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THE EVALUATION OF THE OPTIMAL COLLISION CONDITIONS BETWEEN FOLDED PAPER STRUCTURES

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Abstract. *In this study, the modeling of the folded paper structures used in a traditional Korean game and the optimal collision conditions to win the game were studied. The 3-stage folding process was used to construct the paper structure. In the analysis, the nonlinear behavior of the paper material was considered, but the frictional behavior and gravitational acceleration were ignored in the folding process. A 2-stage process, involving moving and impacting, was used in the collision analysis. Genetic algorithms were used to search for the optimal collision conditions, such as overlapping ratio, impact speed, and impact angle. Direction cosines were used as the fitness for intermediate analysis, and the inverse of impact speed was used as the final fitness. Various approaches were applied to improve the efficiency of the analysis.*

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1 INTRODUCTION

In this study, it was analyzed a traditional Korean game with a rule that the player who causes a overturn in the struck folded paper structure by striking it with a folded paper structure wins. Nonlinear collision analysis scheme was used for the study. The whole analyses in these study were performed by ABAQUS/Explicit.[1]

2 FOLDING PROCESS

2.1 Folded Paper Structure

The material used to construct the folded paper structure, which is the subject of the analysis, was set to A4 paper (297mm x 210mm), which is commonly used as office paper. The folding method involves folding one sheet of A4 paper in half vertically using two folds, and then placing the folded paper with the center overlapped, followed by folding the unoverlapped parts diagonally. In this paper, the parts folded diagonally are referred to as ”wing”, and the overlapped central part is referred to as the ”base”.

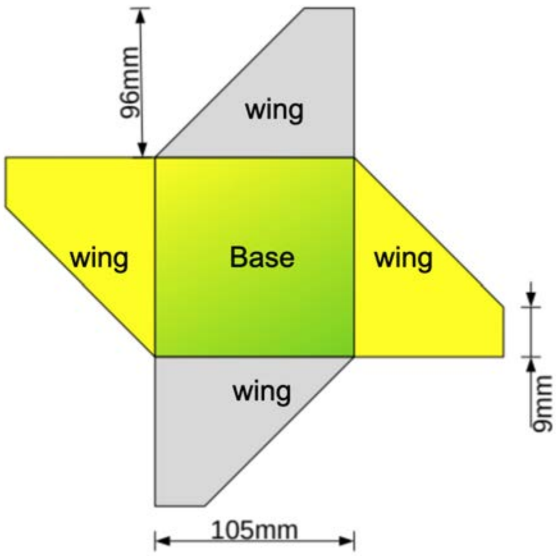


Figure 1: Development figure of paper structure

In this state, the base is composed of four layers, and the wing part is also composed of four layers of paper. The thickness of currently used office paper is typically managed between 0.1 and 0.14mm, with a mass of 80g (80g/m^2) per square meter. In this study, the thickness of one layer of office paper was assumed to be 0.12mm. The material stiffness of the paper material is anisotropic, defined in two directions along the fibers of the paper. In this study, the properties of the machine direction (MD) in the stress-strain material curve, as shown in Figure 2, were used.

2.2 Folding Analysis

In the model used to analyze the folding process of the paper structure under the given conditions, the multiple layers of paper overlap that occur during the folding process were modeled as a single layer without modeling each layer separately. The structural effect due to

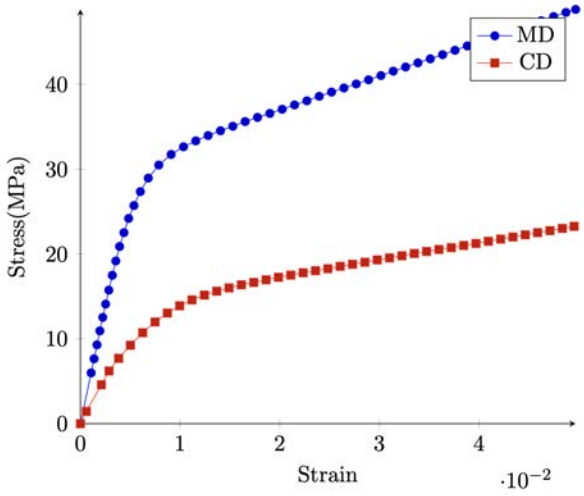


Figure 2: Stress-strain Relation of Paper[2]

the overlap will be manifested as inertial forces caused by the stiffness and mass of the paper with respect to bending. Among these, the inertial force was considered by taking into account the thickness of the overlap between the base and wings. The effect on bending is expected to be dominant at the point where the base and wings meet, where the curvature radius is relatively small compared to other parts during the folding process. Therefore, this part was assumed to behave as a solid body with the greatest frictional force, made up of multiple layers of paper. The initial structure used to analyze the folding process was modeled as a shell element with the shape shown in Figure 3, based on these assumptions. (Figure 3)

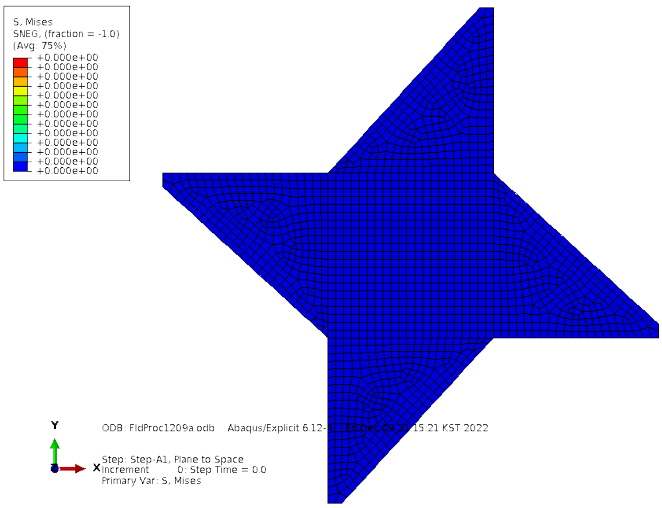


Figure 3: Element mesh of paper structure

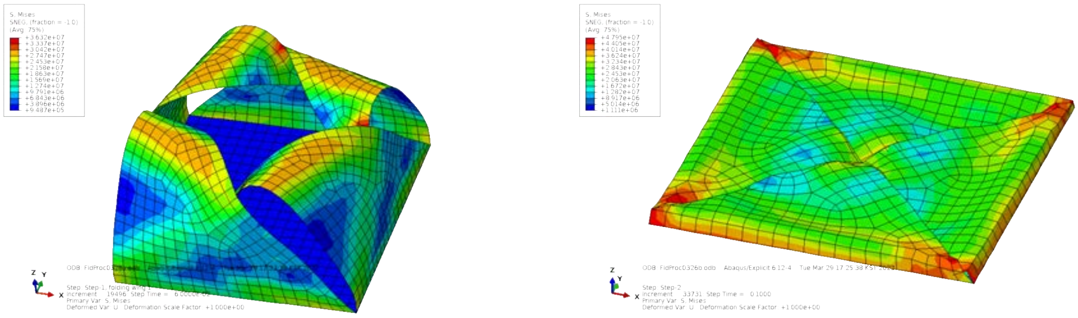
The final shape of the paper structure is determined by the frictional forces between the wings in their twisted position, supporting the restoring forces due to bending in the wings and the base. Therefore, frictional forces must be introduced at the twisted wing position. To create this state, the following steps were taken:

1. Perform a deformation analysis by using displacement boundary conditions to move the

end of the wing from the flat position to the twisted position. (Figure 4a))

2. Apply compression to the upper part of the wing in the twisted position using a rigid plate. (Figure 4b))

These two steps are used as the process of folding the actual paper structure, and they have been implemented through structural analysis.



a) Twisted b) Pressed

Figure 4: Deformed shape of struture in the folding process

However, in the first step, if the end of the wing is displaced to the desired position in a straight line, excessive displacement occurs in the element where interference occurs with the adjacent wing part, resulting in a divergence in the analysis. This corresponds to the case where the paper tears during the actual folding process. In this study, to prevent this phenomenon, the wing part was first deformed to an angle of 80 degrees from the plane while maintaining the wing in a flat position, and then deformed to the final twisted position. If the angle at which the wing is standing exceeds 90 degrees, the aforementioned interference phenomenon occurs when deforming the wing to the final twisted position, leading to a divergence in the analysis.

After positioning the wing's end at the twisted position, an frictionless rigid plate is placed on the upper part of the wing, and the paper structure is compressed by applying a boundary condition of forced displacement. The compression thickness is set to 5mm. In the paper structure studied here, the base consists of 4 layers, and the wings consist of 4 layers each. Taking into account the overlapping at the twisted position, the total number of layers is generally 12. Therefore, if the paper structure is completely pressed, the thickness of the structure would be at least about 1.5mm.

After applying compression, the structure is subjected to gravitational loads and placed on the plate for dynamic relaxation analysis. During this process, the folded structure undergoes a restoration deformation. The final deformed shape resembles a flattened pyramid shape with no vertex at the top. (See Figure 6)

As discussed earlier, in the second stage of the folding process, which is the compression stage, the connection between the base and the wings undergoes significant plastic deformation compared to other parts. After the folding process is completed, the final stress distribution is shown in Figure 7. As expected, the stress distribution is highest at the corner where the smallest curvature radius deformation occurs, while other parts exhibit relatively low stress distribution.

3 COLLISION ANALYSIS

The collision analysis process consists of two steps: moving the striking structure to meet the given collision conditions, and estimating the behavior of the structure resulting from the

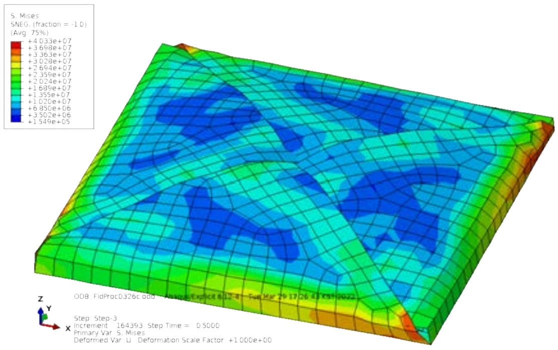


Figure 5: Deformed shape after dynamic relaxation

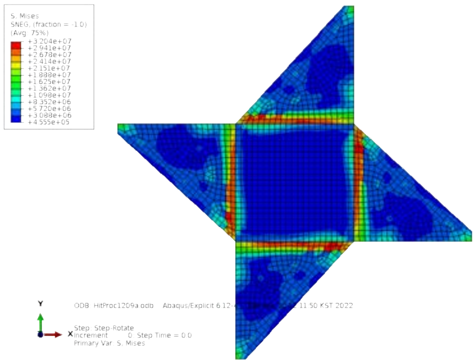


Figure 6: Stress distribution at the end of folding process

collision. The collision conditions considered in the analysis are as follows:

1. Overlap in the x direction (0.1 0.9)
2. Overlap in the y direction (0.1 0.5)
3. Collision angle (0 1.0 rad)
4. Collision velocity (5m/s 15m/s).

In actual games, it is difficult for the striking structure to perfectly overlap with the hit structure, and intentional eccentricity is common due to the nature of the game. Therefore, the degree of overlap was assumed as a collision condition. Similarly, the collision angle cannot be expected to remain perfectly horizontal during collision. The collision speed refers to the speed of the hitting structure when it approaches the struck structure, and the horizontal and vertical forces of this speed are calculated using the collision angle.

3.1 Moving Analysis

Moving analysis is the process of positioning the striking structure at the actual location and angle of collision. This was performed by imposing forced displacements at the boundary conditions. To satisfy the two conditions of collision location and angle, a rotational displacement was generated based on the edge of the striking structure's bottom, and then the analysis was performed to generate horizontal displacement.

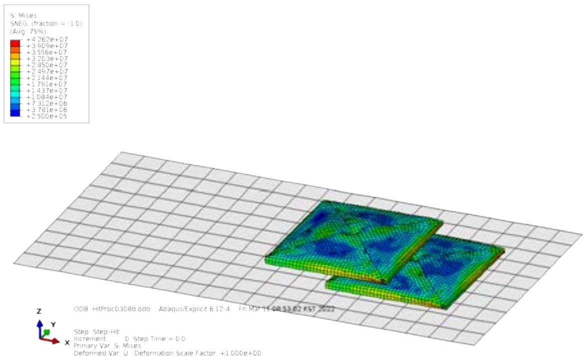


Figure 7: Example of striking position

3.2 Rebounding Analysis

Rebounding analysis is the step where the striking structure causes a recoil behavior to the passivestructure during an actual collision. The striking structure is in contact with the passive structure for a short period of time before it causes a recoil behavior with the ground. The struck structure absorbs the kinetic energy transmitted from the striking structure and generates motion with strain energy. After the two structures fall off the support surface, they vibrate locally but move overall like a thrown object according to the gravitational force. Therefore, it is possible to estimate the behavior after this by using simple motion equations, but since there are cases where secondary collisions occur between the two structures in air, the motion equation of the rigid body was not applied overall.

4 SEARCHING WINNING CONDITIONS

The winning condition of this game is that the struck structure must end up in a final overturned state and the motion must end at the moment of landing after collision. To achieve this final winning condition, the goal of the analysis is to determine the collision location, angle, and velocity. However, since there can be several collision conditions that satisfy the final winning condition for the struck structure, this study defines the optimal collision condition as the one with the lowest kinetic energy, i.e., the lowest collision speed. To find this optimal collision condition, optimization using a genetic algorithm[3] was performed.

4.1 Consist of Collision Analysis

Performing optimization using a genetic algorithm typically requires repeated analyses of various collision conditions. Therefore, both the moving and collision analyses described in the previous section need to be performed repeatedly. However, the rebounding analysis, which involves performing nonlinear dynamic analysis until the struck structure comes to rest due to the kinetic energy transferred from the striking structure, is computationally expensive. Therefore, it was aimed to efficiently perform this process to obtain efficient analysis results. To achieve this, the recoil analysis was conducted in two stages as follows.

4.1.1 Rising Phase

The initial stage of collision behavior is the phase where the struck structure rises due to the impact from the striking structure. In most cases where there is a secondary collision with the striking structure, it occurs in this stage. Based on various analyses, this stage has been set as the first 0.1 seconds after the collision. If the final behavior of the struck structure in this stage does not lead to a reversal, the analysis is terminated in the first stage. The termination condition for the analysis is as follows:

- If the direction cosine of the normal vector of the struck structure's bottom surface is below a certain threshold, and
- if the direction cosine of the normal vector of the struck structure's bottom surface is decreasing.

If the normal direction cosine of the struck structure's bottom surface is less than or equal to the threshold value, and it is decreasing, the analysis is terminated at the end of the first stage. When the bottom of the struck structure is perpendicular to the ground, the direction cosine of the normal is 0, and it is 1.0 when it is overturned. Thus, the above conditions indicate a state where the struck structure is falling downward with its bottom facing down, without overturning, at the time of termination of the first-stage analysis. In general, about three-quarters of the analyses fail to satisfy this condition and terminate during the rising phase.

4.1.2 Falling Phase

This stage is the period of analysis during the collision where the struck structure interacts with the ground in the downward phase, if the termination condition for the rising phase is not met. Similar to the rising phase, the time interval for this phase has been determined through empirical rules based on analysis results, and set at 0.3 seconds.

4.2 Fitness Function

The rising and falling phases each require a fitness function for performing the genetic algorithm. The overall optimization goal should be evaluated in the falling phase, but since about 3/4 of the analysis only involves the rising phase, if the analysis is only performed in the rising phase, a different optimization needs to be performed from the overall optimization. In this study, the optimization goals of the rising and falling phases were defined differently and analyzed accordingly.

1. Raising

$$f_u = \cos \vec{n} \tag{1}$$

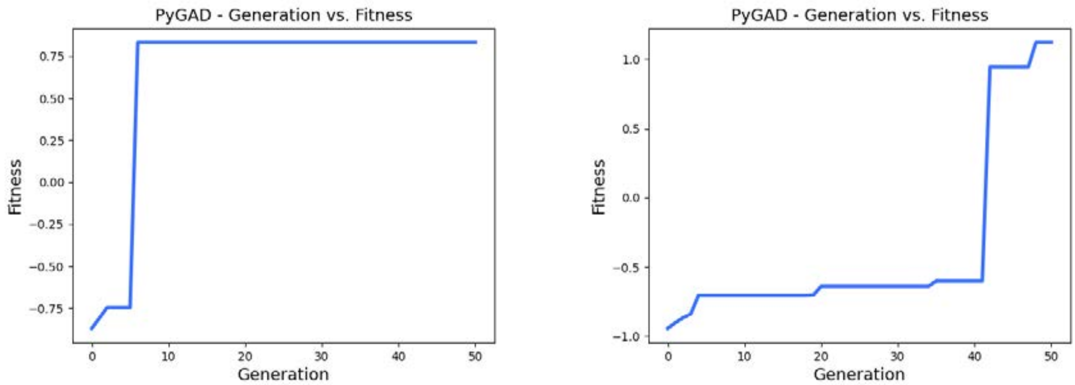
   where, $\vec{n}$ is normal vector of base.

2. Falling

$$f_d = \frac{10}{V_{imp}} \tag{2}$$

   where V_{imp} is collision speed. However, this fitness function is only used in the case of a overturn, and in other cases, the same fitness function as the rising phase was used.

The changes in fitness by generation obtained from performing optimization under the above conditions are shown in Figure 10. The difference between case 1 and case 2 is the phase of the target structure (strike in the inverted state). In both interpretations, successful collision conditions were found to satisfy the winning condition. In this graph, the first occurrence of finding the winning condition is the point where the fitness suddenly increases because the fitness becomes positive when a reversal occurs. In the case of case 1 shown in Figure 10, the winning condition found initially did not improve during repeated analyses, while in the case of case 2, there was one improvement. Such improvements or discoveries of solutions are expected to increase as the number of analysis generations increases.



a) case1 b) case2

Figure 8: Changes of Fitness as Generations

5 CONCLUSIONS

In this study, the folding and collision processes of paper structures used in traditional Korean games were implemented through nonlinear dynamic analysis. Using the folded paper structures, the winning conditions of the game were explored through an optimization process using a genetic algorithm. As a result, it was possible to successfully search for collision conditions that can win the game within the given collision conditions.

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