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論　文　内　容　の　要　旨

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Delamination of white-coated paperboard is one of the most important roles for making a crease line of paper box and tray in the package converting industry, because the folding of crease is well used for making shapes of boxes and trays. The delamination of interlayers occurs during a folding process of creased paperboard. In order to inspect the strength or resistance of delamination, some measuring methods, such as the Z-directional tensile test (ZDTT), the peeling cohesion test (PCT) were examined in the first stage. The delamination and folding mechanism are important for making a high precious size of box, smart folding shapes and a certain strength of folded lines. To measure the resistance of forming and the stiffness of delaminated paperboard are necessary for estimating the folding performance of locally delaminated zone.

First, concerning an in-plane detaching resistance of a white-coated paperboard subjected to a peeling deformation, the z-directional (out-of-plane) tensile test (ZDTT) and the peel cohesion test (PCT) were investigated experimentally and numerically. Since the paperboard is composed of fibrous plies, its detaching mechanism seems to be different from a crack propagation of a fragile material. In this work, an internal breaking criteria and transient de-lamination phenomena of a weak-bonded layer of a white-coated paperboard were experimentally investigated through the ZDTT and the PCT. The detaching resistance in the normal direction was estimated with the proposed non-linear fluffing model using a finite element method (FEM) code to characterize the peeling deformation of the weak-bonded layer. A white-coated paperboard of 0.45 mm thickness (basis weight of 350 $g{\cdot}m^{-2}$) was chosen for conducting the PCT and the ZDTT. An anaphase yielding resistance of detaching was revealed through the ZDTT of the paperboard. The relationship between the pulling force and the curvature radius of delaminated upper layer of the paperboard were discussed in the PCT. The FEM simulation of the PCT of the paperboard was analyzed using an isotropic-elastic model, which was developed through the ring crush test, and compared with the 3 point bending test. The results were as follows: (1) The out-of-plane detaching resistance of in-plane layer of a white-coated paperboard was experimentally characterized through the PCT by the maximum peak line force at the early stage and the stationary line force. These line forces were almost independent to the paper-making direction. (2) A fluffing profile of the de-laminated layer and the thickness of the peeled upper layer experimentally depended on the pulling velocity. (3) Regarding the detaching resistance of peeled layer, a fluffing model was proposed in the developed simulation model. Equivalent fibers based fluffing model that were derived from the ZDTT experiment (approximated as discretely distributed nonlinear springs) well explained the existence of the maximum peak point of peeling force and saturated peel resistance.

Second, to develop a numerical simulation model of the folding process of a creased paperboard and to reveal the deformation characteristics of the creased paperboard, a cantilever type bending moment measurement was experimentally examined with a 0.43 mm thickness white-coated paperboard. To verify the folding response of the creased part, the initial crease (the scored depth) was varied within a certain range, and the lamination numbers were discussed with 2-8 layers. A fluffing resistance model based on the z-directional (out-of-plane) tensile test was initially developed and simulated using isotropic elasto-plastic solid properties. However, since the fluffing resistance was restricted in the normal direction of the detached interface, the in-plane shear resistance was not considered in the early stage. When investigating the folding process of a creased part, it was found that the in-plane shear resistance and its breaking limit was the primary characteristics. Therefore, in this work, in order to characterize the delamination and bulging deformation, the internal breaking criteria was numerically analyzed using a new combination model. A general purpose finite element method (FEM) code MARC was applied to develop a combination model comprising the out-of-plane fluffing subroutine and the in-plane shear glue strength. Through the FEM simulation of the folding process of creased paperboard, the following results were revealed: (1) The simulated bulging profile of the creased part and its bending moment resistance well matched with the corresponding experimental result at the stationary folding state for the folding angle >20°, when using the combination model. The saturated bending moment resistance was characterized by the yielding stress and the folded geometrical mode. (2) The in-plane shear glue strength characterized the bulging patterns of the interlayer delamination in the folding process of the scored zone. (3) The initial delaminated span of the scored zone was estimated as >150% of the creasing width. (4) The initial gradient of the bending moment resistance was characterized by the scored depth and the elastic modulus. (5) The transient response of bending moment at the early stage was characterized by the softening effect model (as partially deleted).

Third, to reveal deformation behavior under a compressive loading using V-Block fixtures, the developed combination model of shear glue strength and fluffing normal strength was conducted for analyzing the bending behavior of creased paperboard, using the in-plane MD tensile properties. An FEM analysis was simulated the compressive load using V-Block fixtures. The simulated folding deformation of the creased part of paperboard was compared with the experiment. The results of this study were as follows: (1) The compressive load tended to decrease with the scored depth and the folded angle. This tendency was well simulated and explained using the combination model. (2) The value of the yield strength characterized the bending moment for a certain large folding angle > 60° . (3) The combination of the fluffing normal and the shear glue strength under the in-plane compressive state was well described the bulging mode of folded portion, when comparing the experimental result for the scored depth of d_{as} = 0.2 mm.