GENERATION AND OPTIMIZATION METHOD FOR THE ASSEMBLY ORDER OF MEMBERS IN WOOD STRUCTURE

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Abstract: To evaluate how the detail design of the building construction system influences the outputs of the system such as the construction steps and the construction period, it is necessary to know the order in which building members are assembled. This paper presents a method for generating and optimizing the assembly order of building members based on an information about the characteristics of the building construction system. This generation and optimization system are composed of three modules, which are an input module using CAD, knowledge-based system (KBS) module for generation of the assembly order of members and its optimization module using Genetic Algorithms (GA).

Keywords: building construction system, assembly order, CAD, knowledge-based system, Genetic Algorithms, wood structure

1 INTRODUCTION

To evaluate how the detail design of the building construction system influences the outputs of the system such as the construction steps and the construction period, it is first necessary to know the order in which building members are assembled. However, evaluating a construction method from a production aspect currently falls remarkably behind the evaluation from functional aspects, and this is especially true for systems that deal with the estimation and the evaluation process of building construction.

Although many types of knowledge-based systems have been developed for use in the fields of architectural or building engineering, most of them deal with construction planning and management; e.g. Cherneff [1], Hendrickson [2], Navinchandra [3]. Few studies have been concerned with the creation of knowledge-based systems for use in evaluating detail design issues related to building construction systems; e.g. Coyne [4], Radford [5] especiall in the field of wood construction.

The objective of this paper is to develop a knowledge-based generation and optimization system that produces the information such as an assemblability or an assembly order of some wood structures.11To generate the possible assembly orders, detailed design information about the joints and connections of building elements is used. This design information initially consists of a detailed description of each individual building member. The information, henceforth referred to as the description formula, is introduced to a computer that processes it using a KBS. Based on this description formula, the system generates possible assembly orders for the building members or components using backtrack function of Prolog. To narrow the assembly order to one, this system then optimize the order based on some criteria using Genetic Algorithms.

This generation and optimization system are composed of three modules, which are an input module using CAD, knowledge-based system (KBS) module for generation of the assembly order of members and its optimization module using Genetic Algorithms (GA). This system is later applied to model wood structure, and the assembly order generated and optimized was verified to be accurate, thereby proving the usefulness of the system in evaluating new wood structure.

2 GENERATION PRINCIPLES

2.1 Determinants of the assembly order of elements

The assembly order of elements in wooden housing construction is mainly determined by the following two factors. One is the design of building system such as physical considerations about the positions of building elements relative to one another, or the jointing method employed, etc. and the other is the practical factor to construct them at the site such as space or on-site resource allocation like the number of employable workers, machines and so on. Although the latter factors usually influence the actual assembly order at the site, they will not be addressed here. In this paper, the author focused on the former factor as the dominant one to determine the assembly order of elements, since the primary objective of the system discussed here is to evaluate how the assembly sequence changes for the different design of building construction systems.

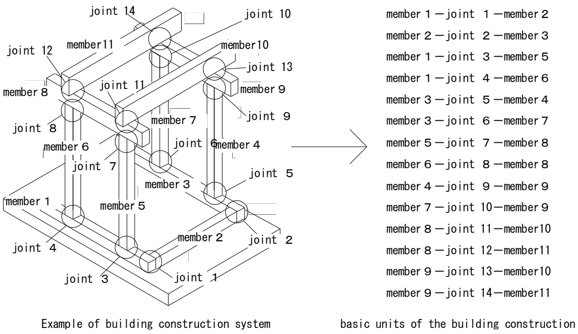


Figure 1. Example of basic units of building construction system.

2.2 Generation principles

In this study, following principles were employed to generate the assembly order of elements in wooden construction. That is, as shown in Figure 1, any wooden construction system can be recognized as a total structure composed of "basic unit" which is defined by two elements and one joint. The assembly order between these two elements is basically determined by their unique spatial relationship and jointing method. So if the rules between the characteristics of the building construction systems and the assembly order are clarified, it might become possible to determine the assembly order of elements belong to the same basic unit based on them. And if the assembly order can be determined in any given basic unit, the assembly order of the total structure will be obtained by using rule of syllogism shown in equation (1).

$$\textbf{prior (i, j)} \wedge \textbf{prior (j, k)} \Rightarrow \textbf{prior (i, k)} \qquad (1)$$

where:

prior (i, j) means element "i" must be assembled prior to element "j".

For example, in Figure 1, if **prior (member1, member6)**, **prior (member6, member8)** and **prior (member8, member11)** are respectively true, then the assembly priority should be given in the following order consequently according to the rule of syllogism between each these two members.

member1→ member6→ member8→ member11

Conversely, if any direct relations or any rule of syllogism are not found between each any two elements, it can be said that no assembly priority exists between them judging from the rules between the assembly order and the characteristics of the building construction systems.

3 THE DESCRIPTION FORMULA

3.1 Recognition of a building construction system

To create a useful knowledge-based system for generating assembly order, it is first necessary to describe each element of a building. The use of a description formula provides the system with the information necessary to recognize the construction system as a whole based on the characteristics of its elements or component parts. Although previous studies have attempted to describe the components of a construction system, a slightly different approach is employed in this paper. As mentioned before, the basic unit of the construction system is defined as a single structure composed of two elements and one joint. According to this definition, every wooden structure in the building construction system can be defined as an assembly of these basic units. For example, although there are eleven members and fourteen joints in the structure shown in Figure 1, it can be divided into fourteen basic units such as the connection composed of "member 1", "member 2" and "joint 1" or the connection composed of "member 2", "member 3" and "joint 2". Based on this format, any given wooden structure can be represented as follows:

$$\boldsymbol{Y} = \Sigma(\boldsymbol{X}) \qquad (2)$$

where:

$\boldsymbol{Y}$ = Overall description of the building construction system

$\boldsymbol{X}$ = Description of the basic unit of the building construction system

3.2 Applying a list structure to the description formula

As detailed in the previous chapter, there are numerous characteristics used to describe a building construction system. However, the hierarchical distribution of the characteristics makes it possible to describe the construction system using a list structure that treats the member attributes as variables. Based on this method, the basic unit (***X*** in equations (2) and (3)) of a building construction system can be represented as follows:

$$\boldsymbol{X = (a, (b, c, d))} \qquad (3)$$

where:

$\boldsymbol{a \in A, b \in B, c \in C, d \in D}$

A = characteristics of elements of “member i”

B = characteristics of elements of “member j”

C = characteristics of joint of between “member i” and “member j”

D = characteristics of connections between “member i” and “member j”

The list structure of the description formula is also suitable when using artificial programming languages such as Lisp or Prolog to process the data.

3.3 Survey on the characteristics of building construction system

In order to derive criteria for judging the assembly order of wooden members, 2,355 connections in three common types of building construction systems for wooden houses currently in use in Japan were surveyed. The construction types surveyed were: traditional post-and-beam, light-framed platform, and industrialized panel construction. First, the assembly priorities were examined for each of the 2,355 connections. A portion of the information was drawn from the results of building site surveys conducted within the last four years, and specialists in the field were interviewed as well. Next, for the same connections, dominant factors to determine the assembly order were extracted and rules between the assembly order and the characteristics of building construction system were generalized.

3.4 Characteristics of building construction system

The basic units of a building construction system have characteristics which can be grouped into three general categories: elements, connections, and joints. Based on the surveys described above, the characteristics that dictate the order of assembly for members in wooden construction systems are as follows.

Elements

1. Function (structural/non-structural, for positioning/not-for-positioning)
2. Direction (vertical, horizontal, diagonal)

Joints

1. Jointing method (lapped, inserted, penetrated, butted)
2. Direction of assembly (the direction from which each member should be assembled)

Connections

1. Spatial relationship (over/under, inside/outside)
2. Connection surface (side-to-side, side-to-end, end-to-end)

4 GENERATION AND OPTIMIZATION SYSTEM OF AN ASSEMBLY ORDER

4.1 Input data and inferred data

Input data are fundamentally composed only of the data which can be easily collected from design drawing even if there is no technical knowledge. It is intended that this system can work in concert with

CAD platform so as to be used by designers or developers of wood construction, data required to generate the assembly order are created using CAD. In this system, AutoCAD is employed as a platform to draw a structure and to input data. Dimension and coordinate value of members are input when they are drawn by CAD, while function or accuracy of position of each member and data of connected member such as jointing or fastening method are input using attribute input function of AutoCAD. Based on these minimum input data, the system acquires various characteristic data of building construction necessary for the judgment of assembly sequence by the inference. They are, for example, direction or shape of members, characteristics of connections such as spatial relation between each member.

4.2 Judging rules to determine the assembly order

Based on the results of the survey, sixteen separate judging rules were deduced. In these rules, knowledge about the relationship between each of the discrete elements - such as type of joint or spatial relationship and the connections to other unit - is obtained through inference based on characteristic data of the building construction system.

These assembly rules to set priority to either member of basic unit are basically categorized into four groups as below:

(1) Rules related to positional and directional adjustment.

If the relationship of positional and directional adjustment exists between two members in the same basic unit, then the member which is positionally or directionally adjusted by the other has a priority in assembly order. For example, to adjust the horizontality of sleeper, a floor post, although it supports a sleeper, is usually assembled after a sleeper (see Figure 2 (a), (b)).

(2) Rules related to structural supporting.

If one member supports the other, then the supporting member is basically assembled first. Judgement on whether some basic unit comes under this rule should be done based on the function, the spatial relationship of members or the joint type. In architectural structure, it is principally true that if one member locates on the other, then lower member supports upper one. But, as the ceiling structure, upper member sometimes supports lower one. So it is very important to judge correctly which member supports the other considering the second or third connections of that basic unit (see Figure 2 (c)).

(3) Rules related to hiding.

If one member hides the other by being assembled to it, then the hidden member is basically

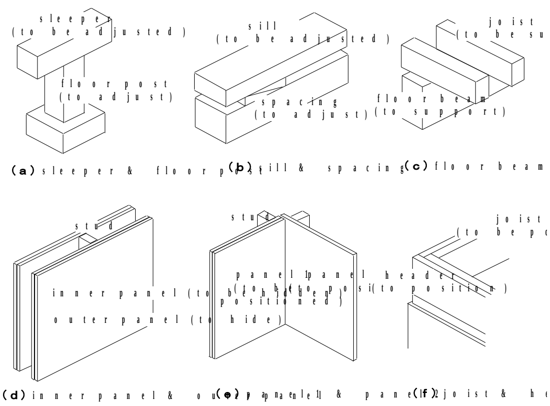


Figure 2. Examples of assembly rules.

assembled first. This rule is basically applied for those connections that are not in a support-be supported relation. Usually, hidden members are those which locate inner position of the other and they are sheet shaped respectively (see Figure 2 (d)).

(4) Rules related to positioning.

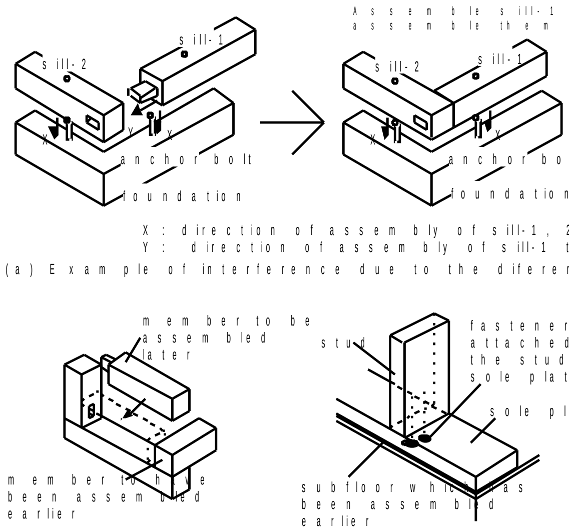
When each two members are supported by another member(s) and cannot be applied any rules above, they come under this rule if one member has a function to guide the position of the other. The member which has this function is usually assembled first (see Figure 2 (e), (f)).

Most basic units of wooden housing construction can be applied any of rules above. If no rules can be applied, it means there exists no priority between two members. Meanwhile, if plural rules can be applied to some basic unit, then the assembly order should be determined by the rule which has the top priority (Rules above are sorted in order of priority).

4.3 Methodology to avoid interference and judgement of assemblability

In wooden housing construction, it occasionally happens that a third member interferes when one member is being jointed to another. This kind of interference between elements typically occurs in three cases as follows:

(1)The case in which a member has plural joints that are to be assembled in different directions at the same time. This is often the case with the traditional Japanese wooden structure. For example, as shown in Figure 3 (a), if two sills should be connected to one another at the corners using a penetrated or inserted joint and must be subsequently connected as a single unit to the building foundation with anchor bolts, then the anchor bolts will interfere the assembly of sills. As such, the sills must first be assembled into the L-shaped single component which may then be fitted to the foundation with anchor bolts. Generally,



(a) Example of interference due to the diferer

(b) Example of interference due to the third member which has already assembled.

(c) Example of interference due to the fas

this type of interference can be avoidable if the direction of assembly for each of the unit's components is unified to a single direction.

(2) The case in which a third member that has already been assembled interferes when one member is being jointed to another. This is similar to the above case, but the different point is that the member to be jointed later does not have any connection with the third one. Figure 3 (b) shows an example of this case.

(3) The case in which fasteners cannot be attached to the joint due to a third member's interference. This is often the case with the light-framed or wood framed platform construction. For example, as shown in Figure 3 (c), the plywood subfloor interferes the sole plate to be nailed to the stud. Generally, this type of interference can be avoidable by conducting a field assembly.

As these examples demonstrate, it is important to specify field assembly of units that will experience interference in these fashions. The judgement of necessity of field assembly to avoid interference is made by the inference mechanism based on the data about the direction and the type of joint which are attributes of the characteristics of the building

Figure 3. Typical examples of interferences between elements.

construction system. Though field assembly is carried out, when an interference is inevitable, those structures are to be judged as impossible structures to assemble.

4.4 Algorithm for the generation of assembly order

Based on the description formula of building construction system and the assembly rules described above, the knowledge-based generation system for the assembly order of elements was developed. The following algorithm was then used to establish an order of assembly for the building system as a whole:

1. Extract the basic unit from the database in which total structure of building is described according to the description formula.

2. Read the list-structured data about the characteristics of its basic unit.

3. Judge the type of connection between two members based on the knowledge base which contains eighteen rules to judge the structural or spatial relations between them.

4. Apply knowledge-based rules about assembly order to each unit. Based on the judgement above, knowledge-based rules about assembly order are next applied to each basic unit to judge which member should be assembled first. This knowledge base about assembly order has sixteen rules.

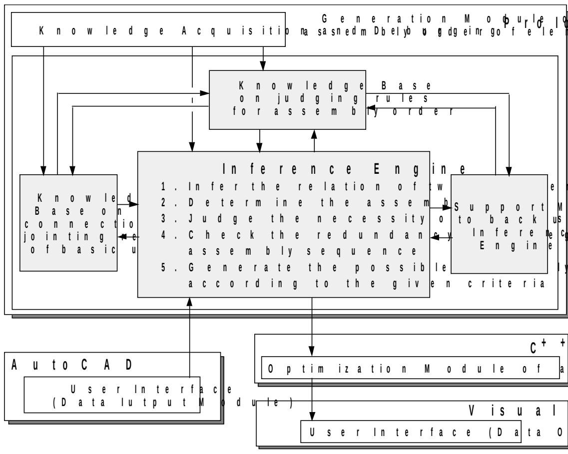
5. Generate an assembly order for each member pairs and write the result into the temporary output list.

6. Check the interference between members.

This can be realized by using the data about the direction of assembly at the joints and the position of related members.

7. Repeat above routine and extract the members to be assembled in field.

8. Check the redundancy in the assembly sequence and, if necessary, eliminate it. As this generation system principally produces the assembly order about each basic unit, there are some redundant sequences. To eliminate these redundancies, check the sequence of assembly order and if it is found out, take away its



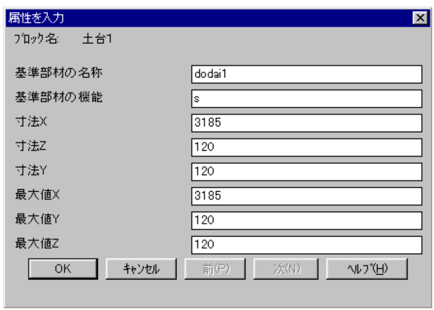
unit from the temporary output list.

9. Conduct a topological ordering of members based on the assembly order and integrate them into continuous assembly sequence.

10. Put out the final results.

4.5 Algorithm for the optimization of assembly order

An enormous number of possible assembly orders of elements can be obtained by the generation method described above. To narrow them into the best one based on some evaluation criteria, an appropriate optimization method is required. There are a lot of op-



timization methods that can be applied to this problem, the author employed a Genetic Algorithm considering the convenience and effectiveness to get an optimum solution. The following is the outline of algorithm used to optimize an order of assembly for the building system as a whole:

(1) Traveling Salesman Problem (TSP) was adopted to formulate this problem. In this formulation, the center of gravity of each member was defined as the place to be visited and 2-dimensional traveling problem was converted into 3-dimensional traveling one.

(2) A chromosome is one set of assembly sequence by which every member of some structure is constructed. The gene in chromosome stands for each member to be assembled and its order means the assembly order of members in some structure.

(3) If the order of assembling each member contradicts the order obtained by the generation system above, that solution gets penalty.

(4) Fitness is calculated for each chromosome as a sum of total traveling distance and penalty.

(5) In calculation of GA, uniform crossover was adopted and the crossover rate and the mutation rate were set as 1.0 and 0.05 respectively.

4.6 Structure of the developed system

The structure and modules of the system employed by the author to generate and to optimize the assembly sequence for building members is shown in Figure 4. This system is constructed using AutoCAD, Prolog, C^{++} and Visual Basic and mainly composed of four modules as follows:

(1) Data input module (Figure 5): As discussed in previous section, input data necessary to generate the assembly order are created at the same time when wood structure is designed and drawn by AutoCAD system.

(2) Generation module: This is the module to generate assembly order of members in structure using the input data created by CAD system. This module is constructed by Prolog and mainly composed of four sub-modules as follows. In inference engine, the logical flow discussed in the previous section is implemented. Support sub-module is composed of

Figure 4. Structure of developed system.

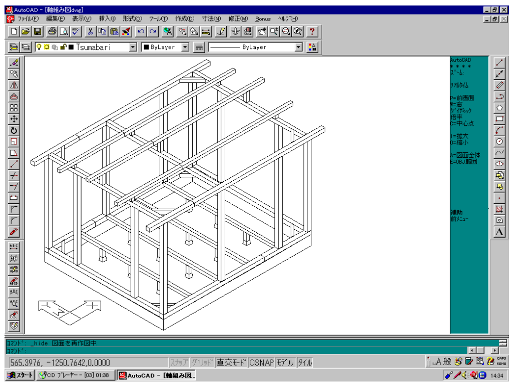


Figure 5. Data input on CAD platform.

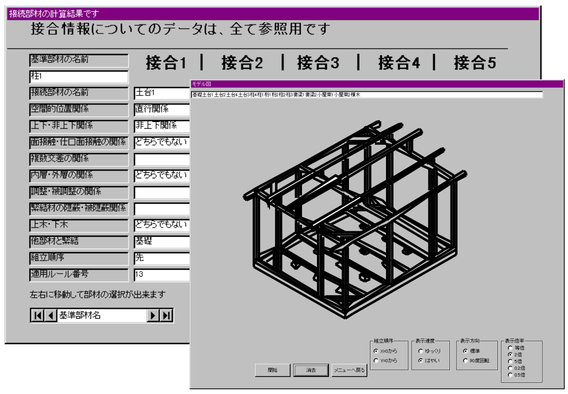


Figure 6. Data output display by Visual Basic.

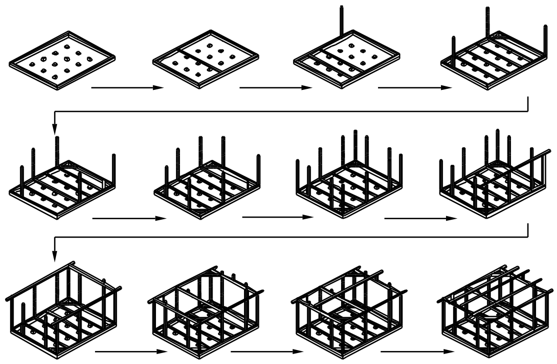
various predicates such as built-in or user-defined ones to support inference engine and knowledge base. Knowledge base on judging rules for the connection of elements is the sub-module that contains knowledge necessary to judge the connection of elements, the assemblability and the interference between elements. Sixteen judging rules for assembly order are stored in knowledge base on judging rules for assembly order. Using the results inferred from the knowledge above, inference engine examines the rule that matches with the present basic unit.

(3) Optimization module: This module constructed by C++ is for optimization of assembly order of members in structure. Information such as the coordinate value of center of gravity of each member and possible assembly order necessary to optimize the order using GA is transferred from the generation module.

(4) Data output module: The output module of generated and optimized result is an important interface with the user and is constructed using Visual Basic to make it object-oriented just shown in Figure 6. The final assembly sequence of each member is visualized by the animation.

5 EVALUATION OF SYSTEM PERFORMANCE

The performance of the generation and optimization system discussed in this paper was assessed by applying this system to the construction process of a wooden structure that is a traditional Japanese post-and-beam construction system. This type of structure system mainly consists of square section lumbers and traditional type of joints to connect. This construction system shares the characteristics of those described earlier in this paper, and it was therefore possible to introduce characteristic data about the system into the knowledge base using the description formula explained in Chapter 3. Generation module of this system can generate as many solutions as possible if certain criteria are given. By comparing these results with the survey conducted at the construction site, it was proved that the assembly order had been properly generated by this module. Based on this generated assembly order, construction sequence of this model structure was optimized as shown in Figure 7. Sills are assembled first followed by floor beams or columns. This optimized assembly order complies with every judging rule described in previous section. This is proved to be the possible optimized assembly



order in terms of a total distance to carry members to construct this structure. Therefore, this system is proved to be useful as an optimization system of assembly order of wood structures. Moreover this system has a function to generate the appropriate assembly order of members reflecting the change of detail design such as joint or fastening type and method. Using another type of model structure, this function was also verified to be accurate to use this system as a tool for design evaluation for wood structures.

6 CONCLUSIONS

The knowledge-based generation and optimization system introduced and discussed here has been verified to accurately generate and optimize an assembly order of each member based on a given set of inputs that describe the individual building members used in a given building construction system for wooden structures. This is a generation and optimization system by which the relationship between macroscopic productional aspects such as construction procedures or construction period and the characteristics of wood construction systems can

Figure 7. Optimized assembly sequence of model wood structure.

be evaluated. Especially, this system was developed carefully to cover the following points;

(1) Input data of this system have been composed only of non-technical information so that the architectural engineers who are not so familiar with wood structures can evaluate the building construction systems easily using CAD.

(2)CAD platform to input the data provides simultaneous evaluation as design characteristics change.

(3) The system can generate the assembly order of all elements judging the necessity of field assembly for three typical cases in wood construction.

(4) The system can optimize the assembly sequence according to the given criteria using GA.

Given sufficient and accurate information about a construction system's components and elements, and as long as such building construction systems are based on the characteristics of existing systems, this system is expected to work effectively. In addition, it is an interesting problem to show the solution for the inverse problem of this system to consider optimum detail for any assembly sequence.

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