SYSTEM FOR DERIVING DIVERSE SOLUTIONS VIA A MODIFICATION METHOD FOR EMERGENT DESIGN

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Abstract

This paper describes efficiency of introducing a modification method that we proposed into a system for deriving diverse solutions. Moreover, a guideline of system parameter is proposed so as to utilize the effect that the modification method brings. Based on the concept of emergent design, the system for deriving diverse solutions can derive diverse and novel design solutions. However, most of the solution candidates that have novel shapes are inapplicable as solutions because of their low mechanical characteristics. For this reason, we have proposed a modification method by increasing and decreasing elements to reinforce the solution candidates. Setting local rules for modification, the method can reinforce the solution candidates without loss of their diversity. Though, the effect of the modification method is not clear, and the guideline of system parameter is not provided. Therefore, we make the effect of the modification method clear by comparing the solutions derived by the system with and without the modification method. Moreover, we provide a parameter guideline of system to effectively utilize the modification method.

Keywords: Diverse solutions, Emergent design, Early design phases, Bio-inspired design

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1 INTRODUCTION

The design process can be roughly divided into two: early and late process. In the early process, which is composed of conceptual and basic design, diverse ideas of design must be obtained from global solution search because the design objective and conditions are unclear. It is difficult to apply the conventional engineering design methodology from the necessity of the setting of the objective function in the early design process. Therefore, in a previous study, the emergent design, a methodology which is applicable from the early design process, has been proposed (Tsukada and Matsuoka, 1997). Emergent design has interactivity between bottom-up and top-down processes, whereas optimum design is a top-down process only. Hence, emergent design is applicable to design problems requiring a global solution search and derivation of diverse solutions. Previously, we have proposed a system for deriving diverse solutions based on the emergent design (Inoue and Matsuoka, 2001). In the case of car body frame design, the system derived diverse solutions and some showed a decrease in weight by more than 13% compared to conventional solutions with no loss of rigidity (Sato, et al., 2011). However, most of the generated solution candidates with novel characteristics are inapplicable as solutions because they do not satisfy the evaluation standard. If solution candidates that do not satisfy the evaluation standard can be modified to become solutions, then solution diversity will increase.

To improve diversity, we have proposed a modification method, which increases or decreases elements to reinforce solution candidates obtained in the bottom-up process (Kito, et al., 2011). In a previous study of cantilevers design, we applied the modification method to solution candidates that did not satisfy the evaluation standard of the mechanical characteristics. As a result, 89% of the solution candidates satisfied the evaluation standard, and increased solution diversity. However, we have not examined the effect of the modification method or provided a guideline for the system's parameters. Herein we report the impact of the modification method by comparing solutions derived by the system with the modification method (proposed system) and the system without the modification method (conventional system) in terms of diversity and mechanical characteristic of solutions. Moreover, we make a proposal of a guideline for its system parameter in order to effectively utilize the modification method.

2 SYSTEM FOR DERIVING DIVERSE SOLUTIONS AND THE MODIFICATION METHOD

2.1 Concept of emergence and an emergent design

There are numerous types of design methods for each process. As the design process moves from the early to late process, the design objectives and conditions gradually become clear. Additionally, the preferred design method changes as the design in the early and late processes has different characteristics. A framework, which consists of "emergent design" and "optimum design", systematizes these design methods (Matsuoka, 2010). Emergent design is a methodology based on the concept of emergence, which is a creation process in life systems (Kitamura, 1996), to derive diverse design solutions in the early process of design where objectives and conditions are unclear. Emergent design has two processes: the bottom-up process and the top-down process. The bottom-up process of emergent design creates design solution candidates through the interaction between structural elements. Normally, it is difficult to establish design conditions in the early design process. Hence, a wide-ranging solution search is necessary to generate new and diverse design solution candidates using a general evaluation standard. In the top-down process, structural elements of the design solution candidates generated in the bottom-up process are regulated to produce a design solution. Using the design objectives and constraint conditions established in the top-down process and numerous iterations to refine the details, the design solution candidates obtained in bottom-up process are optimized. The optimization is performed with minimal modifications of the relationship between elements as possible. In this manner emergent design produces new design solutions while maintaining the diversity of the solutions from the bottom-up process.

2.2 A system for deriving diverse solutions

As a design method for the early design process, we have proposed a system for deriving diverse solutions that consists of two emergence processes: bottom-up and top-down processes. In the bottom-up process, diverse solution candidates meeting the low standard set by the designer are derived, while the top-down process satisfies the constraint conditions, and optimizes candidates that satisfy the constraints. This system derives diverse design solutions by going through these two processes.

The bottom-up process automatically generates diverse design solution candidates by Cellular Automata (CA) (Delorme, 1999., Kato, 1998). In CA, the states of cells in the lattice are updated according to a local rule. In the system for deriving diverse solutions, induction and apical dominance, which are generation characteristics originating in biodiversity as state transition rules in CA, are introduced. Induction is a generation characteristic, which changes a neighboring cell to a specific character, and influences the activation of cell proliferation by the action of a cell on neighboring cells (Figure 1). Thus, a certain element provides a stimulus, which influences the generation of a neighboring element. This can be modeled as the neighboring information vector, which is expressed as Eq. (1).

$$\boldsymbol{v_n} = \sum_{i=1}^{26} b_i w_i \mathbf{e_i} \tag{1}$$

Where n is the number of maximum surrounding elements. i is the surrounding element number. b_i indicates the existence or non-existence of an element (1 or 0, respectively), and w_i is the size of the induction action recorded in a one-dimensional arrangement created when each solution candidate is generated and has a value ranging from 0 to 8. $\mathbf{e}_i$ is the unit vector of the direction to the object element.

Apical dominance is a generation characteristic, which predominately manages the ontogeny, also referred to as the apex, influences the morphogenesis, and controls cell proliferation (Figure 2). This predominant action increases when the apex distance is short. For example, if a plant has the apex in the position shown in Figure 2, then leaf growth is controlled from the apex. Consequently, light can be efficiently received. The positional information vector, which is influenced by relationship of the apex to the object element, can be modeled from the aforementioned character as Eq. (2).

$$\boldsymbol{v_p} = (d_{\max} - d)\mathbf{e_d} \tag{2}$$

Where $d_{\max}$ is the distance between the apex and the most distant cell from the apex. d is the distance between the apex and the object element, and $\mathbf{e}_d$ is the unit vector of the direction to the object element.

By uniting these two vectors, form operating parameter can be defined as k, and the input vector of CA becomes Eq. (3).

$$\boldsymbol{v_{in}} = k\boldsymbol{v_n} + (1-k)\boldsymbol{v_p} \tag{3}$$

If k has a value near unity, then induction tends to strongly influence k. In contrast, k near 0 is strongly influenced by apical dominance, which tends to generate a rhabdoid form or board form. The input parameters in the bottom-up process are the apex position, form operating parameter k, shape generation space, element size, initial element, and evaluation item. The apex position becomes the center of the action for apical dominance, and the form generation space is a space allowing CA to be generated. The element size is the pixel size, which composes solution candidate, and reducing the element size causes the output to be in a detailed form. The initial element position is where the shape generation of CA is initiated. Thus, it is possible for an element to have two or more components and for the part where the element definitely exists in the design to be assumed as the initial element. The generation number is the frequency that the form is updated. Furthermore, the bottom-up process must satisfy evaluation items.

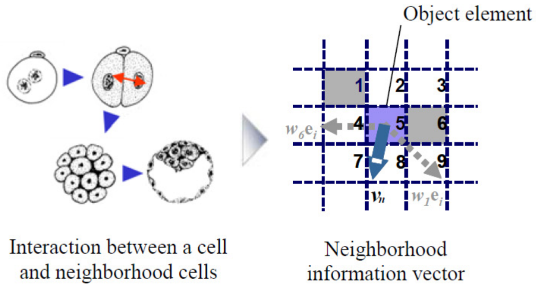

Figure 1. Induction

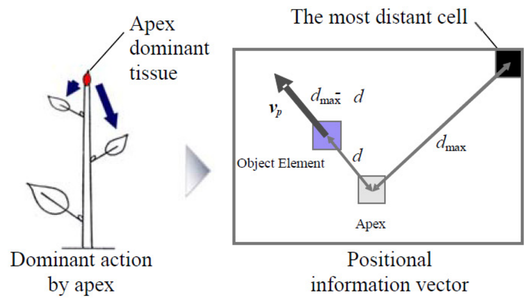

Figure 2. Apical dominance

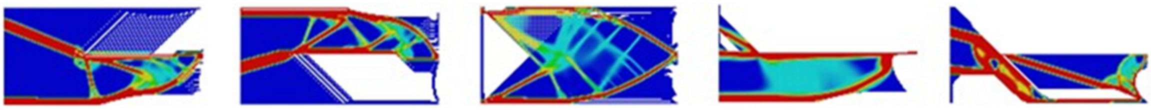

Figure 3. Examples of solutions derived by the system for deriving diverse solutions

In the top-down process, design conditions such as the constraint and loading conditions are set, and diverse solution candidates obtained in the bottom-up process are optimized by the density method, a type of topology optimization (Figure 3). In the density method, form characteristics of solution candidates are reflected to final solutions because solution candidates are optimized in where elements that compose solution candidates exist. However, for the same reason, areas with low strength cannot be reinforced. Thus, most solution candidates are not applicable as solutions because they do not satisfy the evaluation standard for the mechanical characteristics. Hence, it is inferred that if these solution candidates could be modified to applicable solutions, then the diversity of solutions would increase.

2.3 Modification method by increasing and decreasing elements

For the reason described above, we proposed a modification method where elements are increased and decreased according to local rules, which use the stress distribution as an index. The modification method does not have an objective function. The equivalent stresses of the surface element and its neighboring elements determine whether an element is increased or decreased. Solution candidates modified by these altered elements are reinforced while maintaining the characteristics of the figure before optimized by the density method. This method enables the system to derive diverse solution candidates while maintaining diversity. Figure 4 shows the evaluation process of the modification. First, stress on a design solution candidate is calculated via the finite element method (FEM) (Figure 4(a)), and then stress evaluations are conducted on surface elements that compose the design solution candidate (Figure 4(b)). During the evaluation, the elements are increased or decreased by comparing the stress σ_i in the object element and the feasible stress σ_c. If the stress σ_i is lower than the stress σ_c, the object element is deleted (Figure 4(b-1)). However, if the stress σ_i is higher than the stress σ_c and the stress at neighborhood elements σ_j, a new element is added on the opposite side of the neighborhood element (Figure 4(b-2)). The elements are increased or decreased until they reach the trial number, which the designer sets (Figure 4(c)). Each design solution candidate derived in the bottom-up process is modified using this method to derive diverse design solutions that satisfy the feasible stress.

3 DERIVING SOLUTIONS WITH THE MODIFICATION METHOD AND WITHOUT THE MODIFICATION METHOD

s described above, the modification method increases the diversity and improves the mechanical characteristics of the solutions. However, the relationships of the system parameter, form operating parameter *k*, the diversity of solutions, and the mechanical characteristics of solutions are not examined. Thus, the effect of the modification method remains unclear. Additionally, the guideline for the system parameter with the modification method has yet to be provided. In this chapter, we describe the process to obtain solutions for a 2D cantilever-beam using proposed system and conventional system. In the proposed system, solutions are derived via the modification method and the density method. Then we compute the efficiency to derive solutions, mechanical characteristics of solutions, and solution diversity for each system.

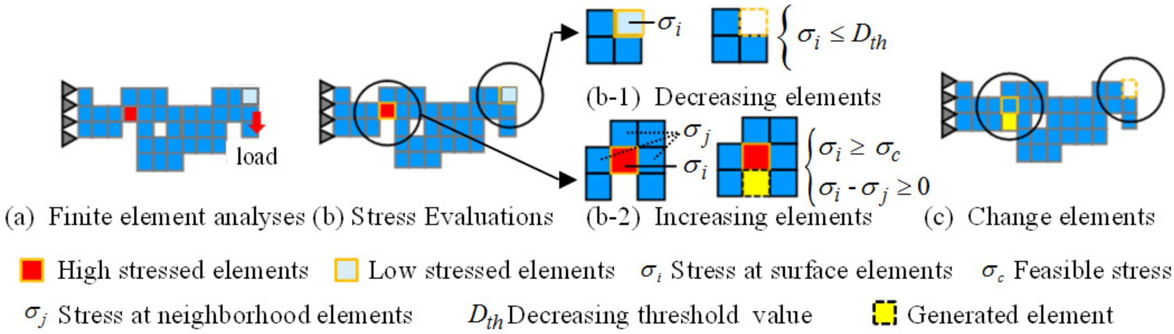

Figure 4. Evaluation process of the modification method

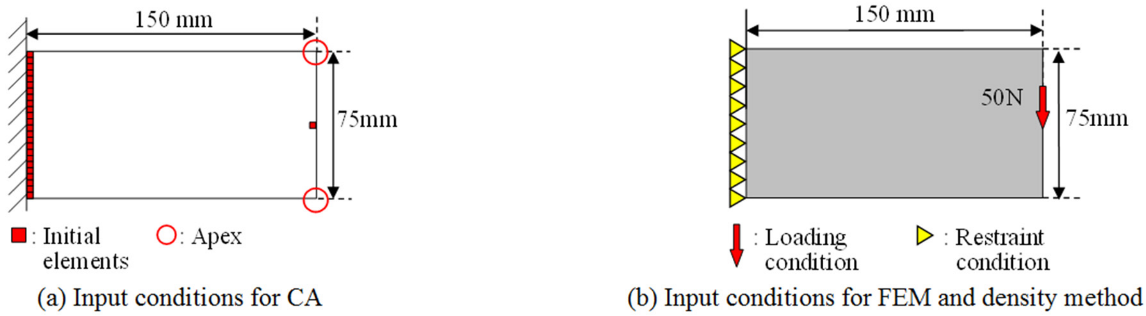

Figure 5. Input conditions

3.1 Input conditions and evaluation standards for the systems

Figure 5 (a) shows input conditions for CA. The generation space and quad element are set to 150 mm × 75 mm and 1 mm × 1 mm, respectively. The initial elements are set on the left side and at the middle point of the right side where the load is applied. Apexes are set on the upper and lower points of the right side. The form operating parameter is changed from 0.1 to 0.9 in 0.1 increments. Additionally, there are two evaluation points: the initial elements should be joined by at least one point and the minimum number of elements should be 2250 (20% of maximum number).

Figure 5 (b) shows input conditions for FEM and density method. We set steel as the material, 210 GPa as the longitudinal elastic modulus, 0.3 as the Poisson ratio, and 7.9×10^3 kg·m^3 as the density. In the modification method, the number of iterations is fixed to 100. The objective function in the density method is set to minimize the compliance, while the mass of solution candidates is constrained to maintain 20% of the maximum mass when the generation space is filled with elements.

Evaluation standards for feasible solutions and thresholds for the modification method are determined based on heuristic justification (Kito, et al., 2011). We set the maximum equivalent stress to 53MPa as evaluation standards for feasible solutions. Then, in the modification method, the feasible stress as increasing threshold is set to 30MPa and the decreasing threshold is set to 30% of the feasible stress.

3.2 Computation of diversity of the solutions

Table 2 shows the diversity of the solutions. To compute diversity, we used Matsuoka's Diversity index *D*, which is defined as Eq. (4) and Eq. (5) (Sato, et al., 2011).

$$S_{ij} = \frac{\sum_{k=1}^{m_{ij}} \delta_{ijk}}{m_{ij}}$$

$$\delta_{ijk} = \begin{cases} 1, & for\ cell[i][k] = cell[j][k] = 1 \\ 0, & for\ cell[i][k] \neq cell[j][k] = 0 \end{cases} \tag{4}$$

$$D = 1 - \frac{\sum_{k=1}^{n=1} \sum_{j=i+1}^{n=1} S_{ij}}{{}_nC_2} \tag{5}$$

This index can quantitatively represent the difference between solution candidates by the coordinates of the elements, and it ranges from 0 to 1 where 1 indicates the highest diversity.

4 COMPARISON OF SOLUTION'S CHARACTERISTICS

4.1 Comparison of diversity

Table 1 shows that the proposed system derives more diverse solutions than the conventional system regardless of the value of the form operating parameter. Additionally, the diversity in the conventional system decreases as the form operating parameter increases. The number of elements that composes a solution is large when form operating parameter has a high value.

Table 1. Diversity of the solutions

		k=0.1	k=0.2	k=0.3	k=0.4	k=0.5	k=0.6	k=0.7	k=0.8	k=0.9	All solutions	Feasible solutions
Diversity of the Solutions	Proposed System	0.589	0.682	0.709	0.718	0.770	0.694	0.634	0.581	0.700	0.723	0.681
	Conventional System	0.496	0.499	0.485	0.484	0.482	0.441	0.426	0.359	0.421	0.477	0.121

The large number of elements, which almost fills generation space, restricts free form generation in generation space. This probably results in less diversity of solutions. On the other hand, the diversity of solutions from the proposed system initially increases as the form operating parameter increases, but then decreases after reaching a maximum when the form operating parameter has a middle value.

In total, the diversity of the solutions from the proposed system reaches 0.723, while that from the conventional system reaches 0.477; according to ANOVA, this difference is statistically meaningful ($p<0.01$). Additionally, as Table 1 shows, a difference greater than 0.5 exists between the diversity of feasible solutions derived by the proposed system and the conventional system. This result indicates that novel geometric characteristics would be rejected in the conventional system solutions because these solution candidates would not meet the evaluation standard, and consequently, feasible solutions would be similar to each other.

4.2 Comparison of diversity Analysis of the characteristics via examples

Figure 6 shows examples of the solution candidates before and after applying the modification method. Figure 6 (a) and (c) are similar to each other prior to the modification, but (a) has more holes. Likewise, examples Figure 6 (b) and (d) are similar to each other prior to the modification, but (b) has more holes. After the modification, Figure 6 (a) has two thin beams extended from the upper and lower edges of the restraint side to the loading point, which are reinforced by thin vertically-lined beams. On the other hand, Figure 6 (c) has two beams, which extend from the upper and lower edges of the restraint side and near the loading point and then extend to the loading point. Meanwhile, Figure

6 (b) has two winding thin beams, which extend from the upper and lower edges of the restraint side to the loading point and are reinforced by some very thin beams like Figure 6 (a). In contrast, Figure 6 (d) has two gently curved beams from the upper and lower edges of the restraint side, which are reinforced by a clump of elements around the loading point. Although Figure 6 (e) and (f) have different coordinates, they are similar to each other prior to the modification. However, after the modification, curve beams in Figure 6 express their difference. From the results, it can be inferred that the modification method can clarify differences in topology and coordinates as well as express specific characteristics. Consequently, the modification method can increase the diversity of the solutions.

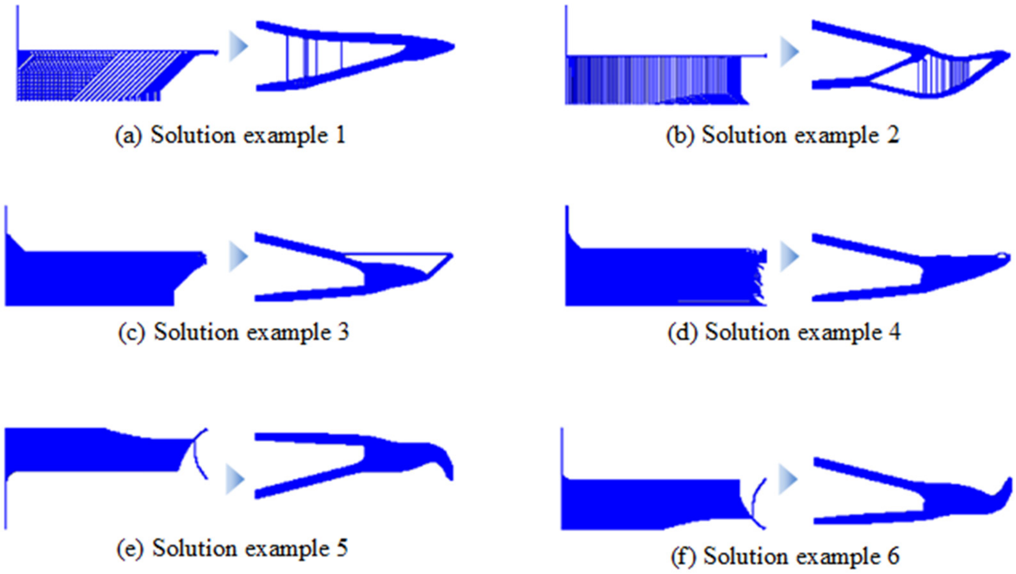

Figure 6. Examples of the solutions derived by the proposed system

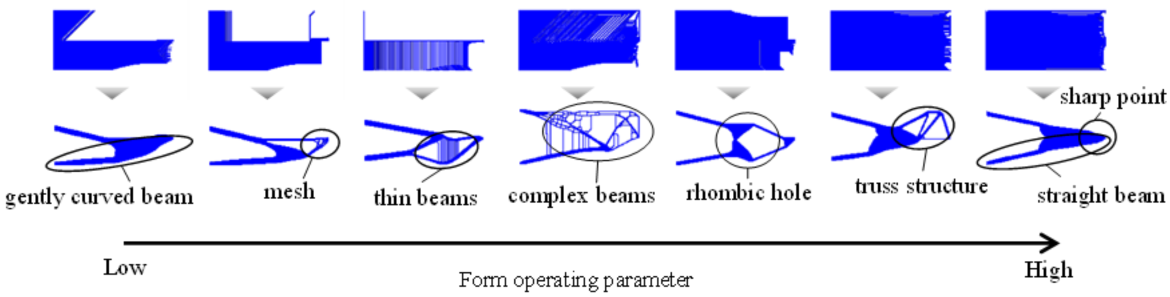

Figure 7. Form operating parameter and characteristics of the solutions

Figure 7 shows examples of solution candidates before and after applying the modification method for each form operating parameter. For low form operating parameters, elements that compose solution candidates tend to concentrate in the upper or lower half. After the modification, solution candidates curved toward the loading point are mainly derived. The curving state and spreading of beams depend on the surface shape, coordinates, and topology of the initial form. In particular, when topological differences such as the number of holes and specific characteristics (e.g., mesh structure and thin vertically-lined beams) are expressed by the modification method, solution diversity increases.

Moreover, when the form operating parameter is high, elements that compose solution candidates tend to fill the generation space, and after the modification, solution candidates with straight and vertically symmetrical beams are mainly derived. The beams of these solution candidates spread widely to the constraint side. If there are holes around the loading point, rhombic holes and truss structural holes are generated.

Besides, when the form operating parameter is a medium value, solution candidates similar to the ones described above are derived evenly. In addition, solution candidates with lots of holes similar to a mesh structure are derived. These solution candidates have intricately tangled thin beams, and express novel characteristics. To conclude, two reasons are responsible for the highly diverse solutions when the form operating parameter has a medium value. One is that many similar solutions are derived when the form operating parameter is low or high. The other is that the solutions have intricately tangled thin beams observed in mesh structures.

5 EFFECT OF THE MODIFICATION METHOD AND PROPOSED A GUIDELINE FOR SYSTEM PARAMETERS

5.1 Effect of introducing the modification method into a system for deriving diverse solutions

The aforementioned results confirm the following effects.

(1) The diversity of feasible solutions increases by reinforcing solution candidates.
(2) Solutions derived by the proposed system can be lighter and stronger than those from the conventional system by repeatedly increasing or decreasing elements in the modification method.
(3) Clarifying differences in topology, coordinates, and surface shapes as specific characteristics can increase the diversity of the solutions.

The mechanical and form characteristics of the solutions can become more diverse and novel, allowing designers to search for solutions in a larger space than previously possible.

5.2 Relationship of the system parameter with derived solutions

5.2.1 Relationship of the system parameter with mechanical characteristics of derived solutions

Figure 6 shows examples of the solution candidates before and after applying the modification method. Using cluster analysis, we divided the solution candidates by coordinating the mechanical characteristics (Figure 8). Cluster analysis can group by distance (Kaufman, 1990). The ward method is used to define the distance of solution candidates. In Figure 8, groups 3 and 4 are light solutions, while groups 4 and 5 are strong solutions with regard to equivalent stress.

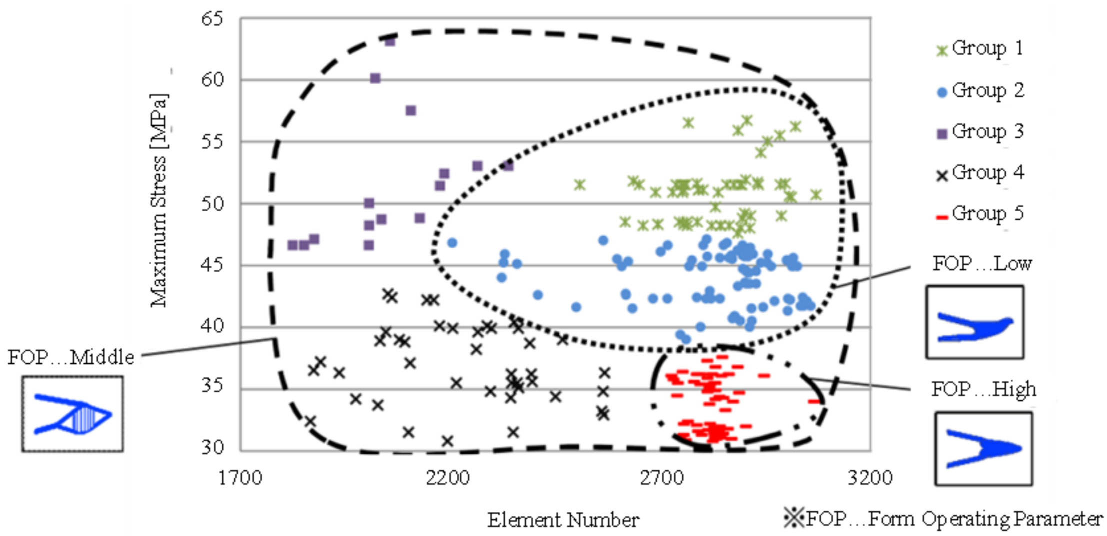

Figure 8. Form operating parameter and mechanical characteristics of derived solutions

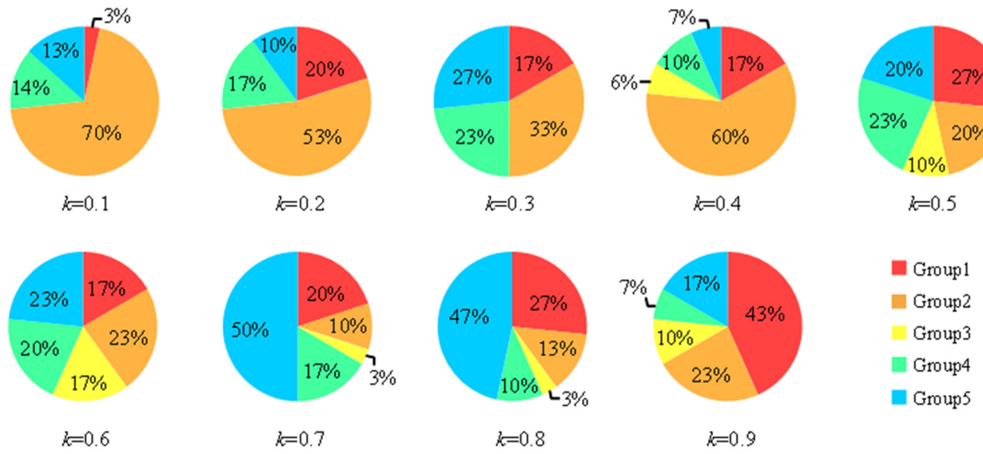

Figure 9. Form operating parameter and groups of the solutions

Figure 9 shows the percentage of solutions in each group computed for each form operating parameter. By looking at Figure 9, we observe the following tendencies.

(1) When the form operating parameter is low or set to 0.9, solutions into a group 1 or 2 tend to be derived.
(2) When the form operating parameter is high, solutions in a group 5 tend to be produced.
(3) When the form operating parameter is medium, solutions tend to be evenly divided into groups 1–5.

These results confirm two tendencies. One is that strong solutions are produced using a high form operating parameter. The other is that diverse solutions are more effectively derived with a medium form operating parameter as light solutions are also found.

5.2.2 Relationship of the system parameter with form characteristics of derived solutions

From the result of paragraph 4.2, we sorted the relationships between the form operating parameter and form characteristics of the solutions. First, elements that composed solution candidates derived by CA tend to concentrate in the upper or lower half when the form operating parameter is low. Differences in the surface shape, coordinates, and topology of these solution candidates are expressed as specific characteristics such as the state of curving and spreading of beams, keeping the diversity of the solutions high. Secondly, elements composed of solution candidates derived by CA tend to fill the generation space when the form operating parameter is high. The coordinates and surface figures of derived solutions are similar due to the high filling rate of the elements in the generation space. However, differences in topology are clarified after the modification. Finally, when the form operating parameter is set to a medium value, solution candidates described above are derived evenly. Additionally, CA yields solution candidates with numerous holes or a mesh-like structure. After the modification, these solution candidates express novel characteristics, increasing solution diversity.
These observations confirm two effective tendencies. First, a setting a low form operating parameter can derive solutions with differences in the surface figure and coordinates. Second, distinct topologies (e.g., a mesh structure) can be derived using medium form operating parameter, increasing the diversity.

5.3 Relationship of the system parameter with derived solutions

We propose a guideline for the system parameter (form operating parameter k) in this section. Figure 8 shows the relationship between the form operating parameter and derived solutions. A high form operating parameter yields strong solutions, whereas a low form operating parameter derives solutions with differing surface figures and coordinates. Additionally, a medium form operating parameter is more effective at deriving diverse solutions, including solutions with numerous topologies such as mesh structures as well as light solutions.

6 CONCLUSION

In this paper, we compare systems for deriving diverse solutions with and without the modification method by examining the efficiency to find solutions as well comparing the mechanical characteristics and solution diversity. Consequently, the effectiveness of the modification method to yield diverse solutions is confirmed. Additionally, the effect of the modification method is clarified by analyzing the proposed solutions. Then system parameter guideline is proposed using the research results, which are summarized below.

(1) Effects of the modification method

- The diversity of feasible solutions increases by reinforcing solution candidates.
- Solutions become stronger and lighter by reinforcing or lightening solution candidates.
- Clarifying differences in topology, coordinates, and surface forms increases the diversity of the solutions.

(2) A guideline to derive diverse solutions with the modification method.

- A high form operating parameter produces strong solutions.
- A low form operating parameter yields solutions with different surfaces and coordinates.
- A medium form operating parameter is the most effective to derive light and diverse solutions.

In the future, we aim to improve the algorithms in the modification method to increase the compliance of the derived solutions.

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