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INVESTIGATION OF STRUCTURAL BEHAVIOR OF WOODEN TRADITIONAL JOINTS VIA FINITE ELEMENT ANALYSIS

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ABSTRACT: With timber buildings becoming increasingly popular, the study of timber structures and joints has gained great attention. As the weakest part of the building, it is fundamental to investigate joints, especially traditional ones. In this research, the structural behaviors of longitudinal joints from Korea and Indonesia were investigated using finite element modeling. *Maettugijjangbu* (Joint 1) and *jumeokangbu* (Joint 2) as Korean traditional joints and *sambungan bibir miring* (Joint 3) and *sambungan bibir lurus* (Joint 4) as Indonesian ones were analyzed. The four types of joints were compared in terms of deformation capacity, and the procedure for investigating their structural behaviors was thoroughly explained. Finite element analysis was performed using linear elastic analysis for orthotropic material. The boundary conditions, loads, and contact surface conditions were input based on design setup. From displacement analysis, it was found that Joint 1 has the smallest deformation in terms of tension and compression load than other joints. Meanwhile, Joint 4 and Joint 3 have the highest deformation under tension load and compression load, respectively. Even though the maximum stress at all joints might be higher than the strength factor (C_f), it is feasible to conclude that Joint 1 performs better than other joints.

KEYWORDS: Structural behavior, wooden traditional joint, finite element modeling

1 INTRODUCTION

Timber buildings have garnered large interest in recent years, due to their advantages of good carbon storage, heat preservation, and sustainability. Modern timber buildings started from the legacy of traditional wooden buildings. As a proven precedent of timber buildings, traditional wooden buildings have good earthquake resistance because of their unique architectural style and structural system. The Korean traditional building, Hanok, uses *ieum* and *machoom* construction method to create solid and durable house [1]. This method allows for wood joints to be assembled without nails. Similarly, Indonesian traditional buildings called Rumah Gadang use mortise tenon joints without metal fasteners [2].

Timber joints are usually the weakest point in timber structures [3]. Although joints or member connections are unavoidable in building structure, timber joints need extra consideration. As structural material, timber has limited size and length which require more joints than other materials. One of the most important traditional joints is in member along with the member direction to extend the length (post to post, beam to beam) or *ieum* in Korean joint classification. This joint is crucial to fulfil the required span of the timber structure. Thus, many studies of these joints have been conducted, especially its mechanical behavior.

Currently, finite element analysis (FEA) is one of the preferred methods to investigate timber joints due to its wide range of applications and type of elements. Even though the resulting capacity of the finite element method is usually lower than the actual value, the result is typically considered to be reliable compared to experimental results [3][4]. Typically, FEA could provide displacement and stress distributions of the structures which are enough to understand the mechanical behavior of joints in preliminary stage.

In this study, traditional joints from Korea and Indonesia were investigated to find their structural behavior using the finite element method. *Maettugijangbu* and *jumeokjangbu* from Korean traditional joints and *sambungan bibir miring* and *sambungan bibir lurus* from Indonesia were analyzed under tension and compression loads. Due to the complex shape of those traditional joints, finite element modeling was used via computer software. Friction and compressive strengths are the most influential factors in the flexural capacity of the joints [5] that are also used in modeling. Friction factor was used in the model setup and compressive strength was used for failure criteria. From the simulation result, the performance of the joints was compared based on joint

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properties and deformation shape. In this study, stress distributions were not elaborated and expected to be further analysis in the future. Thus, only prediction of general failure of the joints was discussed.

2 FINITE ELEMENT MODELING

Four types of joints were examined within the same factors: material properties, boundary conditions, and forces. FEA was conducted using Dlubal RFEM software. Before starting the simulation, mechanics of material, joint models, and design setup are required to be inputted to the software. Then, after the simulation, the results are analyzed using failure criteria of wooden material.

2.1 MECHANICS OF MATERIALS

As an orthotropic material, wood exhibits a variety of mechanical characteristics along three mutually perpendicular axes (natural axes): longitudinal, radial, and tangential. The longitudinal axis X is parallel to wood grain (fiber); the radial axis Z is normal to the growth rings (perpendicular to grain in radial direction); and the tangential axis Y is perpendicular to grain but tangent to the growth rings (Figure 1).

Since this investigation is not directly performed in the experiment, the wood mechanical properties were chosen based on the availability of material library in Dlubal RFEM. Originally, Korean traditional buildings use softwood material while Indonesian traditional buildings use hardwood material. In this study, the material properties are generated to be the same as hardwood grade D30 (DIN 1052:2008-12) (Table 1).

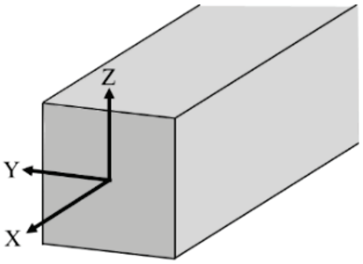


Figure 1: *Wood axis in finite element model*

Table 1: *Wood anisotropy parameters in finite element model*

E_x	$E_y = E_z$	ν_{yz}	$\nu_{xz} = \nu_{xy}$	G_{yz}	$G_{xz} = G_{xz}$
10000	640	0.1	0.045	60	600

Note: E = modulus of Elasticity (MPa), ν = Poisson's ratio, and G = shear modulus (MPa) are mean values. Subscripts xyz in the formula represent the direction of the properties.

The wood material is set as 'Orthotropic Elastic 3D'. This setting is for linear elastic analysis for 3-dimensional models. Following Hooke's law, the elasticity matrix of wood in the software is expressed as:

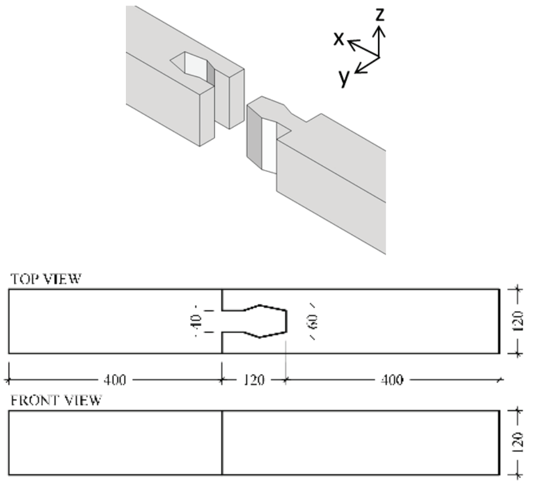
$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ \frac{-\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{xz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} \tag{1}$$

The following correlation exists between principal Poisson's ratio ν_{xy} and secondary Poisson's ratio ν_{yx}:

$$\frac{\nu_{zy}}{E_z} = \frac{\nu_{yz}}{E_y};\ \frac{\nu_{zx}}{E_z} = \frac{\nu_{xz}}{E_x};\ \frac{\nu_{yx}}{E_y} = \frac{\nu_{xy}}{E_x} \tag{2}$$

2.2 JOINT MODELS

Two Korean and two Indonesian traditional joints were chosen from actual traditional buildings: *maettugijangbu* (Korean), *jumeokjangbu* (Korean), *sambungan bibir miring* (Indonesia), and *sambungan bibir lurus* (Indonesia). These joints were analyzed under tension and compression loads. The joints originally come in different sizes and proportions but are adjusted to the same beam size for this investigation. The cross-section size of the beam is 120 x 120 mm. Details of the joints are shown in Figure 2.



(a) Joint 1. *Maettugijangbu* (Korea)

Figure 2-1: *Details of joints (size in millimeters)*

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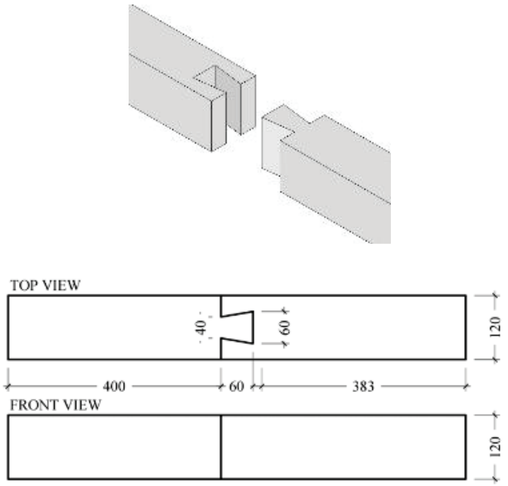
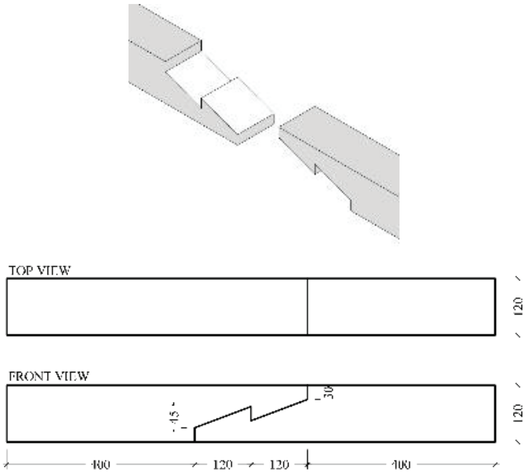
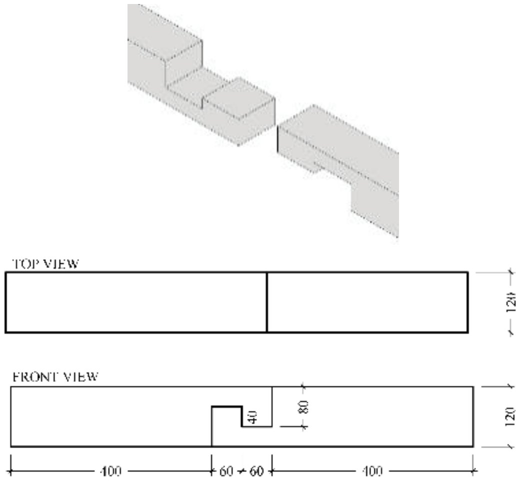


(b) Joint 2. *Jumeokjangbu* (Korea)



(c) Joint 3. *Sambungan Bibir Miring Berkait* (Indonesia)



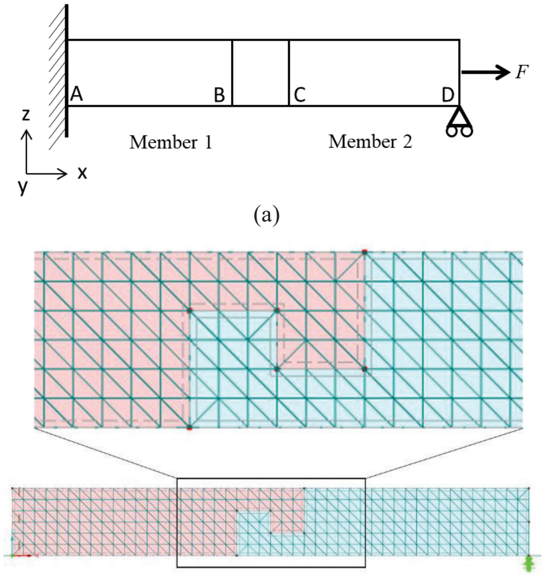
(d) Joint 4. *Sambungan Bibir Lurus Berkait* (Indonesia)

Figure 2-2: *Details of joints (size in millimeters)*

2.3 DESIGN SETUP

After modeling the joint shapes, the next step is to set up the boundary conditions, loads, and surface conditions. The boundary condition is set as a fixed joint on the yz-direction at Point A, and a roll joint at the base on Point D. Then, the joints were applied with nodal loads on the yz-surface of Point D with two conditions: 5 kN tensile force and 5 kN compression force. The length of Points A-B and C-D are 400 mm, whereas Point B-C varies depending on the type of joint (Figure 3a).

Each joint has two solid members, member 1 attached at Point A and member 2 with a roll joint at Point D. Because each member has contact with the other, the 'surface release' setting was used to create separation between the members. The contact surface can be released in this configuration based on the direction and the relationship between the surfaces. The shear between timber members is related to friction force. Based on the wood properties, the friction factor for the D30 wood grade is 0.1875. The finite element was set to 20 mm with a triangular shape element (Figure 3b).



(a)

(b)

Figure 3: *(a) Design setup and (b) FE mesh on Joint 3 from xy-plane*

2.4 FAILURE CRITERIA

Failure at wood connections is typically categorized as either ductile or brittle. The only type of ductile failure is a bearing failure, which occurs before brittle failure or fracture. Meanwhile, brittle failure has three types: splitting, shear failure, and tension failure. However, it is not easy to determine the type of failure in a computer analysis. Thus, the failure analysis of joints is commonly based on evaluating the stress distribution at the joint surface.

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Failure criteria in plane stress [6] are adopted to this investigation. The criterion can be written as follows:

$$\left(\frac{\sigma_x}{X_1}\right)^2+\left(\frac{\sigma_y}{Y_1}\right)^2+\left(\frac{\tau_{xy}}{S}\right)^2\le C_f \qquad (3)$$

where σ_x is the limit stress parallel to wood grains, σ_y represents the limit stress perpendicular to wood grains, τ_{xy} is shear stress parallel to wood grains, X_1 represents the limit strength parallel to wood grains, Y_1 is the limit strength perpendicular to wood grains, S is the shear strength parallel to wood grains, and C_f is the strength factor. The limit stress can be a compressive or tension stress.

Failure occurs when the total strength exceeds the strength factor (C_f =1.0). Based on material properties in Dlubal RFEM, D30 wood grade has compressive strength parallel to wood grains, compressive strength perpendicular to wood grains, and shear strength parallel to wood grains of 23 N/mm^2, 8 N/mm^2, and 3 N/mm^2, respectively. Moreover, D30 wood grade has 18 N/mm^2 for tension stress parallel to wood grain and 0.5 N/mm^2 for tension stress perpendicular to wood grain.

3 RESULTS AND DISCUSSION

The performance of four traditional joints was analyzed in terms of joint properties and deformation. Joint properties were analyzed based on the joint shape and its impact on the structure. Deformation was analyzed based on the maximum value obtained from FEA.

3.1 JOINT PROPERTIES

In this study, the chosen joints are the joint between the timber members in the same direction which usually extends the beam or column length. This type of joint has many subtypes with various joint properties. The joint properties are divided into three aspects: orientation shape, shape complexity, and joint length.

Orientation shape is the direction where the unique shape of joints is created. Joints 1 and 2 have the orientation shape on the xy-plane while Joint 3 and 4 have the main joint shapes on the xz-plane. Despite not being covered in this study, this factor affects gravity loads and when wood properties of tangential (y-direction) and radial (z-direction) to wood grain have different values.

The number of formed contact surfaces between timber members determines the complexity of joint shapes. The joint surface in Joints 2, 3, and 4 have five surfaces, while Joint 1 has seven surfaces. The surface direction angle in the contact surface is another element of form complexity. Joints 1, 2, and 3 have diagonal surfaces besides horizontal and vertical contact surfaces. Meanwhile, Joint 4 has only horizontal and vertical contact surfaces. The diagonal surface creates more impacts on the friction force which increases the joint strength. The analysis of the joint is seen on Figure 4.

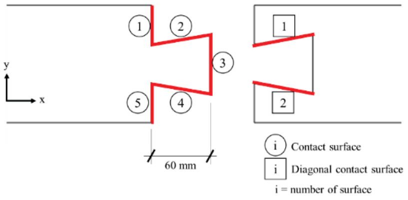


***Figure 4:** Joint properties of Joint 2*

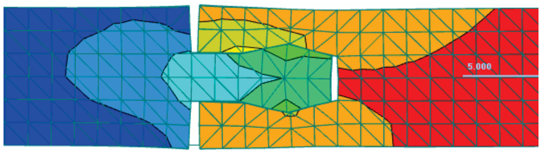
According to design setup, the length of the joints in Points A-B and C-D are the same, but the length of B-C depends on the length requirement of the joints. Carpentry joints are made by crafting the edge of the timber members into male and female shape. This process is related to material waste because crafting the joint reduces the beam length to the specified size of the joint. The length of Point B-C in Joint 1 must be the same as the beam width (120 mm), while Joint 2 is only half of the beam (60 mm). For Joint 3 and 4, the length of Point B-C is originally twice of the beam width (240 mm). However, only on Joint 4, the length of Point B-C is reduced to 120 mm. Thus, in terms of material waste, Joint 2 has less waste than Joints 1, 3, and 4.

***Table 2:** Joint properties*

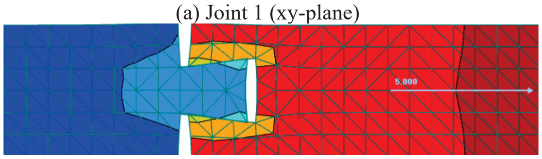
Criteria	**Joint 1**	**Joint 2**	**Joint 3**	**Joint 4**
Shape orientation	x-y	x-y	x-z	x-z
Complexity				
Total contact surface	7	5	5	5
Diagonal surface	4	2	2	0
Joint's length (mm)	120	60	240	120

3.2 DEFORMATION

Deformation on joints under tension and compression load are analyzed using global displacement. Joint 1 exhibits the smallest displacement (0.7 mm) of the four joints under tension load, and the maximum displacement on Joint 2 is close to Joint 1 (0.8 mm). The largest displacement occurred in Joint 4 (5.0 mm), while Joint 3 has a max displacement of 1.9 mm (Figure 7a)

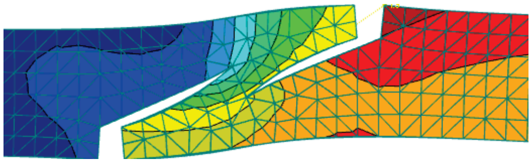


(a) Joint 1 (xy-plane)

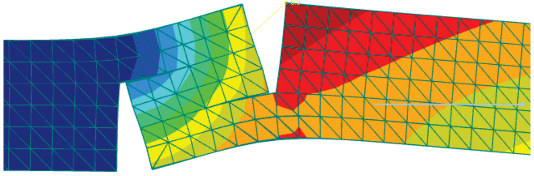


(b) Joint 2 (xy-plane)

***Figure 5-1:** Deformation shape on joints under tension load*



(c) Joint 3 (xz-plane)

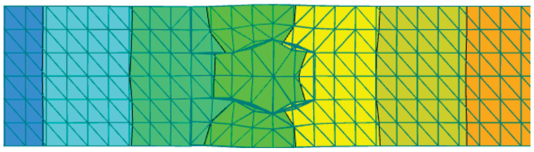


(d) Joint 4 (xz-plane)

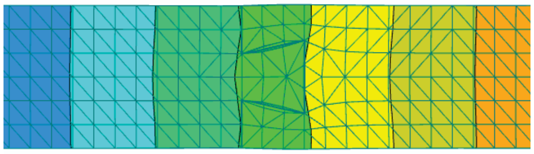
Figure 5-2: *Deformation shape on joints under tension load*

The maximum displacements on Joints 1 and 2 are located at point D, which indicates the higher probability of bearing or shear failure. However, the maximum displacements on Joints 3 and 4 are located at point C, which indicates a high probability of brittle failure such as tear-out failure (Figure 5).

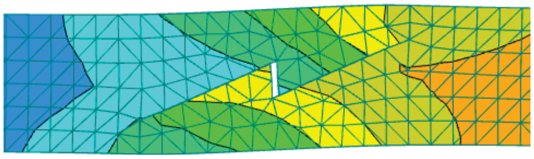
The joints under compression load exhibit unexpected results. Joints 1, 2, and 4 have the same maximum displacement (0.3 mm), as opposed to Joint 3 which has larger displacement (0.4 mm) (Figure 7b). From the deformation shape in Figure 6c, it can be seen that Point B-C on the Joint 3 is bending and shows a gap on the middle of the joint. Meanwhile, the rest of the joints look the same as the initial shape.



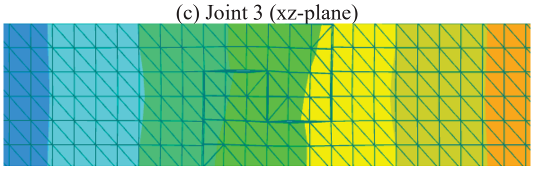
(a) Joint 1 (xy-plane)



(b) Joint 2 (xy-plane)



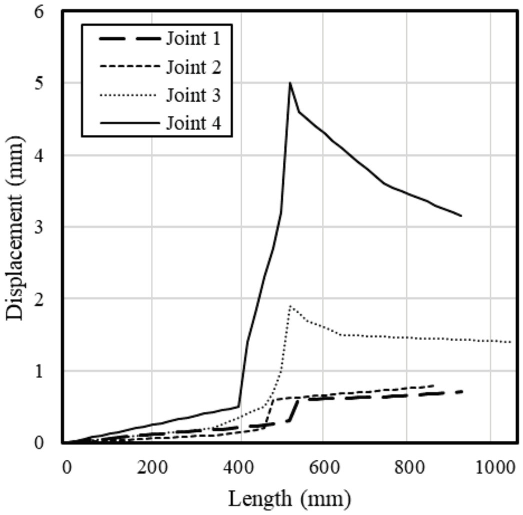
(c) Joint 3 (xz-plane)



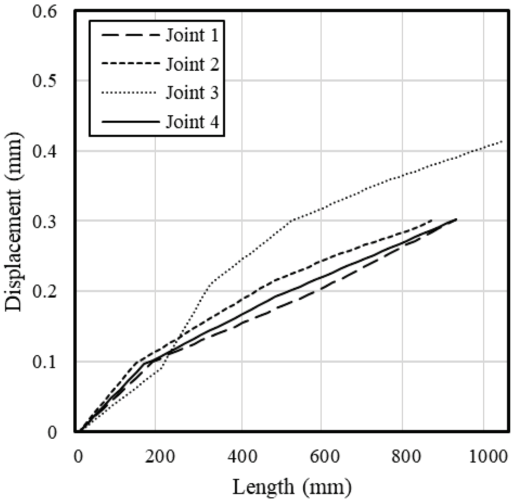
(d) Joint 4 (xz-plane)

Figure 6: *Deformation shape on the joints under compression load*

From the global displacement, it can be concluded that all joints have smaller deformation under compression load than tension load, which alludes to the fact that wood has a higher compressive strength than tension strength. Meanwhile, the joint shape is the most important parameter for a timber joint's structural response under tension load. Yet, there are not many studies on the relationship between joint performance and its shape.



(a)



(b)

Figure 7: *Displacement on beam from Point A-D in (a) tension force and (b) compressive force.*

4 CONCLUSIONS

In this study, the four joints of traditional joints have been investigated using finite element analysis. Deformation capacity was obtained from simulation results using Dlubal RFEM software. For modeling and simulation, several setups were adjusted to the capability of the software.

Based on simulation, Joint 1 and 2 have the smallest displacement compared to the other joints under tension load. It appears that the larger displacement occurred in Joint 4 under tension load while under compression load the larger displacement occurred in Joint 3. Meanwhile, under compression load, Joint 1, 2, and 4 have the same displacement.

Deformation is correlated to stress distribution on the joints. Large displacement has a higher possibility of member failure. Joint failure can be examined by validating the maximum stress on stress distribution to the strength factor (C_f) equation. Thus, the failure occurrence can be checked when the result is above C_f. The inadequate beam size in comparison to the assigned loads is one potential cause of joint failure. Thus, nonlinear analysis is expected in future studies. If the deformation and stress distribution result is connected to the joint properties, a joint with shorter joint length has better compromise than other joints. However, these results still need to be validated for further simulation and experiment.

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