information. First, the processed image can provide the location of the damage and the surface elements in the damaged area can be obtained. Second, the point cloud model provides the depth information of the damage, and the corresponding elements are deleted. However, this method can only obtain the surface shape variation of the component and cannot consider the shape of the crack interior. Moreover, it can only update the geometry model.

To address the above research gap, a novel framework is proposed to provide a solution for crack updating of geometry and structural analysis. The proposed framework is scan-based, breaking the data barrier between surface and FE models, and automate the process in Python, at the same time, providing a full-dimensional geometry update method including crack dimensions and 3-dimensional shapes for cracking and repair updates. This study has three main contributions: (1) Linking crack point cloud model to FE model. (2) Full-dimensional crack mapping methods are achieved. (3) Provide a solution to incorporate the crack damage in FE analyses.

The article is organized as follows: (1) review the state-of-the-art method and related works (Section 2); (2) proposed methodology (Section 3); (3) Crack mapping and FEM updating (Section 4); (4) Conclusion. (Section 5).

2. Related works

The concrete structure in service will produce cracks due to a variety of factors such as nature and traffic, and the expansion of cracks will have an impact on the safety of the structure, especially after the earthquake. Currently, damage inspection of concrete structure is mostly rely on engineers who manually measure the damage on site and judge its impact on the structure more empirically, this is costly, time-consuming, and error-prone.

The promotion of equipment for non-destructive testing provides an alternative to manual measurements, such as TLS(Stałowska et al., 2022), Light Detection and Ranging (LiDAR), or structured light 3D scanners (Alani et al., 2013; Shang et al., 2023). Based on those types of equipment, surface damage is located and identified. For example, Jiang e t al. (Shang et al., 2023) developed a vision-guided UAS with a lightweight convolutional neural network to detect and locate cracks, spalling, and corrosion. Liu et al. (Liu et al., 2019) used the trained U-Net to identify the crack locations from the input raw images under various conditions (such as illumination, messy background, the width of cracks, etc.) with high effectiveness and robustness. Zhang et al.(Zhang et al., 2021) proposed an unmanned aerial vehicle (UAV)-based smart rock localization for bridge scour monitoring. Further, some scholars have performed damage identification from laser-based inspection data. Cho et al. (Li et al., 2018) proposed an effective image processing technique for crack detection on images extracted from the octree structure of TLS data. In addition, many studies have established that defects (cracks) in buildings and structures can be detected successfully from a point cloud. Xu and Yang (Xu and Yang, 2019) proposed a novel view of the signal-to-noise ratio gradient for Gaussian filtering to identify and extra the crack automatically from the point cloud data of the TLS measurement. Kim et al. (Kim et al., 2018) investigated a crack identification method by using a commercial UAV with a high-resolution vision sensor is investigated in an aging concrete bridge.

Point cloud data is a set of points in a 3D coordinate system that represents the shape, position, and texture of a physical object or environment, but they do not provide information about the objects and structures represented in the data. Therefore, the transformation of point clouds into semantic models was introduced, including the addition of semantic information, such as object classification, to data points to make it easier to understand and analyze the information contained in the point cloud (Arayici, 2007). Yan et al. (Yan and Hajjar, 2021) proposed a heuristic-based method to automate the semantic segmentation of laser point clouds collected from a steel girder and thus facilitate the applications of laser scanning in bridge inspection and management. Tian et al.(Xia et al., 2022) presented a combined local descriptor and machine learning-based method to automatically detect structural components from the point cloud. Hyunsoo and Changwan (Kim and Kim, 2020) based on the deep-learning method to classify the components of bridges.

In addition, the lack of information on the design of older structures makes it difficult to build structural analysis models for these structures. Therefore, a conversion from a point cloud model to a structural analysis model has been carried out to address this problem. A variety of automatic approaches are adopted in different steps of the automatic processing of point clouds(Mirzaei et al., 2022). Lu and Brilakis (Lu and Brilakis, 2019) generate the geometric digital twin of an existing reinforced concrete bridge from four types of labeled point clusters by delivering a slicing-based object fitting method. However, beyond the approaches described in these studies for obtaining geometrical parameters, there is still a further need to convert geometries into finite elements for structure. Some studies have considered the direct generation of voxel for FEM. Luigi (Barazzetti, 2016) presented a novel semi-automated method for the generation of 3D parametric as-built models from point clouds. The proposed semi-automated method allows the creation of parametric models from photogrammetric and laser scanning point clouds. To be able to quantify the impact of bridge damage on the structure during bridge operation, the structural analysis model needs to be updated regularly. However, the overall transformation process from point cloud to structural model requires the processing of a large amount of point cloud data, which is a large amount of work and difficult to guarantee accuracy.

Therefore, a combination of 2D images and 3D models has been proposed for model updating. For example, Zhang et al(Zhang et al., 2022) proposed an approach to integrate cracks in 2D images into 3D models to automatically generate finite-element (FE) models is investigated. Cracks are extracted in 2D images, and 3D models are obtained by point cloud processing. A registration algorithm called Iterative Closest Point-based Direct Linear Transformation (ICP-based DLT) is proposed to project cracks onto 3D models, for the automatic generation of FE models. The combined use of 2D images and 3D point clouds greatly improves the efficiency of the model update, however, the 2D images do not capture the depth information of the incoming cracks.

Overall, scan-based point cloud data is widely applicated in structural surface reconstruction. Although there are still many challenges in the reconstruction of 3D structural models relying entirely on point clouds, the effectiveness of identifying and extracting cracks from point cloud data has been well and sufficiently demonstrated. At the same time, the point cloud data has the potential to capture the skeleton of a full-dimensional crack.

3. Methodology

The Scan-to-FEM methodology is proposed for the crack update. The methodology includes four main parts of the work, as shown in Fig 1. Firstly, collecting data about the location of crack and point clouds via TLS. Then, pre-processing of the point cloud is required, the noise, and background are removed, and only the crack is retained. In order to preserve the overall shape and structure of the point cloud while making the points in the cloud uniformly distributed according to a certain density value, a downsampling process is implemented. Then, the crack coordinates are extracted. Secondly, the point cloud coordinate information is used as input along with the element and node coordinates of the FEM. The mapping between the point cloud model and the FEM is done via Python and an ANSYS readable APDL language is automatically generated for the crack update and structural analysis. In addition, if the cracks are repaired, the FE model will be updated again to resurrect the elements that are about to be killed.

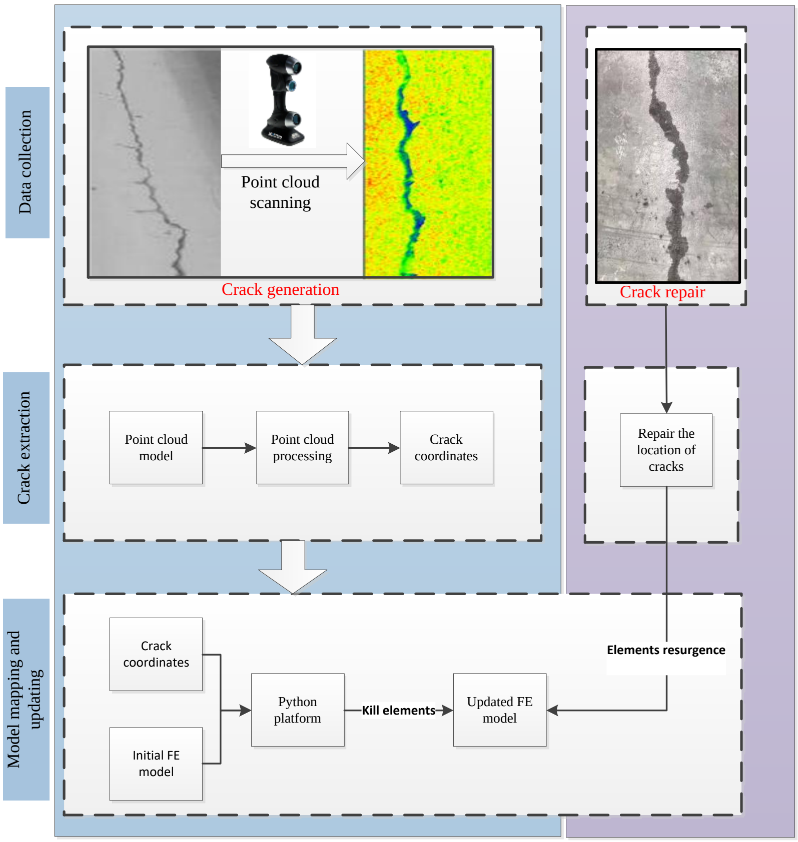


Fig 1. Overall methodology

4. Crack mapping and FEM update

4.1 Crack extraction

To illustrate the methodology proposed in this paper, the part of the crack dataset (Stałowska et al., 2022) is used as an example and mapped onto the FEM of the concrete wall. Point cloud data is first pre-processed using CloudCompare software. CloudCompare is a popular open-source tool for point processing and visualization. During this process, a space method is adopted to down-sampling the minimum space between points is 0.0001m, after outlier removal, denoising, segmentation, and cropping to obtain the 3D spatial coordinates of the cracked area, and the whole process is shown in Fig 2.

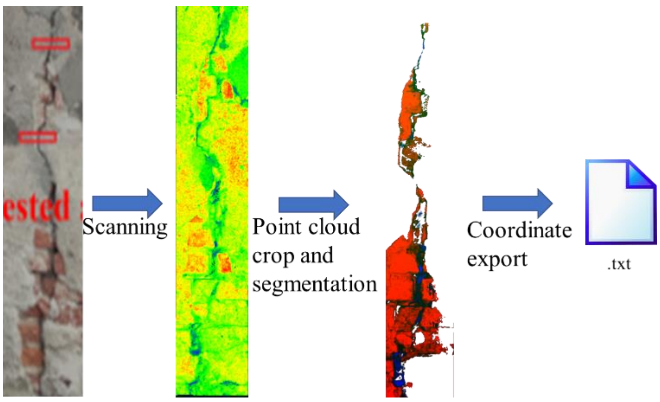


Fig 2. The process of the crack extraction

4.2 Crack mapping and updating

After extracting the coordinate of the crack , this part will descript the process of crack mapping and updating. Firstly, a initinal FE model of the wall is built in ANSYS, using SOLID65 element, the plain concrete wall with a modulus of elasticity of 35,200 MPa, axial compressive and tensile strengths of 40 MPa and 4 MPa respectively, Poisson's ratio of 0.2 and density of 2400 kg/m3. SOLID65 is used for the 3D molding of solids with or without reinforcing bars. The solid is capable of cracking in tension and crushing in compression. Then , mapping the crack form point cloud model to FE model. Since the point cloud only provides information about the surface of the component, and both the damaged areas and the internal healthy areas are blank in the point cloud, it is arduous and time-consuming to identify the damaged elements by simply matching the point cloud and FE model. To efficiently update the FE model, an automated FE model updating and analyzing method is proposed and implemented based on Python. By mapping, the element in the finite element model where the crack is located is identified. As shown in Fig 3, the full-dimensional shape of the crack can be accurately represented in the FEM. Finally, the method of setting up Life and Death elements is used to simulate crack cracking and repair. Kill element utilized for simulating the crack opening area, which can effectively simulate the crack without affecting the convergence of the structural calculations, compared to deleting the cell (Alam and Wahab, 2005; Yun et al., 2018; Zidani et al., 2015). Killed elements by multiplying the stiffness matrix of deactivated elements by a small factor, so that their effect on the global behavior of the model is negligible. In addition to this, when the crack is repaired, the killed elements can be reactivated. Note that the SOLID65 element is defined by 8 nodes, and when the range of coordinates where the crack is located covers one of the nodes, the element where the node is located will be killed.

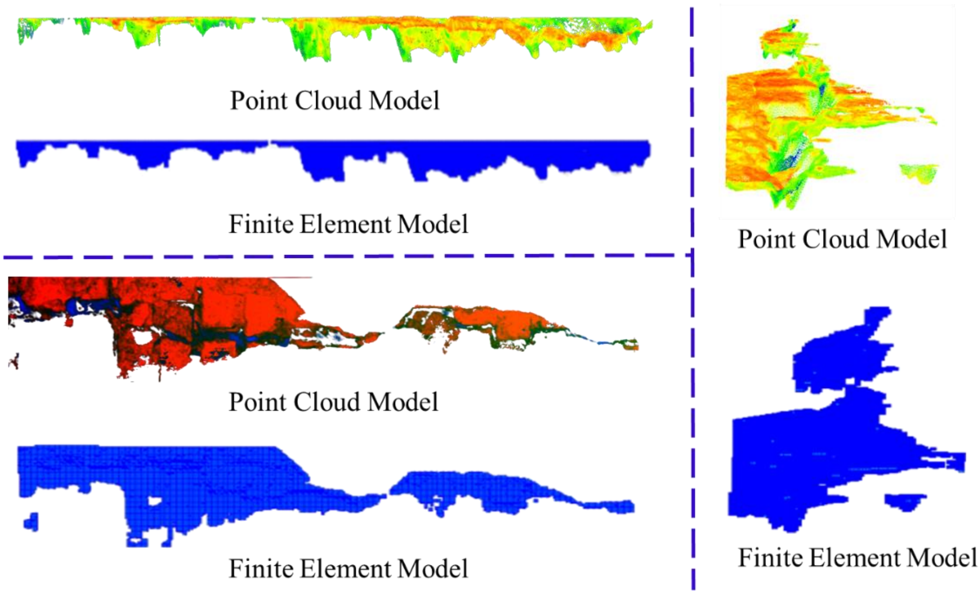
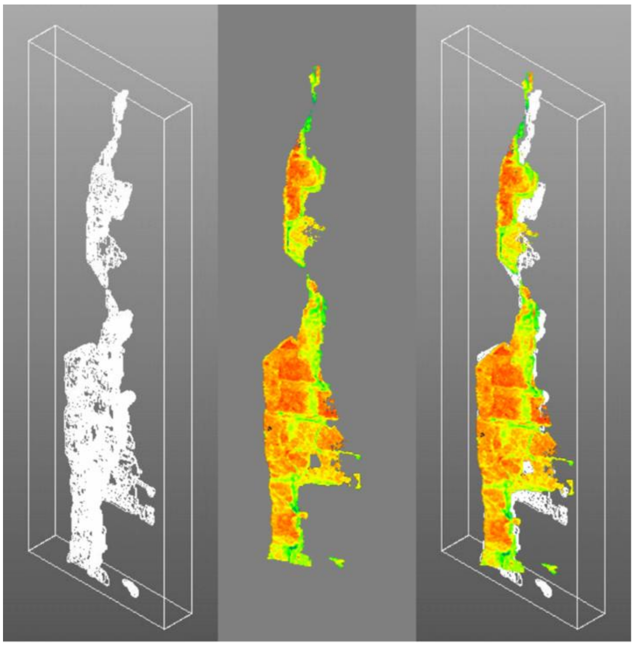


Fig 3. Crack mapping

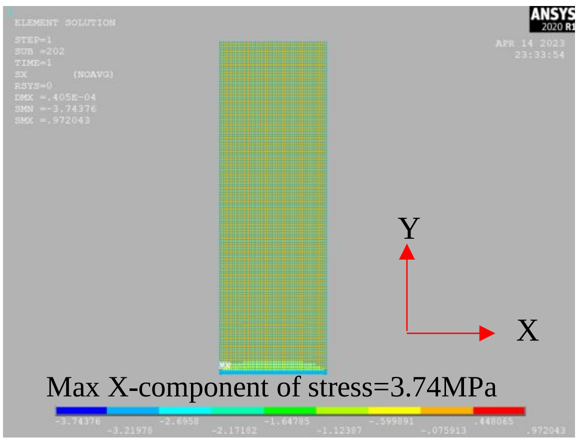


FEM with crack — Point cloud model of crack — Mapping comparison

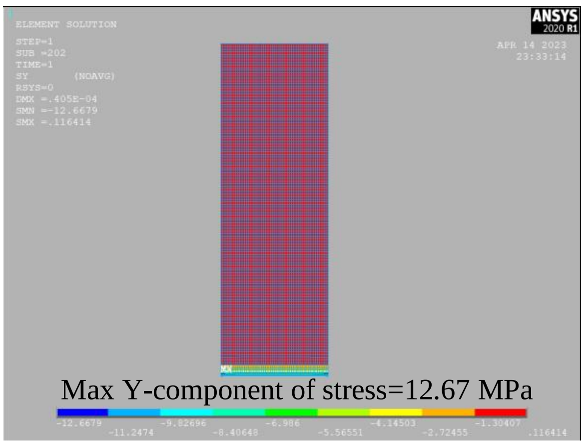
Fig 4. Crack updating

4.3 Non-linear analysis after crack updating

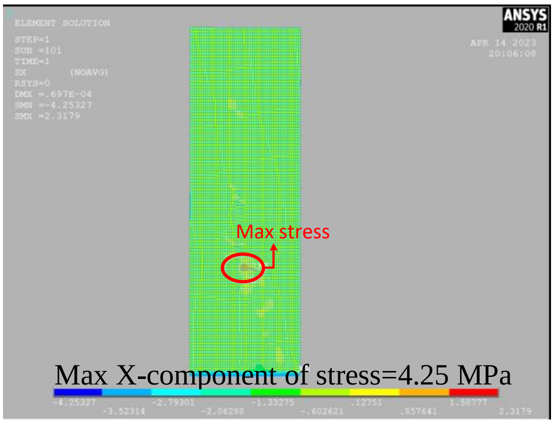
After the mapping and updating of the cracks completed, the structural analysis is then carried out in this paper. In order to show the changes in the structure before and after the crack renewal, The structure is analyzed non-linearly with full restraint at the bottom of the wall and a 1MPa surface load applied at the top. A comparison of the analysis results before and after the cracks is renewed is shown in Figure 4. As can be seen in Figure 4, cracks are effectively included in the structural analysis. The incorporation of cracks causes stress concentration in this structure, resulting in an increase in the maximum structural stress. In this case study, the maximum X-component stress increased by 13.64% and the maximum Y-component stress increased by 14.29% after the cracks were updated.



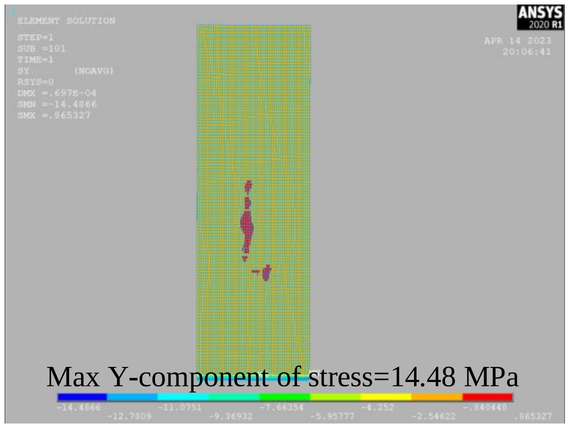
Stress-X (before updating)



Stress-Y (before updating)



Stress-X (after updating)



Stress-Y(after updating)

Fig 4. Comparison of stress distribution

5. Conclusion

This study presented an FM model-updating method based on the point cloud model .with the aim of incorporating the surface damage e.g. crack, spalling, into FE analysis. The following conclusions were drawn:

1. A framework of damage extraction, mapping, model-updating, analysis, repair and updates is proposed based on 3D point cloud model. The point cloud data can collect by TSL, automatic mapping can be achieved based on Python. Furthermore, the model-updating, analysis, repair, and updates used the FE model.

2. This paper proposes an Point-to-Node-Element method automated mapping method from a crack point cloud model to a finite element model that can accurately restore the full-dimensional shape of a crack.

3. Updating cracks by setting up life and dead elements not only simulates the structural failure of the crack but also allows for the elements in the crack to be reactivated when the crack is repaired.

The method requires a high degree of finite element mesh accuracy and cell type, and is less efficient in updating surface damage for large concrete structures, so in the future, it will be optimised for this problem.

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