https://doi.org/10.20965/ijat.2014.p0365

Paper:

Topology Optimization for Polymeric Foam Shock-Absorbing Structure Using Hybrid Cellular Automata

Wonho Lee, Jinhoon Kim, and Changbae Park

R&D Solution Lab., Digital Media Communication R&D Center, Samsung Electronics Co., Ltd.
129, Samsung-Ro, Yeongtong-gu, Suwon-si, Gyeonggi-do 443-742, Korea
E-mail: whbest.lee@samsung.com
[Received December 10, 2013; accepted February 24, 2014]

Foam shock-absorbing structures such as cushioned packages are often utilized to protect various products from mechanical shock and vibration during transportation. The goal of packaging design engineers is to design a cushioned package structure that improves the shock-absorbing performance and minimizes the volume of the package. Some optimization techniques, combined with computational simulation, provide engineers with a way to design an optimal structure. In this paper, we propose a modified topology optimization method suitable for a polymeric foam shock-absorbing structure under dynamic drop loads in multiple directions. Our approach uses a heuristic topology optimization method, known as the Hybrid Cellular Automata (HCA). The HCA algorithm uniformly distributes internal energy density and controls the relative density of Cellular Automata (CAs) making up the design space. This allows the algorithm to maintain or increase the performance of shock absorption and to decrease the amount of material. In particular, this paper presents a modified Solid Isotropic Material with Penalization (SIMP) model for foam materials, which parameterizes the design region and interpolates the material properties. We attempt to optimize a simple bottom-cushioned package for a refrigerator by using the proposed foam SIMP model with commercial software: LS-DYNA for drop dynamic simulation and LS-OPT/Topology for the HCA algorithm. Drop simulation and topology optimization are performed considering multiple drop-directions. As a result, our method removes elements that are not related to the shock-absorption performance and provide an optimal cushioning structure using foam material.

Keywords: topology optimization, hybrid cellular automata, foam, SIMP, drop simulation

1. Introduction

A cushioned package is primarily used to protect fragile items from mechanical shock or vibration encountered during shipment, transportation and handling. In particular, polymeric foam materials, such as Expanded PolyStyrene (EPS), Expanded PolyEthylene (EPE), and Expanded PolyUrethane (EPU), are widely used for cushioning materials because they provide superior shock-absorption at low cost [1–3]. However, manufacturers have attempted to decrease material costs by reducing volume and improving the shock-absorbing performance. To reduce environmental pollution, manufacturers should reduce the usage of foam material. Moreover, secure cargo space is necessary to reduce delivery charges and storage fees.

Many engineers have studied computer simulations and optimization methods for these purposes [4–9]. Drop and shock problems have been numerically simulated by using explicit nonlinear dynamic solvers, such as LS-DYNA, ABAQUS, and PAM-CRASH. This, numerical simulation helps engineers to virtually evaluate the performance of the shock-absorption in the cushioned package design to determine the design parameters of thickness and contact areas. In addition, designers have used special methodologies, such as the Taguchi method, optimization based on meta-modeling, and axiomatic design, to determine an optimal foam structure [5–8]. However, most studies achieve optimization by adjusting some parameters to define the final geometry of the cushioned package, and engineers must apply advanced analysis techniques for their designs.

Topology optimization is a mathematical approach that optimizes material layout within a given design space and for a given set of loads and boundary conditions that meets the requirements for maximizing the performance of a structure [10]. This method, based on Finite-Element Analysis (FEA), provides engineers with an optimal topology and a conceptual design. In addition, it ensures that the initial conceptual design satisfies target performance in the initial design phase. One example is the stiffness or weight of structures.

However, it is difficult to apply topology optimization in the design of the cushioned package to protect products from drop-shock including dynamic loading conditions. These are nonlinear dynamic problems that are inappropriate applications for topology optimization. Conventional topology optimization methods require derivative information which is not appropriate or efficient when nonlinearities are involved in FEA, including changes of contact status, geometric deformation and material properties [11–18]. Particularly when nonlinear problems involving large deformation are considered, low-density finite elements cause serious numerical problems because their tangent stiffness matrices lose positive definiteness. Some novel algorithms to resolve these difficulties have been introduced such as the Element Connectivity Parameterization (ECP) method [13]. For drop or crash simulation including dynamic loads, the Equivalent Static Loads Method (ESLM) and Hybrid Cellular Automata (HCA) are known as suitable approaches [14].

ESLM transposes the original nonlinear dynamic optimization problem into an iterative linear optimization process with linear static multiple loading cases for optimization. Therefore, the method exhibits highly nonlinear structural behavior, owing to the linearization of the optimization problem and the decomposition of the dynamic process into discrete static load cases [14, 15].

Recently, in another approach, difficulties in topology optimization due to nonlinearities have been solved by using HCA, which is a heuristic and gradient-free approach. Tovar developed an HCA algorithm for structural topology optimization to implement a bone remodeling mechanism with various local control rules [16, 17]. An extension for crashworthiness was performed by Patel in 2006 [18]. They proposed the Solid Isotropic Material with Penalization (SIMP) model for piecewise linear-plastic material and successfully applied it to crashworthiness problems to determine an optimal shock-absorbing structure with FEA.

In this paper, we present an optimization procedure for the cushioned package structure of foam material using the HCA algorithm with explicit nonlinear FEA under drop-impact loading conditions. The HCA algorithm for a shock-absorbing structure controls the relative mass distribution with both local design rules based on the cellular automaton paradigm. To interpolate foam material properties, the foam SIMP model is proposed, modified from a conventional SIMP model. Moreover, we consider the relationship between relative density and internal energy density to determine the penalty value of the foam SIMP model depending on load condition.

In practice, the proposed foam SIMP model is applied to optimize the topology of a cushioned package for a refrigerator under multiple drop impact loading conditions in five directions. This type of application, using topology optimization for a cushioned package, is very rare. There is a clear difference in the optimal results between the piecewise linear elastic-plastic SIMP model and the foam SIMP model, owing to the nonlinear stress-strain relation of foam material and its compressible characteristic. These results of topology optimization for foam are compared with design theory for the cushioned package. Moreover, the proposed method can help package designers easily determine the initial concept design.

LS-OPT/Topology is employed to perform the HCA algorithm with LS-DYNA for drop-impact simulation [19].

2. Topology Optimization Using Hybrid Cellular Automata

The theory of Cellular Automata (CAs) was formalized by John von Neumann at the end of the 1940s. It is a discrete approach studied in computability, mathematics, theoretical biology and microstructure analysis [12]. Several algorithms for structural analysis and/or design of structures based on the CA paradigm are presented in the literature. In conventional CA, the state of a cell is based on local design variables. For structural optimization, however, the state of a CA can be defined by rules that combine local design variables with global design variables or globally calculated field variables; e.g., stress, or internal energy density. Thus, the state of a CA is determined by using a combination of local and global information, which is entitled HCA [16, 17].

In LS-OPT/Topology, the shape of the cells is the same as the shape of hexahedral elements [19]. The state of a CA defines its characteristics and comprises both design and field variables. In dynamic problems like crashworthiness or drop-shock simulations, the structure must absorb maximum energy and maintain low peak loads transmitted to the occupants or products low. Tovar and Patel suggested that the goal of achieving uniform Internal Energy Density (IED) in a structure is the objective for optimization, and the mass is constrained. This objective is appropriate for the design of a foam cushioned structure because it is the same goal. Therefore, the state of a CA consists of the relative density $x_i(t)$ and the internal energy density $U_i(t)$ at time t.

The optimization problem is formulated as,

$$\begin{cases} \min\limits_{x} \sum\limits_{i=1}^{N} (U_i(x_i) - U_i^*), \\ \text{subject to} : \sum\limits_{i=1}^{N} \rho_i(x_i) V_i \leq M^*, \\ x_{min} \leq x \leq 1, \end{cases} \qquad (1)$$

where N is the number of cells (elements); U_i is the IED of the ith cell; U_i^* is the set point of the IED determined from mass fraction as Eq. (2); x is the relative density value; x_{min} is the lower bound value; V_i is the volume of the ith cell.

The set point U^* of the IED is defined as,

$$U^{*(k+1)} = U^{*(k)} \left(\frac{M^{(k)}}{M^*} \right), \qquad (2)$$

where k is the time or iteration number and the set point of the IED is updated iteratively by using the ratio of the current mass, $M^{(k)}$, and the set point mass, M^*.

The state update rules represent the heart of the CA-based topology optimization method and are conducted in two steps in LS-OPT/Topology. The first rule is the field variable update, at which the IED obtained from explicit dynamic simulation is a field variable in the HCA algo-

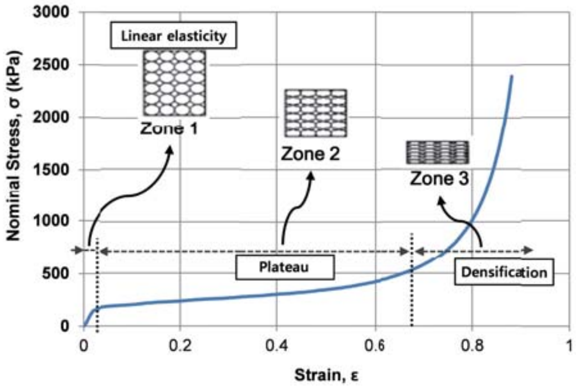


Fig. 1. Polymeric foam stress-strain curve in compression.

rithm and the average internal energy density $\bar{U}_i$ of the ith cell is defined as,

$$\bar{U}_i = \frac{1}{\hat{N}} \sum_{j=0}^{\hat{N}} U_j, \quad (3)$$

where $\hat{N}$ is the number of neighbors defined in the CA neighborhood.

The second rule is the local variable update at which the relative density is a local variable. The local control rule seeks to minimize the deviation between a target U and the averaged U, and updates the relative density.

$$x_i^{(k+1)} = x_i^{(k)} + K\left(\frac{\bar{U}_i^{(k)} - U_i^{*(k)}}{U_i^{*(k)}}\right) \quad (4)$$

where K is the scale factor, which is similar to the proportional constant in a Proportional Integral Derivative (PID) controller. In fact, Tovar proposed local control rules using a PID controller [17].

These state update rules are repeated until the stopping criteria are satisfied, such as the number of iterations or a change in the topology. In addition, they contribute to eliminating some numerical problems in conventional topology optimization methods, such as check boards and singularities.

3. Characteristics of Polymeric Foam Materials

Polymeric foams are very suitable as the protective packaging material for energy-absorbing structures. The most common deformation mode of foam is compression. Foams can undergo large compressive deformations and absorb considerable amounts of kinetic energy during dynamic compression. Foams are usually not strong in tension or shear and are rarely intentionally subjected to deformation in these modes. The Poisson's ratio of foams is almost zero, and their behavior characteristics are divided into three zones: an initial region of linear elasticity (Zone 1), a flat plateau compaction region (Zone 2), and a densification zone (Zone 3), as shown in **Fig. 1**. In the initial region, foams may display some stiffness owing to the strength of the matrix material itself. After yielding, the gaseous component is affected. In open cell foams, the gas pressure may increase sufficiently to break the cell wall, thereby releasing the gas to the atmosphere. This results in a permanent rupture in the cell and disregarded damage to the foam material. On the other hand, if the matrix is sufficiently strong, the cell remains unbroken, but collapses and begins to behave much like the matrix material in its stress-strain relation [1–3].

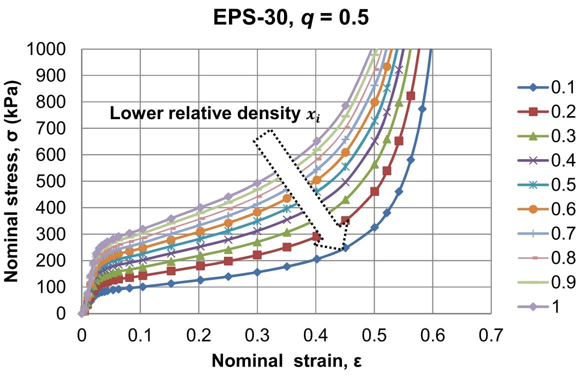
EPS is a foam material of cushioned packages, usually used for appliances like televisions, refrigerators, and air conditioners. We used the "LOW_DENSITY_FOAM" material model (MAT57) of LS-DYNA to express the mechanical behavior of EPS. Nominal stress (engineering stress) versus strain data, obtained by quasi-statically compressing a cubic specimen along one direction, is required to use the low-density foam model in LS-DYNA [20]. The stress-strain relation is actually dependent on strain rate. In this study, the effect is not considered, to avoid confusion resulting from the similar changes between the stress-strain relation dependent on strain rate and the penalized stress-strain relation mentioned in next section.

4. Solid Isotropic Material with Penalization for Foam Material

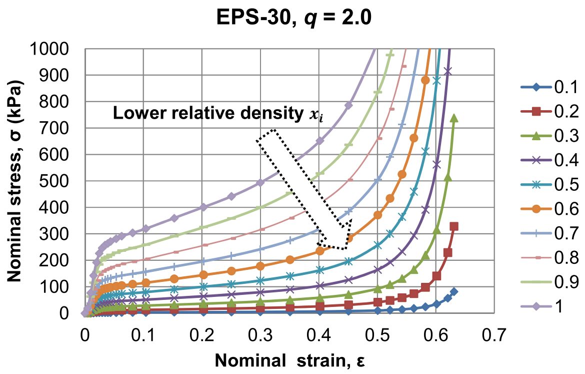
In topology optimization paradigm, SIMP, called the density based approach, is a simple and widely used method to parameterize the design region and to interpolate the material properties for the design variable. SIMP enables the relative density of elements as a design variable to be polarized into 0 or 1 by a power law during iterations to determine the optimality condition [10, 18]. In the other words, the SIMP model depends on a power law approach for material interpolation.

Patel applied the HCA algorithm for topology optimization to crashworthiness problems by using a SIMP model for piecewise linear elastic-plastic material [18]. Goezt proposed a SIMP model for the Johnson-Cook material model [21]. We have wondered whether a piecewise linear elastic-plastic model can be applied, with no changes, to the topology optimization of cushioned packages using foam materials. The mechanical behavior of foams obviously differs from elastic-plastic material models, which necessitates a model that accounts for nonlinear compressibility. The maximum strain of foam on the cushioned package is designed at 0.4 to 0.5 in the plateau region presented in **Fig. 1**. In particular, the Poisson's ratio of foams is nearly zero, and it can induce a topology unlike general elastic material. Therefore, a new SIMP model for polymeric foams is required to present the stress-strain relation for relative density.

In this study, a modified SIMP model that penalizes the stress-strain relation of polymeric foam under compres-



(a) Penalty value $q = 0.5$



(b) Penalty value $q = 2.0$

Fig. 2. Material penalization of EPS-30 for the foam SIMP model.

sion is defined as

$$\rho_n(x_n) = x_n \rho_0 \quad \ldots\ldots\ldots\ldots \quad (5)$$

$$\sigma_{Fn}(\varepsilon, x_n) = x_n^q \sigma_F(\varepsilon) \quad \ldots\ldots\ldots\ldots \quad (6)$$

$$(0 < x_{min} \leq x_v \leq 1,\ q > 0,\ 0 \leq \varepsilon \leq 1)$$

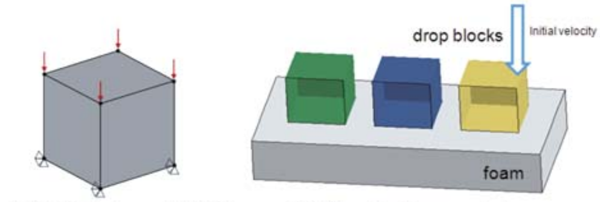
where x_n is the relative density of element n, x_{min} is the minimum of the relative density, and the density is denoted by ρ. The subscript 0 refers to the base material properties; σ_F is the stress value for the strain, ε, and interpolated with x_n. The penalty factor, q, is a very important coefficient for determining the final topology of a nonlinear material like foam; this is mentioned in the next section. **Fig. 2** represents penalization examples of the foam SIMP model.

LS-OPT/Topology 1.0 only supports the piecewise linear elastic-plastic material model of LS-DYNA. Therefore, we must modify a file for penalization and the model of material to apply the proposed foam SIMP model; this is discussed in the following chapter.

4.1. Determination of Penalization

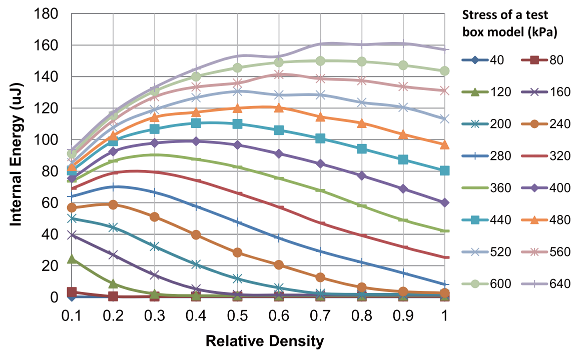
We must discuss the densification region, where stress increases rapidly. Although low relative density induces low stiffness, low relative density can have high internal energy owing to high stress in the densification region at high strain. This characteristic ensures caution in the selection of penalization coefficient q. Although the penalty value recommended for the elastic SIMP model is from 2.0 to 3.0 [22], we verified that this value is not proper for nonlinear foam material; a similar viewpoint was reported by Patel [18].

To verify this characteristic, a numerical compression test was conducted under uniaxial load for an isotropic cubic material element, as shown in **Fig. 3(a)**. In **Fig. 4**, the relative density versus internal energy relation is very different for each stress condition because of the nonlinear stress-strain relation of the foam [1]. In the HCA algorithm, the local update rule that adjusts the relative density of Eq. (4) requires the decreasing monotonic relationship between the IED and the relative density to rapidly con-

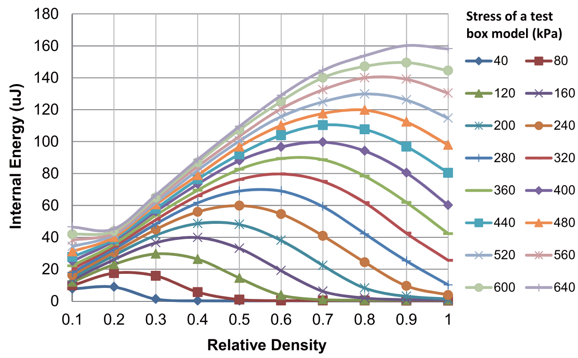


(a) IED test model [18] (b) Simple drop model

Fig. 3. Test simulation models to determine penalty value q.

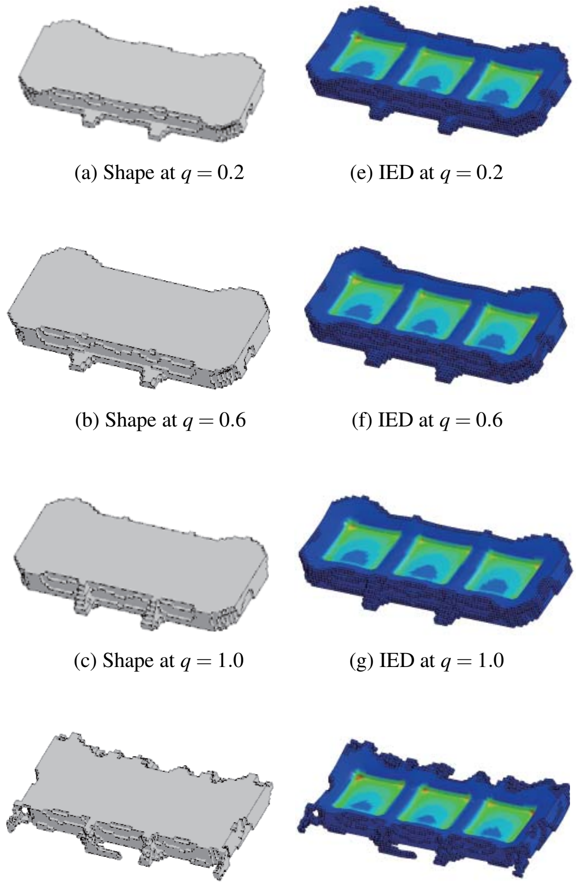


(a) Penalty value $q = 0.6$



(b) Penalty value $q = 1.6$

Fig. 4. IED-relative density relationship using the proposed foam SIMP model.



(a) Shape at $q = 0.2$ (e) IED at $q = 0.2$

(b) Shape at $q = 0.6$ (f) IED at $q = 0.6$

(c) Shape at $q = 1.0$ (g) IED at $q = 1.0$

(d) Shape at $q = 1.6$ (h) IED at $q = 1.6$

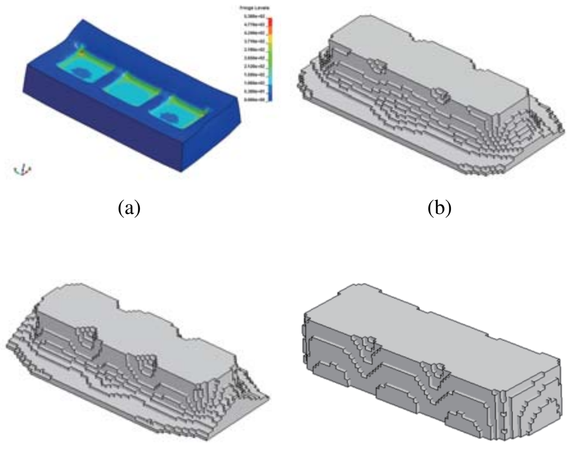
Fig. 5. Topology optimization results of a simple drop model for penalty values.

verge at the optimum value and to achieve clean topology. However, a high q value can result in a reverse slope at the middle relative density under most stress conditions. In the other words, the selection of relative density, adjusted by the update rules, is uncertain, when internal energy is located at a point of inflection. Therefore, the experimental results in **Fig. 4** can be used to determine the q value.

To observe the effect of penalty q, an optimization test was conducted for a simple drop simulation model, illustrated in **Fig. 3(b)**. Three rigid blocks were dropped in the direction of gravity. We optimized the HCA topology for some q values and **Fig. 5** presents the results. A comparatively high q encourages unclean topology because the relationship between the IED and the relative density is not monotonic. Therefore, a low value of penalty q is appropriate for the proposed foam SIMP model.

4.2. Comparison of Linear Elastic-Plastic and Foam SIMP Models

Figure 6 shows the results of HCA topology optimization for the piecewise linear elastic-plastic SIMP model and the foam SIMP model, respectively. This figure confirms the differences between the two models. In the case of foam, elements not contributing to energy absorption



(a) (b)

(c) (d)

Fig. 6. Comparison of SIMP models: stress distribution when (a) three simple boxes drop on the foam cushion, (b) piecewise linear elastic-plastic SIMP model ($\nu = 0.3$), (c) piecewise linear elastic-plastic SIMP model ($\nu = 0.01$), and (d) proposed foam SIMP model.

are clearly removed in the vertical direction, as shown in **Fig. 6(d)**. On the other hand, the piecewise linear elastic-plastic model induces a pyramidal shape owing to the effect of Poisson's ratio. Despite the low Poisson's ratio ($\nu = 0.01$), the same result is shown in **Fig. 6(c)**. This structural characteristic observed from topology optimization shows that the proposed foam SIMP model is a better choice when conducting topology optimization using a nonlinear foam material.

4.3. Mass Fraction

The mass fraction is the ratio of the target against the initial mass, which is used as the termination condition for iterations. **Figs. 7(a)**, **(b)**, **(c)**, and **(d)** show mass fractions of 0.7, 0.5, 0.4, and 0.2, respectively. When compared with initial volume, only contact areas remain.

4.4. Comparison Between Rigid and Flexible Body

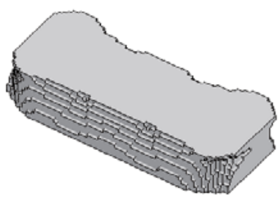
In **Fig. 3(b)**, three of the boxes are modeled as rigid bodies. When using flexible bodies, different topology is obtained owing to the stress distribution of foam induced by the deformation of boxes in **Fig. 8(c)**.

5. Implementation and Application

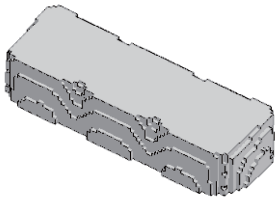
The usability of the proposed foam SIMP model and the possibility of topology optimization for the design of a cushioned package are confirmed through the application of a bottom cushion for a top-freezer refrigerator.

5.1. Finite Element Modeling for Drop Simulation

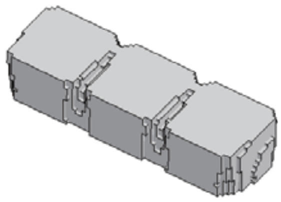
HCA topology optimization requires the IED as the field variable, which is obtained from FEA and used to



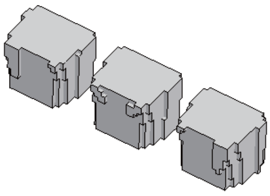
(a) Mass fraction 0.7



(b) Mass fraction 0.5

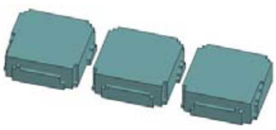


(c) Mass fraction 0.3

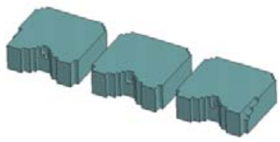


(d) Mass fractions 0.2

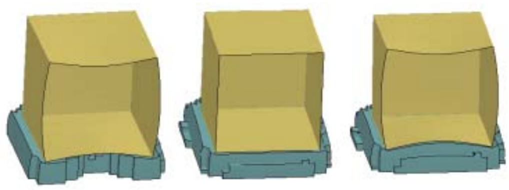
Fig. 7. Effect of the mass fraction in the HCA topology optimization.



(a) Using rigid bodies

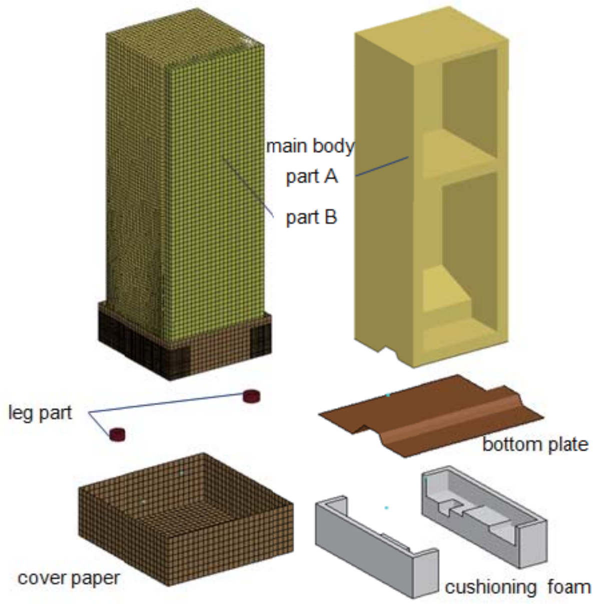


(b) Using flexible bodies

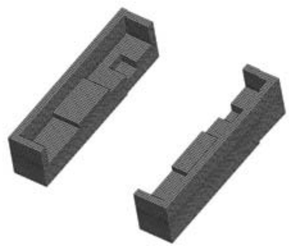


(c) Deformation of flexible bodies at the peak of acceleration

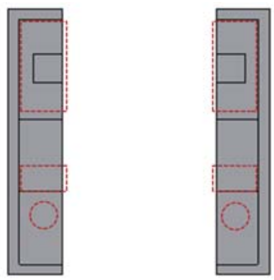
Fig. 8. Comparison of rigid and flexible bodies.



(a) Simple refrigerator parts and a cushioned package with a cover paper



(b) Initial design



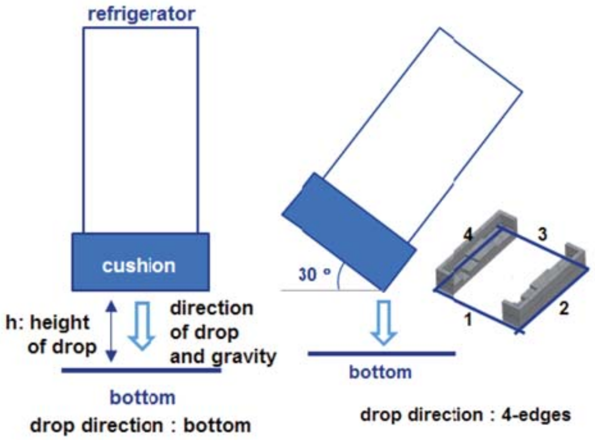
(c) Faces contacted with foam and refrigerator bottom part

Fig. 9. Finite-element model and assembly for the simplified refrigerator and cushioned package.

update design variables such as the relative density. We conduct drop impact simulation and present the optimal foam structure for a top-freezer refrigerator as an application of the proposed method. The body of a refrigerator is simply modeled as a rigid body to reduce simulation time. As shown in **Figs. 8(b)** and **(c)**, the use of a flexible body is preferred to determine topology considering gravity, mass, and stiffness. Parts with heavy mass are modeled as lumped mass elements. The cushioned package is composed of two symmetrical parts. Two circular legs are attached in front of a bottom plate, which supports the weight of the refrigerator. All elements of the foam are specified as the cells and design regions for optimization. The contact areas and thickness of the package can be designed, along with the theory of package design [2, 23].

Figure 9(c) illustrates contact areas between the cushioned package and the refrigerator. The contact areas always experience contact pressure during drop-shock loading, so element elimination from adjacent cells is almost impossible. Drop loading conditions are illustrated in **Fig. 10**.

According to the cushioned package design method, the selection of contact areas and thickness of the package is essential; this is calculated from the energy absorbing performance. When contact areas, drop height, and damaged acceleration are determined, the height of the package can be determined from FE drop simulation. This assumes that the damaged acceleration is 65 G. The possibility of damage is evaluated with the damage boundary, simplifying the process of determining the shock fragility of products [23]. To define the thickness of the cushioned package, drop simulations are conducted and the acceleration-time data are determined, as shown in **Fig. 11**. This means that decreasing the foam thickness induces an increase in the acceleration of parts. From the results, the thickness of foam was chosen as 70 mm to satisfy the damaged acceleration of 65 G.



(a) (b)

Fig. 10. Drop loading conditions for the cushioned package and refrigerator.

5.2. Topology Optimization Process Implementation

Topology optimization requires the process integration technique to conduct seamless and iterative optimization procedures. LS-OPT/Topology provides basic automation functions that modify models, initiate the solving process, and gather analysis results, including post-processing, by connecting to necessary software such as LS-DYNA and LS-PREPOST. However, LS-OPT/Topology only supports piecewise linear elastic-plastic models. At the beginning of the optimization procedure, we replace the material input file created by the LS-OPT/Topology with a new material file that is suitable for the proposed foam SIMP model. The material file includes the penalized stress-strain curves depending on the relative density, according to Eqs. (5) and (6). **Fig. 12** shows the process diagram to modify the default SIMP model of LS-OPT/Topology to the proposed SIMP material model.

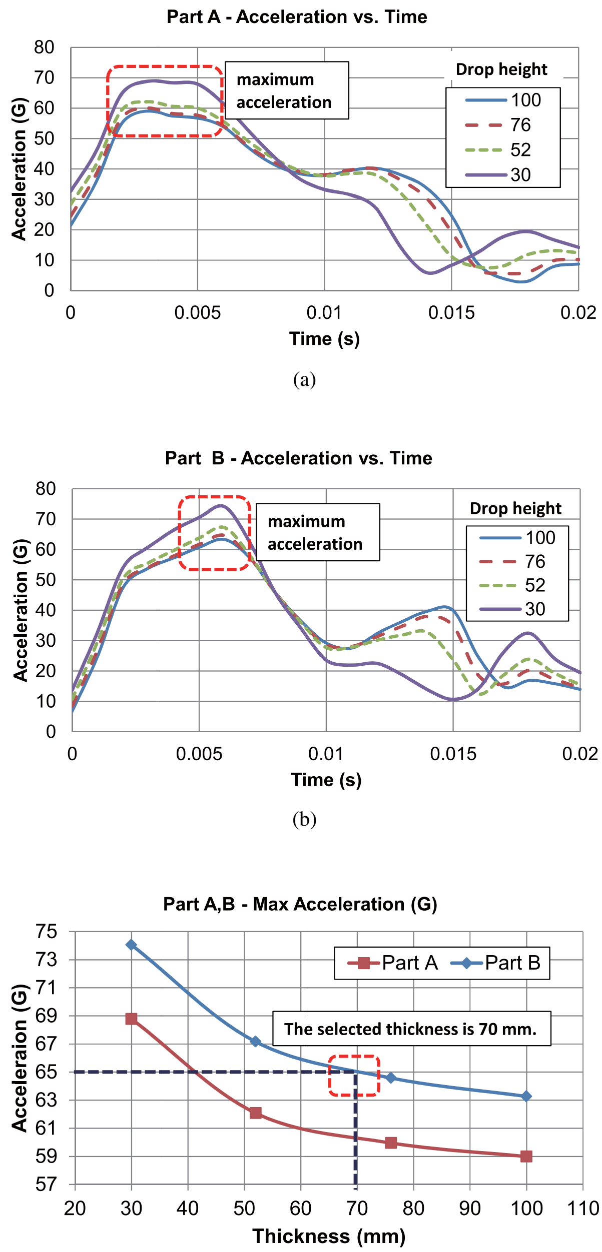
5.3. Topology Optimization and Drop Simulation for Downward and Multiple Directions

In most energy-absorbing appliances, foam is loaded only once. However, during transportation, packaged products such as home appliances can be exposed to multiple directive impact loadings as well as vertical loading. An optimal structure considering only the vertical direction has less mass and volume at the edges of the refrigerator and is frangible in the other loading directions. **Fig. 10(b)** shows possible drop directions on the bottom and edges.

Therefore, we conduct optimization considering multiple loading conditions at four edge directions to determine the reasonable structure. The objective is modified to reflect the results of multiple drop simulations, such as Eq. (7).

$$\hat{U}_i = \sum_{LC=1}^{N_{LC}} \alpha_{LC} U_i^{LC} \qquad (7)$$

where the subscript LC refers to a particular load case, α_{LC} is the weight factor for each LC, N_{LC} is the number of load cases, and $\hat{U}_i$ is the weighted sum of the IED for the element i. In this problem, the weight factor, α_{LC}, is equal to 1 and N_{LC} is 5 at the bottom and 4 at the edges.



(a) (b) (c)

Fig. 11. Determination of package thickness: (a), (b) average acceleration of parts A and B, and (c) polynomial metamodels that represent the maximum acceleration of parts A and B.

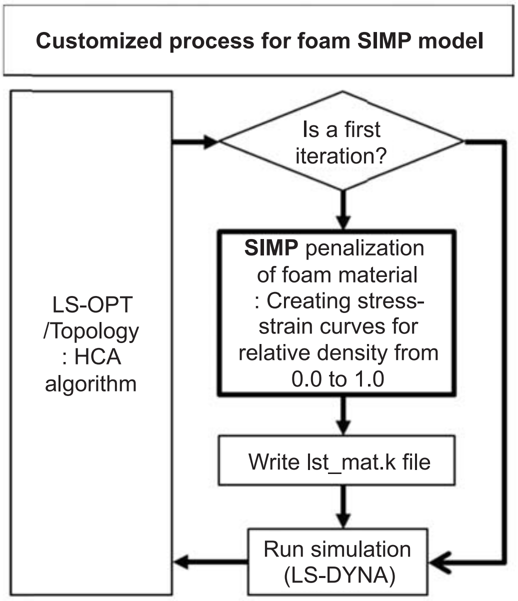
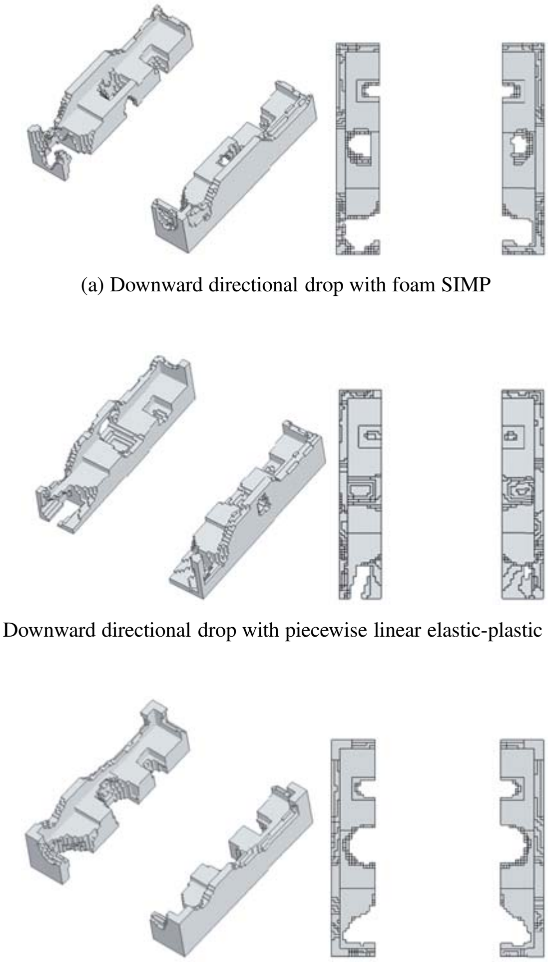


Fig. 12. Customized topology optimization procedure to apply the proposed foam SIMP model using LS-OPT/Topology.



(a) Downward directional drop with foam SIMP

(b) Downward directional drop with piecewise linear elastic-plastic SIMP

(c) Multiple directional drops with foam SIMP

Fig. 13. Results of topology optimization using the proposed foam SIMP model.

Table 1. Reduction in volume for downward and multiple drop cases.

Case	Volume (cm^3)	*Ratio of reduction (%)*
Initial design	29319	–
Downward drop	21261	27.5
Multiple drops	21299	27.4

5.4. Result and Discussion

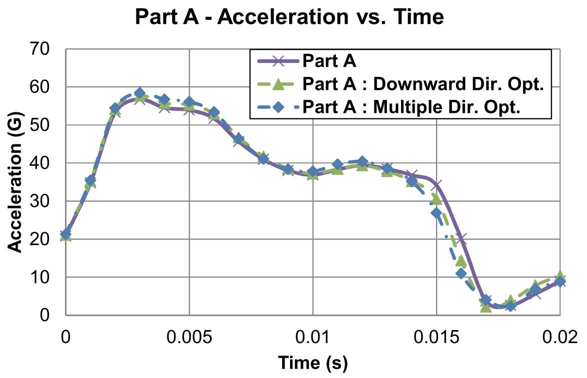
Figure 13(a) shows the topology resulting from the HCA algorithm considering foam material under a loading condition in the downward direction. **Fig. 13(b)** shows a result of the piecewise linear elastic-plastic model. As already noted, pyramid shapes are shown in **Fig. 13(b)** owing to the Poisson's ratio. However, in the case of the foam SIMP model, elements are clearly removed in the vertical direction and the characteristics of polymeric foam are accurately reflected. Primarily, cells experiencing high compression and internal energy density are removed as a result of shock transferred from the bottom. In other words, they contribute to shock absorption with high internal energy density, while removed cells do not contribute by compressive deformation.

Figure 13(c) shows the results considering multiple drop directions. When considering only the downward drop, the elements of the front edge region are excessively removed from a lack of compression. On the other hand, in multiple directions, the elements of the edge region remain and elements having low internal energy are removed. The ratio of mass reduction in the two cases is equal, as shown in **Table 1**. Therefore, topology considering multiple loading conditions is successfully optimized.

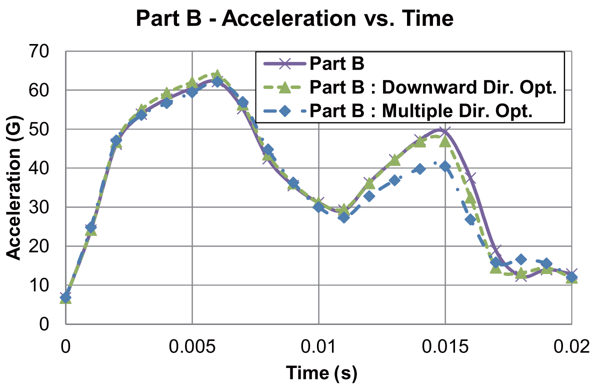
The optimal cushioned package is compared to the initial cushioned package using the accelerations of parts A and B in **Fig. 14**. Although the volume and mass are reduced considerably, the difference in acceleration is very low.

Figure 15 shows a plot of the IED and the density distribution history during iterations. The initial changes of the IED suggest that many elements are deleted in the initial iterations because no compressive elements are definitively separated by low internal energy.

These results validate the proposed foam SIMP model as useful for the HCA topology optimization of a foam cushioned package. In addition, topology optimization considering multiple drop loading conditions was successfully applied for the cushioned package design. These results are not unusual in cushioned package design, and are explained by the principles of design modification proposed in the some studies [5–7]. We proposed that design modification can be more simply achieved by using the HCA algorithm, topology optimization, and FEA.



(a) Part A



(b) Part B

Fig. 14. Comparison of acceleration results of refrigerator parts determined from the drop simulation for original package design and the optimized designs for downward and multiple drop directions.

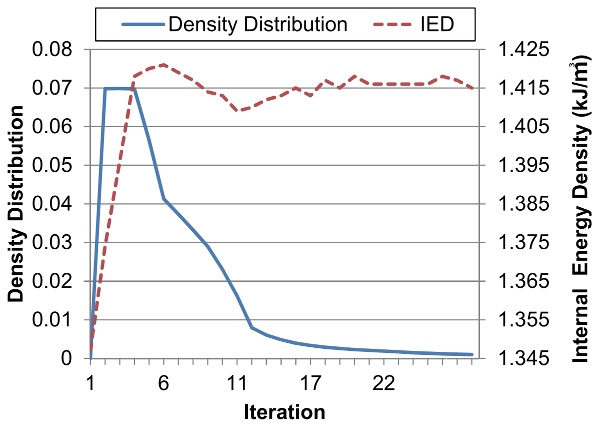


Fig. 15. IED and density distribution history during iterations.

However, it is important to understand that the optimal configurations in **Fig. 13** are just finite elements; they are different with a real geometry, and do not consider the manufacturing process of injection molding, in which the direction of extraction is one of the design factors. Accordingly, when designing the shape of the actual package, we must understand the elimination of elements from the optimal results and its effects, as well as the manufacturing conditions. One simple example of the package design induced from the results is shown in **Fig. 16**. The example is simply provided as a helpful illustration of this concept.

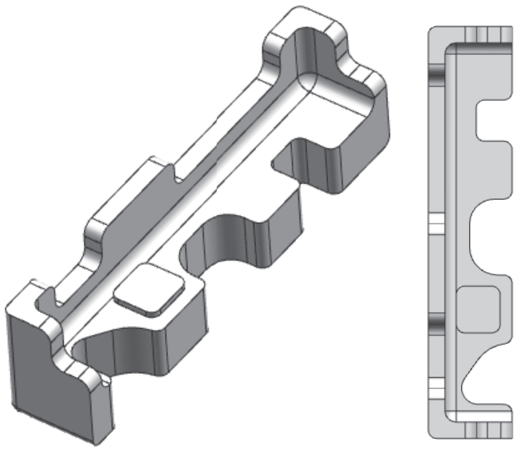


Fig. 16. Example design of the cushioned package inspired by the results of topology optimization using foam SIMP model.

Table 2. Computational time for HCA topology optimization of a refrigerator cushioned package.

Items	*One dir.*	*Multiple dir.*
Hardware	Athlon II X4 3.0 GHz, 4 cores, 4 GB RAM	
Target density distribution	1%	
Drop simulation time	0.1 s	
Solving time per iteration	10 min	
Total iterations	24	28 (×5 dir.)
Total time for optimization	240 min	1400 min

The computational time and hardware for the application are detailed in **Table 2**. During explicit dynamic structural analysis, solving the time step size depends on deformable parts, including the element size, density, and elastic modulus. In this application, we model the cushioned part and adjust the minimum time step size to meet the simulation time of 10 min for the drop time of 0.1 s. We believe that the computational time for multiple drop directions in **Table 2** is very reasonable when considering the product design environments.

6. Conclusion

We propose a new topology optimization method that is suitable for a polymeric foam shock-absorbing structure, such as a cushioned package, under drop load conditions in multiple directions. Topology optimization considering dynamic behavior is very rare, owing to difficulties such as calculating sensitivity or combining with dynamic simulation. To overcome the limitations of conventional topology optimization, owing to drop-shock dynamics as well as the nonlinearities of material, geometry, and contact, we used the HCA algorithm of LS-OPT/Topology, a commercial topology optimization tool. In addition, we present a modified SIMP model for foam materials that conventional or commercial topology optimization tools do not support. The proposed model parameterizes the design region and interpolates the material properties to describe behavior and characteristics. Numerical experiments demonstrate that the proposed foam SIMP model is more appropriate than other models.

We propose a new topology optimization method suitable for the polymeric foam shock-absorbing structure such as a cushioned package under drop load conditions of multiple directions. Topology optimization considering dynamic behaviors is very rare due to difficulties such as calculating sensitivity or combination with dynamic simulation. To overcome the limitations of conventional topology optimization due to drop-shock dynamics as well as the nonlinearities of material, geometry and contact, we used HCA algorithm of LS-OPT/Topology, commercial topology optimization tool. In addition, we present a modified SIMP (Solid Isotropic Material with Penalization) model for foam materials that conventional or commercial topology optimization tools don't support. The proposed model parameterizes the design region and interpolates the material properties to describe behavior and characteristic. It is shown that the proposed foam SIMP model is more appropriate through numerical experiments.

The application to a simple bottom-cushioned package of a refrigerator was conducted by using the proposed foam SIMP model with LS-DYNA for explicit dynamic structural simulation and LS-OPT/Topology for the HCA algorithm. As a result, we showed that our novel approach successfully provides an optimal cushioning structure in which elements not related to the shock-absorbing performance are effectively removed. In addition, we showed that the proposed method agrees with the basic design principles in cushioned package design by comparing the piecewise linear elastic-plastic and the proposed foam SIMP model.

References:

[1] M. Avalle, G. Belingardi, and R. Montanini, "Characterization of polymeric structural foams under compressive impact loading by means of energy-absorption diagram," Int. J. of Impact Engineering, Vol.25, pp. 455-472, 2001.

[2] "Packaging with Styropor," BASF, 2006.

[3] B. Croop and H. Lobo, "Selecting Material Models for the Simulation of Foams in LS-DYNA," 7th European LS-DYNA Conf., 2009.

[4] S. W. Booh, K. T. Kim, and W. J. Chung, "Drop/Impact Analysis of Electronic Products with Packaging Materials," Trans. of the KSME (A), pp. 228-234, 1995.

[5] K. Y. Seok, K. W. Yoon, J. M. Na, and C. B. Park, "Analysis of Package Drop and its Application for Optical Disc Drives," Proc. of the KSNV Engineering Conf., pp. 177-182, 2004.

[6] D. H. Kum, W. J. Kim, S. D. Kim, and S. H. Park, "Optimal Design for Cushioned package of a Heavy Electronic Product Using Mechanical Drop Analysis," Trans. of the KSNV, Vol.14, No.2, pp. 128-135, Feb. 2004.

[7] C. S. Kim, B. K. Base, and D. Y. Sung, "Drop Analysis of a Package and Cushion Performance of Drum Washing Machine," Trans. of the KSME (A), Vol.34, No.11, pp. 1733-1740, Nov. 2010.

[8] J. W. Yi, D. Y. Ha, S. W. Lee, J. M. Lim, G. J. Park, "Development of Design System for EPS Cushioned package of Monitor Using Axiomatic Design," Trans. of the KSME (A), Vol.27, No.10, pp. 228-234, Oct. 2003.

[9] Y. Y. Wang, C. Lu, J. Li, X. M. Tan, and T. C. Tse, "Simulation of drop/impact reliability for electronic devices," Finite Element in Analysis and Design, Vol.41, Issue 6, Mar. 2005.

[10] M. P. Bensøe and O. Sigmund, "Topology Optimization, Theory: Methods and Applications," Springer-Verlag, Berlin, 2003.

[11] T. Goel, W. Roux, and N. Stander, "A Topology Optimization Tool for LS-DYNA Users: LS-OPT/Topology," 7th European LS-DYNA Conf., 2009.

[12] M. M. Abdalla, S. Setoodeh, and Z. Gürdal, "Cellular automata paradigm for topology optimisation," IUTAM Symp. on Topological Design Optimization of Structures, Machines and Materials: Status and Perspectives, pp. 169-180, 2006.

[13] G. H. Yoon and Y. Y. Kim, "Element connectivity parameterization for topology optimization of geometrically nonlinear structures," Int. J. of Solids and Structures, Vol.42, Issue 7, pp. 1983-2009, Apr. 2005.

[14] A. Erhart, P. Schumacher, N. Lazarov, H. Műllerschön, "Topology optimization with LS-TaSC and Genesis/ESL for crash-loading," LS-DYNA Forum, Germany, 2012.

[15] M. K. Shin, K. J. Park, and G. J. Park, "Optimization of structures with nonlinear behavior using equivalent load," Computer Methods in Applied Mechanics and Engineering, Vol.196, Issue 4-6, pp. 1154-1167, Jan. 2007.

[16] A. Tovar, N. M. Pater, AK. Kaushik, G. A. Letona, and J. E. Renaud, "Hybrid cellular automata: a biologically-inspired structural optimization technique," In Proc. of the 10th AIAA/ISSMO Symp. on Multidisciplinary Analysis and Optimization, AIAA 2004-4558, 2004.

[17] A. Tovar, N. M. Patel, G. L. Niebur, M. Sen, and JE. Renaud, "Topology Optimization Using a Hybrid Cellular Automaton Method With Local Control Rules," J. of Mechanical Design of ASME, Vol.128, pp. 1205-1216, 2006.

[18] N. M. Patel, "Crashworthiness design using topology optimization," Dissertation, University of Notre Dame, 2007.

[19] W. Roux, LS-OPT/Tolopology 1.0, Livermore Software Technology Corporation, 2010.

[20] J. O. Hallquist, "LS-DYNA Theory Manual," Livermore Software Technology Corporation, 2006.

[21] JC. Goetz, H. Tan, J. E. Renaud, and A. Tovar, "Structural topology optimization for blast mitigation using hybrid cellular automata," Proc. of the GVSETS, 2009.

[22] M. P. Bendsøe and O. Sigmund, "Material interpolation schemes in topology optimization," Archive of Appied Mechanics, Vol.69, pp. 635-654, 1999.

[23] WESTPAK, "Cushion Material Testing," Technical Papers, http://www.westpak.com. [accessed Apr. 16, 2012]

Name:
Wonho Lee

Affiliation:
Senior Engineer, R&D Solution Lab, Digital Media Communication R&D Center, Samsung Electronics Co., Ltd.

Address:
R3 19F, 129, Samsung-Ro, Yeongtong-gu, Suwon-si, Gyeonggi-do 443-742, Korea

Brief Biographical History:
2005- Samsung Electronics Co., Ltd.

Main Works:
- Mechanical CAE
- Development of CAE infra / system / software for mechanical designers

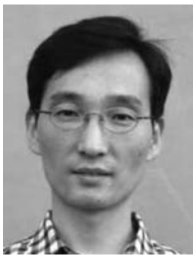
Name:
Jinhoon Kim

Affiliation:
Principal Engineer, R&D Solution Lab, Digital Media Communication R&D Center, Samsung Electronics Co., Ltd.

Address:
R3 19F, 129, Samsung-Ro, Yeongtong-gu, Suwon-si, Gyeonggi-do 443-742, Korea

Brief Biographical History:
1999-2002 Hankook Tire Co, Central R&D Center
2003- Samsung Electronics Co., Ltd.

Main Works:
- Mechanical CAE
- Development of CAE infra / system / software for mechanical designers



Name:
Changbae Park

Affiliation:
Principal Engineer, R&D Solution Lab, Digital Media Communication R&D Center, Samsung Electronics Co., Ltd.

Address:
R3 19F, 129, Samsung-Ro, Yeongtong-gu, Suwon-si, Gyeonggi-do 443-742, Korea

Brief Biographical History:
1994-1999 DAEWOO Heavy Industry
2000- Samsung Electronics Co., Ltd.

Main Works:
- Mechanical CAE
- Development of CAE infra / system / software for mechanical designers