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A PC based FE model as an innovative learning tool in structural mechanics

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ABSTRACT: Recent developments in digital technology make it possible to create interactive 3D models for structural analysis in a user-friendly software environment. In addition, the technology for creating 3D models of real structures using point cloud data for various users is also developing rapidly. Such rapid change may raise concerns about a developing gap between traditional structural mechanics education based on beam theory and the modern structural analysis scheme. However, if it becomes possible to efficiently perform structural analysis by recreating structures in cyberspace without special skills, it will be beneficial to cultivate a sense of structural mechanics for beginners. In this study, we investigated the feasibility and simplicity of constructing a point cloud-based structural analysis model to capture the general trend of deformation and stress in a structure. Specifically, we constructed a point cloud model from photographs of an approximately 2m long steel plate girder bridge using the SfM technique, meshing the model, and assembled a solid FE model using only general functions of packaged software without any special operations for model modification. We compared the strain in the constructed model under static loading with the actual measured values for the bridge. The model properly calculated the deflection shape, and it will help learners understand structural mechanics.

KEY WORDS: Structure from Motion, Point cloud model, Structural mechanics.

1 INTRODUCTION

Our predecessors have taught us that the history of structural mechanics is a repeated process of observing phenomena through experimentation, and then formulating and systematising them [1], [2]. Today, students can learn about systematised structural mechanics efficiently. In exchange for these fruits, many students are passive and just learn how to solve problems.

On the other hand, recent developments in structural analysis software have made it possible to precisely analyse structures' deformation and stress distribution with complicated shapes and materials. In addition, it has become possible to model even existing structures easily using point cloud technology[3]. Researches have been conducted on utilising point cloud data for structural analysis. However, they require advanced or complex procedures developed by each researcher[4], [5]. We have yet to fully benefit from them in structural engineering. Bridging the gap between cutting-edge structural analysis technology and traditional structural mechanics education or feeding back the latest technology to the learning of beginners will increase the attractiveness of this engineering area.

The authors investigated the technique of constructing precise structural models of actual structures from point cloud models using SfM (Structure from Motion) or photogrammetry techniques. We have also developed a method for converting point cloud models into 3D FE models that can be used for structural analysis. Through this research, it has become possible to model the damaged actual structures with a certain degree of precision and to evaluate the stress of damaged members. On the other hand, modelling point clouds into appropriate shapes of FE models requires a relatively complicated procedure, and fine-tuning of parameters is also necessary individually. The precise evaluation of structural performance with automated procedures from point cloud data is the ambitious goal; however, even if the analytical accuracy is somewhat limited, more straightforward procedures will enhance the possibility of structural mechanics.

In this study, we investigated the feasibility and simplicity of constructing a point cloud-based structural analysis model to capture the general trend of deformation and stress in a structure. Specifically, we constructed a point cloud model from photographs of an approximately 2m long steel plate girder bridge using the SfM technique, meshing the model, and assembled a solid FE model using only general functions of packaged software without any special operations for model modification. We compared the strain in the constructed model under static loading with the actual measured values for the bridge.

2 FE MODEL FROM POINT CLOUD

2.1 A model bridge and point cloud model

A simple steel girder bridge, an out-of-service railway bridge located on a test bed consisting of two main girders made of rolled I-shaped steel[4], was subject to study. The length of the girder is 2.4 m, and the total width of the bridge is 1.1 m. The steel surface was generally rusted, but there was no significant reduction in thickness. A damaged state was prepared by grinding a 200×68.5 mm area on the top surface of the lower flange at the mid-span of one girder.

The static loading experiment was conducted by placing steel plates on top of the main girders to create a two-point loading

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condition as shown in Figure 1. The loading weight is 80 kN. Strain gauges measured strain at the mid-span of girders.

The point cloud model of the bridge was constructed using SfM. A SONY α6500 digital camera captured 2,969 images from around the bridge. The vertical and horizontal overlap rates were set to 80% or more. The Agisoft's Metashape (ver1. 6. 5. 11249) loaded captured images and constructed a tie point cloud with high accuracy. Then, a point cloud model was constructed at medium quality and high-depth filter settings. Figure 2 shows the point cloud model of the bridge. There were no missing points in the entire point cloud. Table 1 shows the plate thickness of the damaged bridge at the center cross-section of the span. The average error was 1.1 mm, and the model was generally accurate. The reduction in plate thickness of the damaged area was also modeled.

2.2 Conversion method into FE model

Because the number of points in the point cloud model was enormous, a voxel grid was set on the point cloud, and a voxel downsampling was applied to create nodes. The grid size, which was set to 9mm or 18mm in this study, corresponds to the mesh size of the FE model. The centroid of the point cloud within the grid was then calculated as the node of the FE model.

The girders were divided into web and flanges using the maximum and minimum z-coordinates of the web. The maximum and minimum values were calculated by using the normal vector for each point.

To create a cross-section, align only the x-coordinate value of each point along the component's axis to the same plane. An outline of a section was created along the component's axis. The shape of the outline was controlled by a shrink factor determined by trial and error for each component.

Figure 3 shows the concept of element generation. A 2D Delaunay triangulation was first performed on each cross-sectional outline, dividing the 2D region into triangles using an arbitrarily set group of nodes. Next, the process of generating solid elements was applied to all cross-sections where 2D Delaunay triangulation was performed. For each triangular element on the S_n cross-section, the closest point on the S_{n+1} cross-section was found, and triangular solid elements were formed by connecting these points. Lastly, the web and flanges were reconnected using a similar way of generating the solid elements of each component.

The elements and node information were exported to a NAS file and then imported into the structural analysis software Midas NFX. The constructed FE model of the damaged bridge, which is called Model A, will be shown in Figure 4. The analytical result will be discussed in Chapter 4.

3 A SIMPLE METHOD FOR POINT CLOUD BASED FEM

The recent development of image processing technologies and laser ranging technologies have brought about several options to obtain point cloud models of structures. If more straightforward procedures can be utilized to construct the FE model from the point cloud model, structural analyses will be much more user-friendly for non-professional users. Therefore, the authors explored a method to compose an FE model using only general software without original codes. The proposed steps are as follows:

Figure 1. Static loading experiment.

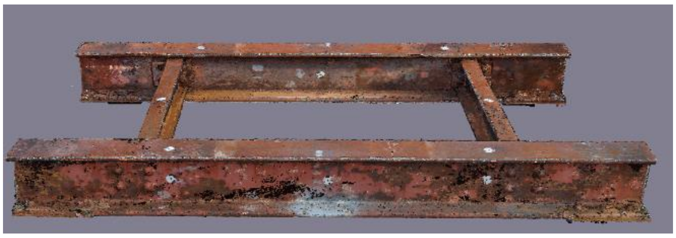

Figure 2. A point cloud model of a simple girder bridge.

Table 1. Plate thickness (mm).

		Real	P.C. model
Upper flange (G1)		20.0	19.6 (-0.4)
Web (G1)		15.0	13.1 (-1.9)
Lower flange (G1)	outside	15.0	12.6 (-2.4)
	inside	10.0	10. (+0.4)
Upper flange (G2)		20.0	19.7 (-0.3)
Web (G2)		15.0	12.2 (-2.8)
Lower flange (G2)		20.0	20.1 (+0.1)

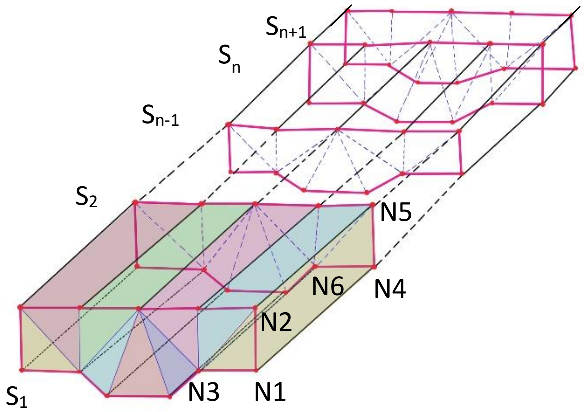

Figure 3. Concept of elements generation.

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I. Loading the point cloud data by scanning and meshing software for point cloud data.
In this study, Autodesk ReCap Pro loaded the same point cloud data in the previous chapter. Downsampling is also conducted in the software to 25% of the original point cloud model.

II. The meshing of the point cloud model
Convert the point cloud to a mesh using the scan-to-mesh service from ReCap with the medium-quality setting.

III. Converting the meshed data into a 3D object
Recap Photo converts the meshed data to 3D object data in an FBX format. The target face count is decimated by 90%.

IV. Transformation of the mesh body into a solid body
Autodesk Fusion opens the FBX file and closes the mesh. The mesh body has mass and volume, and then the mesh body is converted into a solid body with the facet option.

The constructed FE model of the bridge, which is called Model B, will be shown in Figure 5, and the analytical result will also be discussed in Chapter 4.

4 LINEAR STATIC LOADING ANALYSES

Linear static analysis is conducted for the constructed 2 FE models; Model A was originally developed by the authors [4], and Model B was the proposed simple model in this study. The boundary conditions in the FE models were applied to the points on the underside of the sole plate, assuming the simple support condition. For the loading conditions, vertical downward loads of 80 kN in total acted at 4 points 400 mm away from the midspan to the support. In Model A, distributed load acted on nodes within the experimental loaded area. On the other hand, 4 concentrated loads were applied in Model B because the size of the automated generated mesh was not uniform and was larger than that of Model A. Commercial software Midas NFX for Model A and Fusion for Model B calculated the stress and deformation of the model.

Figure 4 and Figure 5 show the longitudinal bending stress distribution and the enlarged deformation in Models A and B, respectively. Both figures show that stress distribution and deformation indicate positive bending in the structure.

In the damaged area of Model A, tensile stress increases due to the introduction of damage at the midspan of the lower flange, and compressive stress predominates in the loaded area. The error in the experimental result was about 6% for the nodal longitudinal stress at the damaged point.

On the other hand, the stress value of Model B is generally half of the stress of Model A. The thickness of plates was generally identical to the point cloud model and the actual structure in both FE models. However, the web plates of Model B have some thick parts due to rivets of connection and the roughness of the paint, and they may cause the reduction of stress. The error in the calculated stress is caused by such mesh configuration of Model B because both models are generated from the same point cloud data. Additionally, due to the low density of nodal points, a local torsional deformation occurs in the upper flange because of the eccentric loading at the upper flange, which was not observed in the experiment.

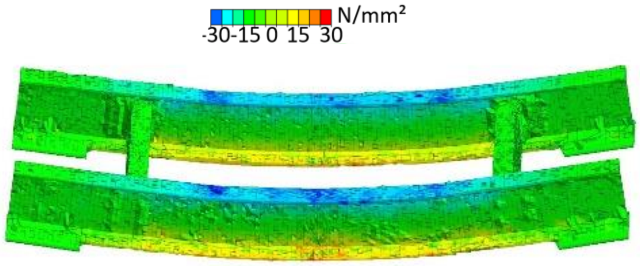

Figure 4. The analytical result of Model A.

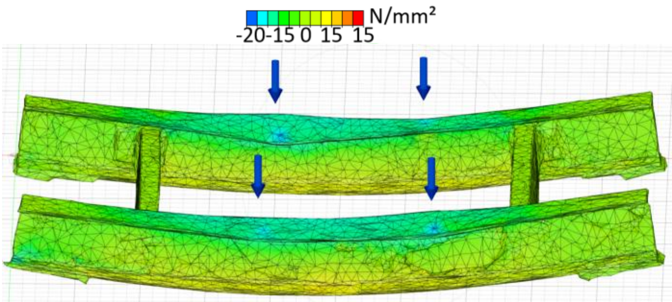

Figure 5. The analytical result of Model B.

5 CONCLUSION

The authors have developed the construction method of the FE model from point cloud models. Because straightforward procedures will enhance the possibility of structural mechanics, we investigated the feasibility and simplicity of constructing a point cloud-based structural analysis model using only general functions of packaged software without any special operations for model modification. From the analytical results of a 2m long steel girder bridge, the global tendency of deformation and stress of the structure could be obtained, although the precision of calculated stress needs to be improved. The reproducibility and stability of composing mesh and solid are also subjects to be improved. However, future developments of this technique will provide a powerful tool for learners in structural mechanics and motivate the development of innovative construction design and effective maintenance methods.

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