Automatic Generation of Weld Models for Railway Rolling Stock

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Abstract—The air-conditioning equipment and other structures attached to railway rolling stock are plate objects joined by a spot or an intermittent welding. The finite element (FE) modeling of such plate objects is very time-consuming due to the large number of spot and intermittent welds that must be modeled. We developed automatic weld modeling technology, with the aim of reducing the procedures for FE modeling. Applied to a test cover model, the technology reduced the modeling time to 1/3. And FE stress analysis showed that the result accorded to an experimental data within an error range of 11%.

Keywords-component; FEM; spot weld; intermittent weld; shell mesh; beam mesh

I. INTRODUCTION

Plate objects, such as the air-conditioning units and other structures attached to the bodies of railway stock, are structurally analyzed by finite element (FE) modeling [1]. In the structural simulations of such plate objects surface FE modeling is performed to decrease the number of meshes. In normal structural analyses, solid-type meshes, such as tetrahedral or hexahedral meshes are used for simulation accuracy. These solid-type meshes are created from 3D-CAD data [2][3].

However, for railway rolling stock, the FE models are large and not solid-type mesh generation is time-consuming. The mesh generation time can be decreased by using a surface-type mesh, such as a quadrilateral or triangular mesh, for the structural analysis of plate objects. To make surface-type meshes for plate objects, medial surface models are used [4]. To run simulations of plate objects in a short time, we developed an automatic medial surface generation technology, which renders a pair of faces and generates medial surfaces from them. It is easy to generate medial surfaces automatically. The sheet metal parts of air-conditioning equipment are jointed by bolt welding, bead welding and spot-welding. How the welds in FE models are simulated is important. Railway rolling stock consists of many sheet metal parts joined by spot welds and intermittent welds to ensure the structural integrity of railway stock body structures.

Because of the large number of spot and intermittent welds in railway stock body structures like air-conditioning units or their covers, the time consumed by the modeling operations is a serious issue. The method of weld modeling affects the analysis accuracy. Also important is ease of modeling so as to decrease modeling operations. There are around 200 or 300 spot welding and intermittent welds in air-conditioning units. Manual FE weld modeling involves a number of operation procedures. In creating FE models of spot and intermittent welds, the modeler has to edit points and lines to simulate the welds in the shape model before making mesh models.

This paper describes technology that automatically creates spot and intermittent weld models. We demonstrate the analytical accuracy of FE models, which contains spot-welding and intermittent welding compared to experimental results.

II. FE MODELING METHOD

A. Automatic Medial Surface Generation

We have developed a three-dimensional (3D) CAD/CAE coupled system, called "CADAS", which makes the analytical mesh models used in the computational simulation [5][6]. CADAS translates 3D-CAD models designed by a product designer into computational models. In addition to the automatic mesh generation, we have developed technologies for automatic medial surface generation and for shape cleaning and simplification.

Figure 1 outlines the system architecture of CADAS, which is composed of CADAS/GEO, CADAS/PRE, CADAS/POST, and CADAS/VIEWER functions. The CADAS/GEO functions generate mesh models automatically. Mesh types are triangular, quadrilateral, tetrahedral, and hexahedral. When the operator selects a mesh type to make mesh models in advance, CADAS/GEO generates the mesh data translated from the CAD model. By making the CAD data and translating it to the CAE base model, the product designer can generate the mesh data.

For the mesh model, it is possible to generate the mesh data manually by using CADAS/PRE. After the mesh data have been created, it is converted to the input data of the
analysis software (CADAS is compatible with various kinds of software). CADAS/POST presents the simulation result. CADAS/VIEWER presents the results of the structural analysis and does so without the need for user-learning operations. CADAS/POST checks the analysis results, such as the structural- or fluid-analysis results. CADAS/VIEWER is used to confirm the analysis results during the design-review process.

Figure 2 shows the algorithm for the medial surface generation technology [7]. The medial surface technology renders a pair of faces to generate medial surfaces in a shape model. The medial surfaces are created at the center of the pair of faces in the shape model. After medial surfaces have been generated, the sheet thickness is retrieved and set to the medial surfaces. The sheet thickness is derived when a program renders the pair of faces in the shape model. For an air-conditioning cover model, whose shape model consists of around 770 faces, the generation of medial surfaces takes three minutes.

B. Spot Weld Modeling

To reduce the FE modeling time, we developed simulated weld modeling technology. Spot and intermittent welds joining sheet metal pieces are modeled by points and lines in the shape model. In a FE model, the beam and shell meshes correspond to the spot and intermittent welds. The beam and shell meshes in a FE model correspond to the lines and surfaces in the shape model.

In a spot weld, a point and line are simulated and a beam element is modeled. The diameter of the beam cross-section corresponds to the nugget diameter of a spot weld. In an intermittent weld, lines in the shape model are simulated as welding lines. Intermittent welding lines correspond to lines in the shape model.

In spot welding simulation, several methods can be used for FE modeling [8]. In FE modeling for automobiles, spot welds are often used for crash analysis [9][10]. The spot welds are modeled by shell and beam elements (Fig. 4-(i)) or solid meshes (Fig. 4-(ii)), such as tetrahedral meshes. Spot welds are usually modeled by solid meshes. In addition, shell and beam elements of spot welds are often utilized for shell mesh models [11][12].

In FE analysis, the hexahedral mesh models provide the best accuracy. Models based on shell and beam meshes show good accuracy.

\[ Q_0 = \sqrt{Q_{s1}^2 + Q_{s2}^2} \]  

In the FE modeling of spot welds, two pieces of sheet metal joined by a spot weld correspond to surface data and the nugget part of the spot weld is substituted for a beam element. This modeling method is used for a shell analysis, and it shows whether the simulated model agrees with the measured results.

A shaved load \( Q_0 \) at a spot welding point is given as total shearing force \( Q_{s1} \) and \( Q_{s2} \).

The stress at the beam element concentrates at the edge of the nugget part. Inside the nugget part, the stress weakens. A cross section of a beam element is round in shape and the radius of the beam corresponds to the nugget radius. Then, the length of the beam element is equivalent to sheet thickness. The material of the beam element is the same as the plate material. However, if the plate material at the top of the nugget is different from that at the bottom of the nugget, it is difficult to set the material data automatically. The material data for the top piece of sheet metal is not always the same as that for bottom one; therefore, it is better for an operator to define the material data. The operation procedure for the spot-weld modeling is as follows (Fig. 5).
(i) The operator picks master face F1, inputs weld pitch, nugget diameter, the beam element direction, and selects welding start point A
(ii) The program makes spot welding points B, C, and D and extends them to make lines and intersecting points B', C', and D' to slave face F2
(iii) The program assigns the K-point to calculate shear stress and sets material data

When an operator inputs the spot position, pitch, nugget diameter, and material data, the section data of the beam element are set. The positions of spot-welding points are calculated on the basis of the welding start point A. Point B is generated by moving point A to the offset distance in the x-axis of master face F1.

Spot point B at master face F1 is projected to slave face F2 and copied as point B'. Spot point C is generated by moving point B by the inputted distance. Point C is projected to slave face F2 and copied as point C'. Points D and D' are the same as points C and C'. Projected lines BB', CC', and DD' compose beam elements. Shell meshes are generated at master face F1 and slave face F2. When the shell meshes are made, spot-welding points B, C, D, B', C', and D' are generated as nodes.

For the assignment of the K-point, the operator can select the spot welding start point or the x-axis, y-axis, z-axis, or arbitrary directions.

Figure 6 shows an example of spot-weld models. In air-conditioning equipment, there are more than 300 spot-welding points. Our technology makes points and lines as beam elements automatically, reducing the spot weld-modeling time to 1/5 that of the manual procedure.

C. Intermittent Weld Modeling

When the welding length and welding pitch are input as parameters, the program makes an intermittent-welding model (Fig. 7)[13][14][15].

Intermittent welding is modeled by lines and faces. In a volume model, weld geometries are modeled by volume parts. When the operator inputs the welding face, welding lines, weld length, and pitch in an interactive way, the program makes welding lines, which simulate the intermittent welds. After the lines have been created, a tying configuration is established between weld lines. The procedure for intermittent-weld modeling is as follows (Fig. 8).

(i) The operator inputs intermittent-welding length and weld pitch
(ii) The program makes welding lines on a weld surface and divides lines by the welding length and pitch
(iii) The program ties divided weld lines and surface

The program creates intermittent-weld models automatically in a short time compared to current manual operations, where the operator has to edit to divide lines in a weld length and set lines as welding lines to tie the configuration. The developed program makes intermittent-weld modeling easy: all the operator has to do is select the target line and face and input the weld length and pitch.

For air-conditioning equipment on railway rolling stock, the number of intermittent welds is 52, and time for making the intermittent weld models is reduced to 1/4.

Figure 7. Intermittent welding system.

Figure 8. Schematic of FE intermittent welding model.
III. FE ANALYSIS RESULTS

We applied the developed technology to an air-conditioning equipment model in the railway rolling stock and compared the results to experimental results to confirm that weld modeling by shell and beam elements has a good accuracy.

For the test, we used an air-conditioning cover model with 112 spot welds. All spot welds were modeled by beam elements. The constraint was that bolted joints are tied in all directions. We assumed that when the inside surfaces of the cover model are subjected to distributed pressures, the beams attached to the cover are stressed strongly.

We have measured the stress of cover model when two different distributed loads gave to the inside and outside in cover, and compared an experimental data to analysis data. The direction of distributed load is normal direction of the cover. Table I shows the ratio of FE analysis result and experimental result, when the experimental data are as 100. We measured the maximum principal stress at four different points in a cover model of air-conditioning equipment. We selected four points for measuring strong and weak values of the maximum principal stress.

<table>
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<tr>
<th>Case of load condition</th>
<th>FE analysis result</th>
<th>Experimental result</th>
<th>Precision Error</th>
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<tr>
<td></td>
<td>111</td>
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The FE analysis results showed that the stress was concentrated at the center of beam on a cover model of air-conditioning equipment in a railway rolling stock, and the maximum principal stress value agreed with the experimental results within an error range of 11%. The stress concentrated parts in experimental results was same as those in FE analysis results. For a cover model of air-conditioning equipment with spot in railway rolling stock and intermittent welds, our technology reduces the time for spot- and intermittent weld modeling to less than 1/3.

IV. CONCLUSION

We developed automatic weld modeling technology that reduces the operation time for making FE models. For a test cover model of air-conditioning equipment, the modeling time is reduced to 1/3. The results of a FE stress analysis agreed with the experimental data within an error range of 11%.

REFERENCES