Topology Optimization of Bonnet-like Plate Using Carbon Fiber Reinforced Thermoplastics Subjected to Different Criteria

M.Sc. Thesis

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Abstract

The evolution of fiber composites has resulted in a new paradigm of material selection for automotive industries. In specific, Carbon Fiber Reinforced Thermoplastics (CFRTP) has shown its advantages in the feasibility of mass production as well as its high strength to weight ratio; allowing significant weight reduction compared to conventional steel largely in dominance today. In automotive sectors where weight saving is a major factor in operation, material shift from steel to CFRTP could be an inevitable and societally profitable future of automobiles. In the thesis, topology optimization is conducted on a bonnet-like plate using CFRTP subjected to various load cases and criteria regarding vehicle safety. Furthermore, results of such optimizations are compared to that of existing optimization results using the same material but designed for stiffness only. Finally, conducted optimization is analyzed and verified by Finite Element Analysis (FEA). The purpose of the proposed thesis is to promote vehicle safety and initiation of mass production of automotive parts by the use of CFRTP materials; updating the use of conventional steel components currently in dominance today in automotive industries.

1. Introduction

Industries that make use of Carbon Fiber Reinforced Thermoplastics (CFRTP) are currently dominated by aerospace and supercar industries. For such reason, CFRTP are known to the public as expensive materials. But through extensive research on composite materials, the prices of CFRTP materials are declining [1]. With respect to the declining prices of CFRTP, the trend in the automotive sector is rapidly moving towards CFRTP for its eco-friendly solutions when it comes to final design of products; CFRTP give plausible properties in recyclability and high strength to weight ratio. Such properties raised CFRTP as a valuable candidate to replace conventional steel.

As of 2013, automotive market was still dominated by the use of steel; contributing to 71% of all automotive parts [1]. If CFRTP can be mass produced as automotive components, driving performance and effect of CO₂ emission can be greatly improved [2]. Furthermore, if CFRTP can satisfy or even improve pedestrian safety proposed by European Enhanced Vehicle-safety Committee (EEVC), CFRTP will not only be considered, but will rather be stationed as a new material for future use purposed for initiation of mass production of automotive components.

From airbags to three-point safety belt developed by Volvo [3], industries have largely focused on, and conducted extensive research on human safety by implementing driver safety. Unfortunately, pedestrian safety was largely put aside due to the fact that much of the fatalities occurred in vehicle to vehicle collisions and not vehicle to pedestrian collisions; vehicle to vehicle collisions provided at least 85% of all fatalities in traffic accidents in the United States [4]. It wasn’t until the early 1970s when EEVC started proposing testing procedures for pedestrian safety [5]. Such driver focused
research has resulted in partly satisfying outcome: according to U.S. Department of Transportation, total fatalities due to traffic accidents in the United States dropped from around 43,000 to 33,000 from 2004 to 2013 yet pedestrian fatalities have more or less been stationary during the same time period [4].

Problems regarding pedestrian safety can also be seen with the BMW’s i3 electric vehicle. In 2013, BMW has initiated mass production of new electric vehicle, i3 composed of CFRTP body frame. According to BMW, by the use of CFRTP, i3 has solved battery weight problems that are considered most crucial in most electric vehicles [5]. But there are considerable problems regarding pedestrian safety. In 2013 BMW has tested the i3 with New Car Assessment Program (NCAP). Although the i3 received high rating in driver safety with 80% in safety value, pedestrian rating was at mere 50% according to NCAP head impact testing. From the results, NCAP has described vehicle safety regarding pedestrian safety of the BMW i3 as the following, ‘the bonnet provided protection to the head that was predominantly marginal with poor results.’ Consequently, the BMW group optionally equipped the i3 with pedestrian warning with city brake activation system. But even with such safety system, NCAP has announced that the system only improves pedestrian safety by 10%. As noted, vehicle safety is a crucial factor to consider when CFRTP components are manufactured for mass production in vehicle industries. Also, regarding pedestrian safety, it is clear that CFRTP bonnet component must meet safety protocols proposed vehicle safety organizations.

In 1974, EEVC proposed that pedestrian casualties may be partially solved by redesign of car fronts [6]. As proposed, an automotive component that largely influences the safety of both the pedestrians and the drivers is the bonnet, and according to studies conducted by Otte (1999), the head is most frequently injured in vehicle to pedestrian collisions. Therefore, in order to improve human safety in automobiles, and to conduct topology optimization in regards, behavior of the bonnet upon vehicle to vehicle accidents, and behavior of both the bonnet and the human head upon vehicle to pedestrian accidents should be studied.

Of the CFRTP group, chopped Carbon fiber Tape reinforced thermoplastics (CTT), and the ultra-thin chopped carbon fiber tape reinforced thermoplastics (UT-CTT) will be tested against steel for various optimization processes. Both the CTT and the UT-CTT are composed of randomly oriented unidirectional pre-impregnated tapes. The tapes are manufactured with carbon fiber (TR50S, Mitsubishi Rayon Co., LTD.), and the major differences of CTT and UT-CTT are the tape thickness and the resin; resulting in different material properties. These materials are relatively new types of thermoplastic composite materials. Not all research regarding the material is finalized, and thus, the materials are yet to be considered to be mature, and are yet to be ready for commercial use. Intensive research is currently being conducted in Japan to elevate these materials to mature level in hopes to encourage their application in mass production.

The intention of the proposed thesis is to provide safety prioritized solution, whilst maintaining the highest possible weight reduction of the CFRTP bonnet component through topology optimization. Conducted optimization will then be verified by the use of numerical analysis. The proposed thesis is not intended to provide material properties of the CFRTP materials, but rather to adopt material properties from previous research conducted in prof. Takahashi’s laboratory at the University of Tokyo. The limitation of this thesis is that the molding conditions in manufacturing CFRTP, the
possibility of scatter modulus due to tape scatter, and other factors that may influence the material properties of CFRTP are neglected; therefore assuming idealized material properties. When preliminary research regarding the mentioned limitations is complete, and the materials are considered mature, application of such optimization would be possible in various automotive industries to initiate mass production of automotive parts.

2. Method

Today, optimization methods are extensively used in product development as a tool for optimizing design solutions throughout the product development phase [8]. There are multiple optimization processes that can be applied in the analysis of proposed materials. Throughout the analysis, Multi-disciplinary Design Optimization (MDO) is carried out. In specific, Sequential Dynamic Programming (SQP) via MATLAB is used as a tool for optimization. SQP is one of the methods of a nonlinear optimization using iterative processes. Much of the work focuses on creating adequate constraint functions and objective function. SQP is beneficial in a sense that the constraint functions can be in the form of both equality and inequality conditions. SQP also request for set of bounds for variables that has direct influence on the objective function which can greatly improve computation cost if bounded correctly.

Regarding approaches on optimization of vehicle components, many researches have utilized stiffness as constraining function in order to develop stiffest structure with the least amount of component weight. Although this type of optimization is beneficial for components such as the body frame and chassis; as these components most crucially require rigidity, stiffest structure is unsuitable for components such as the bonnet; as such factor will result in least amount of deformation, which is, according to work energy theorem given as equation [6] below in section 2.4, highly undesirable for components that should be designed for energy absorption in order to provide safety upon impact or collision.

In this thesis, with the considerations regarding energy absorption mentioned above, three considerations are imposed, and therefore, three optimization processes are formed: 1. critical buckling load given compressive membrane load, 2. Tsai-Hill Criterion given various membrane loads and in-plane shear load, 3. Multi-constraint combination of Head Injury Criterion and Tsai-Hill Criterion given impact load. With all three optimization processes, objective is to maximize weight reduction, and therefore, thickness of the bonnet is minimized. The motivations behind the three considerations as well as method of Finite Element Analysis is described below.

2.1 Theory and boundary conditions

In all three optimizations, classical plate theory proposed by Kirchhoff is used, i.e. a mathematical description of the mechanics of flat plates [13]. Plate theory assumes small thickness compared to planar dimensions [13] and therefore reduces the full 3-dimensional problem to a 2-dimensional problem. Unlike theory proposed by Reissner-Mindlin, classical plate theory ignores the effect of shear, and such contribution is rightfully neglected if the length to thickness ratio is large [8], which is the case for a bonnet like plate.

In Plate theory, by the use of Hooke’s law, the quantities of stress and strain can be referred as tensors represented by the use of stiffness and compliance matrices.
Likewise, stiffness and compliance matrices are composed of 9 components of stress and strain, forming matrices of 9 by 9. But in general, there exist symmetric tensors, which in turn transform 9 by 9 matrices into 3 by 3 matrices in Plate theory [8]. Hooke’s law for a plate is then represented as follows:

\[ Q = \begin{bmatrix} A & B & D \\ \end{bmatrix} \]  
\[ [1] \]

\[ [2] \]

The 3 by 3 matrices represented in equation [1] and [2] are formed with material properties of the material of interest; characterized by 5 engineering constants. For an in-plane isotropic plate, engineering constants can be further reduced, thus the matrices can be characterized with 3 engineering constants.

Assume now that some load \( N \) or moment \( M \) is applied to the plate represented in figure 1. Then mid-surface strain \( \varepsilon_0 \) and curvature \( \kappa \) can be represented with the following equation:

\[ \varepsilon_0 = A \varepsilon + B \kappa, \quad \kappa = D \varepsilon \]  
\[ [3] \]

Where A, B and D matrices are extensional stiffness matrix, extension-bending coupling matrix and bending stiffness matrix respectively calculated using stiffness matrix Q from equation [2] and \( z_i \) representing the through thickness distinct position within the plate [8]. A, B and D matrices are then utilized to calculate properties such as critical buckling loads and deflections of a plate.

Regardless of which theory is used, boundary conditions are crucial factor in both analytical and numerical calculations. On the edges of a closed bonnet, there exists supporting component that limits the movement of the bonnet. In most loading conditions, all four edges of the bonnet are clamped, i.e. totally prevented to move. The only case when not all edges are clamped from movement is in the case of buckling. The Critical buckling optimization mentioned below, uses boundary conditions as the following: two edges parallel to loading direction are free, and other two edges perpendicular to loading direction are fully clamped. The two edges parallel to the loading directions being free is a proper assumption since the bonnet upon frontal collision is designed to deflect vertically upwards and buckle in order to increase energy absorption. However, it is important to note here that the two edges perpendicular to the loading directions being fully clamped is a debatable assumption. In reality the boundary condition of a bonnet is neither fully clamped nor simply supported but fall somewhere in between these two
conditions. In the thesis, fully clamped boundary condition is used since the primary concern of the work is pedestrian safety regarding head impact, and fully clamped condition gives more conservative results in regards. Tsai-Hill Criterion optimization and Head Injury Criterion and Tsai-Hill optimization, boundary follows fully clamped condition in all four edges. Unlike the case of buckling, when head impacts the bonnet, or when shear or membrane tension loading is present, supporting components that stop the movement of the bonnet will correspond to fully clamped condition.

Boundary conditions and the corresponding equations needed to calculate deformation properties of a plate is commonly found and represented by Kirchhoff-Love plate theory, now more commonly known as the Plate theory, which is utilized in the thesis. For example, for a fully clamped plate, deflections and rotations are 0 along the edges so that:

\[ [4] \]

Conditions in equation [4] are as expected in fully clamped condition since no deflection or rotation is possible if there exists a rigid component securing the edges from any sort of movement. In fully clamped condition, deflection and rotation are only possible away from the edges, such that \( x/a \) and \( y/b \) components are not 0 or 1; where \( x \) is location along \( x \)-axis divided by total horizontal length \( a \), and \( y \) is location along \( y \)-axis divided by total vertical length \( b \) represented in figure 2 above.

Other boundary conditions such as free edge, simply supported edge, point support, and variations of free edges and clamped edges also exist and are similarly represented in Plate theory and corresponding equations are also available.

2.2 Optimization method 1: Critical buckling

In order to take vehicle to vehicle collisions into consideration, and to simulate similar conditions of an NCAP frontal crash test, optimization process is constrained in the form of critical buckling load, i.e. critical buckling load of steel, CTT and UT-CTT is matched using equality constraint function. In reality, vehicle to vehicle collisions, or vehicle to an object collisions do not always follow testing conditions provided by NCAP’s frontal crash test; collision could occur with a considerable impact angle, or only portion of the vehicle could come in contact with the crashing object. Therefore, critical buckling optimization conducted in the thesis only accounts for one of many NCAP vehicle crash tests. Since the history of automobiles began, large number of frontal collisions has been simulated using steel bonnet in order to take account for driver safety. Such simulations have resulted in crumple zone requirements on a bonnet to increase energy absorption through buckling. It is difficult to exactly understand how composite materials will behave beyond elastic regime. Rather, it is assumed here that the iterative frontal collision simulations in the past assures that the safety protocols are met using
steel bonnet, and thus, if the critical buckling load of the CFRTP bonnet and steel bonnet are matched, CFRTP bonnet will also meet proposed safety protocols.

2.3 Optimization method 2: Tsai-Hill Criterion

Due to dynamic driving conditions of a typical automobile, the bonnet, as well as most other components, will experience various loading conditions. Implementing Tsai-Hill Criterion, consideration is made so that the bonnet component complies with a failure safe design when it comes to loading conditions rising from cornering and other driving conditions. It is difficult to concretely define every loading case on a bonnet. It is therefore more practical to consider various membrane loading cases and in-plane shear loading case. In optimization using Tsai-Hill Criterion, membrane loads in x and y direction both in compression and tension, and in-plane load in x-y or y-x direction represented in figure 1 giving shear load are considered (table 1). Due to the nature of CFRTP, its strength in compression is significantly lower than in tension. Such nature of CFRTP, if membrane loads are in the form of tensile load, will promote higher weight reduction than that of compressive loading case. Therefore, to note the highest weight reduction (tension), the lowest weight reduction (compression), and the average weight reduction, optimization is simulated N = 50 iterations.

<table>
<thead>
<tr>
<th>Loading case</th>
<th>x membrane</th>
<th>y membrane</th>
<th>x-y shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tension</td>
<td>Tension</td>
<td>x-y</td>
</tr>
<tr>
<td>2</td>
<td>Tension</td>
<td>Compression</td>
<td>x-y</td>
</tr>
<tr>
<td>3</td>
<td>Tension</td>
<td>Tension</td>
<td>y-x</td>
</tr>
<tr>
<td>4</td>
<td>Tension</td>
<td>Compression</td>
<td>y-x</td>
</tr>
<tr>
<td>5</td>
<td>Compression</td>
<td>Tension</td>
<td>x-y</td>
</tr>
<tr>
<td>6</td>
<td>Compression</td>
<td>Compression</td>
<td>x-y</td>
</tr>
<tr>
<td>7</td>
<td>Compression</td>
<td>Tension</td>
<td>y-x</td>
</tr>
<tr>
<td>8</td>
<td>Compression</td>
<td>Compression</td>
<td>y-x</td>
</tr>
</tbody>
</table>

Table 1: Loading cases

The membrane loads and shear loads are represented as \( N_x, N_y, \) and \( N_{xy} \) or \( N_{yx} \) in the figure 1 above. The weight reduction is averaged from 50 optimization simulations, and standard deviations for the results are also noted. For each simulation, the process is constrained so that the Tsai-Hill Criterion never exceeds a value of 1 for steel, CTT and UT-CTT. Also the process is constrained so that the Tsai-Hill Criterion value for CTT and UT-CTT never exceeds that of steel. With such consideration failure safe design is promoted using CTT and UT-CTT.

2.4 Optimization method 3: Head Injury Criterion and Tsai-Hill Criterion

Head injuries in vehicle to pedestrian collisions pose a serious threat to life, and complete recovery is often not possible [10]. In vehicle to pedestrian collisions, the head is also the most frequently injured body region resulting in death [11]. Therefore injury risk to the head must be reduced, and such consideration is the highlight of this optimization. In optimization using Head Injury Criterion (HIC) and Tsai-Hill Criterion, three considerations are prioritized to decrease head injury upon impact. First, and most importantly, secondary impact must be avoided. Unlike the bonnet, organ components such as the engine are not designed to deflect upon collision. Therefore, upon impact to
such components, it is predicted that head injury will significantly worsen. Second, in line with expectation given in first prioritization, bonnet must follow failure safe design; implementing Tsai-Hill Criterion. If the bonnet material fails upon head impact, secondary collision is inevitable, and therefore failure of the bonnet must be avoided. Finally, given condition in first prioritization, the bonnet must deflect as much as possible to maximize energy absorption yet staying in the limit of secondary collision. Fulfillment of such considerations is expected to decrease HIC value and thus decreasing the likelihood of head injury. HIC is calculated using the following equation:

\[ \text{HIC} = a \cdot G \left( \frac{t_2}{t_1} \right) \]

Where \( a \) is given as the multiples of gravitational acceleration \( G \), and \( t_1 \) and \( t_2 \) represent impact time interval of less than 15 ms giving maximum HIC value.

In order to calculate the deflection required, a couple of steps are taken. According to Rover Group [12], the critical impact load regarding skull fracture, observed from cadaver experiments is given as 4 kN. Using such load and specifications given in EEVC testing procedure stated in section 2.6 in this report, deflection is calculated via total work and change in kinetic energy relations (the Work-Energy Theorem) given as:

\[ W_{net} = \Delta KE + \frac{1}{2} F z^2 \]

Where \( W_{net} \) is the net work, \( \Delta KE \) is change in kinetic energy, \( F \) is force, \( z \) is vertical deflection, \( m \) is mass and \( v \) is velocity. Force in this case is the critical impact load proposed by the Rover Group [12], and mass and velocity are stated by EEVC testing procedure. Therefore the only unknown is the vertical displacement, and with 65 [deg] impact angle consideration suggested in EEVC and NCAP head impact test, displacement is calculated using equation [6] as 67.1 [mm]. A more detailed utilization of equation [6] with actual numbers is as follows.

<table>
<thead>
<tr>
<th>Known parameters from EEVC testing procedures, and Rover group recommendations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical impact load ( F=4kN )</td>
</tr>
<tr>
<td>Head mass ( m=4.8kg )</td>
</tr>
<tr>
<td>Change in impact velocity ( \Delta v=(40kmh-0kmh)=40kmh=11.11ms )</td>
</tr>
<tr>
<td>Head to bonnet impact angle=65°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculation using equation [6] with known parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4kN \Delta z=124.8kg \cdot 11.11ms \cdot 2 \sin(65°) )</td>
</tr>
<tr>
<td>( \Delta z=67.1 \text{mm} )</td>
</tr>
</tbody>
</table>

HIC is an indirect approach to assess head injury. Concussion and skull fracture phenomena are closely matched with cadaver experimental results using HIC [12]. Although HIC is a good approach to assess injuries largely related to linear acceleration, HIC cannot, and is not a good approach to assess injuries largely related to rotational acceleration and straining of the brain such as hematoma and Diffused Axonal Injury.
(DAI) [20]. Rotational acceleration and straining of the brain should be considered in the future, but with current testing methods, it is stated by EEVC that, ‘Rotational accelerations have been discussed by EEVC WG, however, it was concluded that insufficient data is available to propose an acceptance level’ [13]. In the future, testing methods considering both linear and rotational accelerations should be developed, and optimization should be conducted in regards.

2.5 Geometry

In order to compute scaled comparison to that of existing stiffness optimization conducted by Ohori (2015), and also to comply with EEVC testing procedure geometry requirements, dimensions are chosen in regards, and are represented in figure 3 below. EEVC requires wraparound area of 1.5~2.1 [m] by 1.0~1.5 [m], and in Ohori’s journal, plate dimensions of 50 [mm] by 40 [mm] with thickness of 1.5 [mm] is used. Therefore, dimensions used by Ohori (2015) is scaled 3,000%; giving geometry of 1.5 [m] by 1.2 [m]. The thickness of the plate is maintained at 1.5 [mm]. Such scaled geometry fulfills the geometry requirement set by EEVC. Also, the bonnet component is more closely represented with the scaled geometry since most vehicle bonnets have planar dimensions in the range of 1~2 meters: this also explains why the EEVC also requires wrap around dimensions to be the similar range.

![Figure 3: CAD representation of plate via KeyCreator from KUBOTEC](image)

2.6 EEVC testing procedure

Since the 1970s, EEVC started proposing testing procedures including head impact test. EEVC is a committee with the task to improve pedestrian protection and to coordinate necessary research [13]. Head impact test to the bonnet top from EEVC is described as the following [13]:

1. Impactor: Spherical impactor of 4.8 [kg] mass with an accelerometer mounted in the center of the sphere
2. Impact velocity: 40 [km/h] equivalent to 11.11 [m/s]
3. Impact angle: 65 [deg]
4. HIC: Calculated from the accelerometer shall not exceed 1,000

Such requirements proposed are assumed to decrease the likelihood of head injury rising from linear acceleration.

2.7 Numerical analysis

The finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations [15]. FEM cuts a structure into several elements and then reconnects them at discrete nodes. This process results in a set of simultaneous algebraic equations and the problem
becomes finite, unlike continuum problems [16].

To check the validity of optimizations performed in MATLAB, critical buckling optimization results are analyzed using ANSYS, developed by ANSYS, INC., and Head Injury Criterion and Tsai-Hill Criterion optimization results are analyzed using LS-Dyna, developed by Livermore Software Technology Corporation. In LS-Dyna, a model of a head impactor is available that can calculate HIC, and for such reason, two different solvers are utilized in this proposed thesis. Since the bonnet thickness is very small compared to its planar dimensions, and also to lower computational cost, shell elements are used to mesh the bonnet component in both solvers.

3 Material

3.1 Bonnet

CTT and UT-CTT are formed by cutting unidirectional carbon fiber into smaller segments. Then the fibers are dispersed in water as shown in figure 4 (left). The water is drained, and fibers are heated to evaporate moist. Finally the fibers are compressed to form a laminate shown in figure 4 (right).

![Figure 4: Dispersion of carbon fiber tapes, surface representation of UT-CTT](image)

For both CTT and UT-CTT, in-plane isotropic property is assumed. Table 2 presents the material properties of the three materials used in the work.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Steel</th>
<th>CTT</th>
<th>UT-CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ [g/cm³]</td>
<td>7.80</td>
<td>1.35</td>
<td>1.50</td>
</tr>
<tr>
<td>E₁ [GPa]</td>
<td>211</td>
<td>34</td>
<td>41</td>
</tr>
<tr>
<td>E₂ [GPa]</td>
<td>211</td>
<td>34</td>
<td>41</td>
</tr>
<tr>
<td>G₁₂ [GPa]</td>
<td>81</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>G₁₃ [GPa]</td>
<td>81</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>G₂₃ [GPa]</td>
<td>81</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>ν₁₂</td>
<td>0.30</td>
<td>0.33</td>
<td>0.28</td>
</tr>
<tr>
<td>σ₁₁</td>
<td>780</td>
<td>315</td>
<td>528</td>
</tr>
<tr>
<td>σ₂₂</td>
<td>780</td>
<td>315</td>
<td>528</td>
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<tr>
<td>σ₁₃</td>
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<td>370</td>
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<tr>
<td>σ₂₃</td>
<td>780</td>
<td>240</td>
<td>370</td>
</tr>
<tr>
<td>Resin</td>
<td>PP</td>
<td></td>
<td>PA6</td>
</tr>
<tr>
<td>V₉ [%]</td>
<td>-</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>Supplier</td>
<td>TOYOBO CO., LTD.</td>
<td>Industrial Technology Center of Fukui Prefecture</td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Material properties of steel, CTT and UT-CTT [19]

3.2 Head

Components of the head, in detail, can be represented using finite element model as shown in *figure 5* below. The model is developed at KTH Royal Institute of Technology in Stockholm [20], [21].

![Finite element model of the human head](image)

*Figure 5: Finite element model of the human head [21]*

However, for standardized impact testing procedure proposed by EEVC and EURO NCAP, much simpler model is used such as NCAP head model and Hybrid III dummy model represented in *Figure 6*. For NCAP head model, components consist of a rigid sphere coated with a rubber hull [23], and Hybrid III model consists of two brain hemispheres and a rigid skull bone [24]. Both head models are equipped with an accelerometer at their center of gravity [23], [24].

![NCAP head and Hybrid III dummy head models](image)

*Figure 6: NCAP head (left) and Hybrid III dummy head (right) model [23], [24]*

4 Result

4.1 Analytical result

This section is separated into four different subsections. In the first three subsections, results regarding optimization condition, component thickness, and component weight are treated. In the final subsection, weight reduction percentage for the three optimizations as well as weight reduction percentage of existing stiffness optimization is compared.

4.1.1 Critical buckling

<table>
<thead>
<tr>
<th></th>
<th>Steel</th>
<th>CTT</th>
<th>UT-CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization condition</td>
<td>-</td>
<td>Optimized</td>
<td>Optimized</td>
</tr>
<tr>
<td>Critical buckling</td>
<td>-</td>
<td>OK</td>
<td>OK</td>
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</tbody>
</table>
### Table 3: Critical buckling optimization conditions

<table>
<thead>
<tr>
<th>Constraint form</th>
<th>Steel</th>
<th>CTT</th>
<th>UT-CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical buckling load [N/m]</td>
<td>938.59</td>
<td>938.59</td>
<td>938.59</td>
</tr>
</tbody>
</table>

4.1.2 Tsai-Hill Criterion

<table>
<thead>
<tr>
<th>Optimization condition</th>
<th>Steel</th>
<th>CTT</th>
<th>UT-CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsai-Hill Criterion</td>
<td>-</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Constraint form</td>
<td>Inequality</td>
<td>Inequality</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>Iterations</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Relative standard deviation percentage [%]</td>
<td>± 0</td>
<td>± 5.46</td>
<td>± 4.85</td>
</tr>
</tbody>
</table>

Table 4: Tsai-Hill Criterion optimization conditions

![Tsai-Hill Criterion, Thickness Optimization](image1)

Figure 9: Component thickness (Tsai-Hill Criterion)

![Tsai-Hill Criterion, Weight Optimization](image2)

Figure 10: Component weight (Tsai-Hill Criterion)

### 4.1.3 Head Injury Criterion and Tsai-Hill Criterion

<table>
<thead>
<tr>
<th>Optimization condition</th>
<th>Steel</th>
<th>CTT</th>
<th>UT-CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td>Infeasible</td>
<td>Optimized</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Head Injury Criterion constraint</th>
<th>-</th>
<th>Violated</th>
<th>OK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsai-Hill Criterion constraint</td>
<td>-</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Constraint form</td>
<td>-</td>
<td>Inequality</td>
<td>Inequality</td>
</tr>
<tr>
<td>Deflection [mm]</td>
<td>67.10</td>
<td>36.60</td>
<td>70.20</td>
</tr>
</tbody>
</table>

Table 5: Head Injury Criterion and Tsai-Hill Criterion optimization conditions

Figure 11: Component thickness (multi-constraint)

Figure 12: Component weight (multi-constraint)

4.1.4 Weight reduction percentage comparison

The two figures below show the final results of all optimizations as well as results from stiffness optimization conducted by Ohori [19]
4.2 Numerical result

Using numerical analysis, the criterion was checked after finalizing the optimization: optimization method 1: critical buckling analysis was conducted in ANSYS, and optimization method 3: multi-constraint (HIC and Tsai-Hill Criterion) analysis was conducted using LS-Dyna. Optimization method 2: Tsai-Hill Criterion numerical analysis was neglected since the optimization was iterated 50 times and conducting 50 numerical analyses was deemed to be too costly.

4.2.1 Critical buckling

<table>
<thead>
<tr>
<th>Component thickness [mm]</th>
<th>Steel</th>
<th>CTT</th>
<th>UT-CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.50</td>
<td>2.75</td>
<td>2.60</td>
</tr>
</tbody>
</table>
Critical buckling load [N/m] | 895.04 | 902.61 | 896.95
Result deviation compared to analytical results [%] | 4.6 | 3.8 | 4.4

Table 6: Critical buckling numerical results

![UT-CTT bonnet representation at critical buckling load (ANSYS)](image)

Figure 15: UT-CTT bonnet representation at critical buckling load (ANSYS)

4.2.2 Head Injury Criterion and Tsai-Hill Criterion

<table>
<thead>
<tr>
<th>Component thickness [mm]</th>
<th>Steel</th>
<th>UT-CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td></td>
<td>2.56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Head Impactor</th>
<th>Free Motion Headform FMH (LS-Dyna)</th>
<th>Free Motion Headform FMH (LS-Dyna)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impactor mass [kg]</td>
<td>4.54 ± 0.05</td>
<td>4.54 ± 0.05</td>
</tr>
<tr>
<td>Impact angle [deg]</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Impact velocity [km/h]</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Maximum deflection [mm]</td>
<td>39.4</td>
<td>61.6</td>
</tr>
<tr>
<td>Result deviation compared to analytical results [%]</td>
<td>41.3</td>
<td>12.3</td>
</tr>
</tbody>
</table>

| HIC                      | 819.6 | 649.2   |
| Peak acceleration [Gs]   | 108.34 | 80.19 |

Table 7: Multi constraint numerical results
Figure 16: Representation of Head Injury Criterion simulation (LS-Dyna)

Figure 17: HIC results for steel (Resultant acceleration [Multiples of G], Time [ms])

Figure 18: HIC results for UT-CTT (Resultant acceleration [Multiples of G], Time [ms])
5 Discussion

5.1 Critical buckling

Analytical results from critical buckling optimization did not vary significantly compared to its numerical simulation conducted via ANSYS. Less than 5% difference between the analytical and numerical simulations was observed for steel, CTT, and UT-CTT. The difference could be partially explained by couple of simulation deviations between the analytical and numerical methods. First, in the analytical simulation, classical plate theory is used. In the numerical simulation, Reissner-Mindlin theory, or more complex theory is used. Theory such as one proposed by Reissner-Mindlin, as mentioned in the method section, could give slightly more accurate results by taking shear deformations into account but classical plate theory is believed to provide very similar results since the geometry of the bonnet-like plate has high length to thickness ratio. Another explanation could be the meshing of the plates in numerical simulation. Since FEA is never a definite solution, but rather an approximated solution, finer mesh
will most likely always give a better approximated results. But the tradeoff of using finer mesh is the high computation time and increasing amount of data. With such considerations, 40 by 40 elements were used in the model.

With less than 5% error between the analytical and numerical simulations, the proposed thickness and weight reduction using critical buckling optimization promote a definite material advantage using both CTT and UT-CTT.

### 5.2 Tsai-Hill Criterion

For the optimization with respect to the Tsai-Hill Criterion, only analytical simulation was conducted. As mentioned in the method section above, 8 different loading cases were possible, and therefore 50 analytical simulations were conducted; giving variation in optimized results due to different material strengths in tension and compression. It was observed that in the tension-tension loading case, maximum thickness and weight reduction was possible using both CTT and UT-CTT. However, the opposite phenomenon was observed in the compression-compression loading cases; giving lowest thickness and weight reduction.

As shown in the results section, lowest weight reduction in the case of compression-compression loading cases for CTT and UT-CTT were 44% and 60% respectively, and highest weight reduction in the case of tension-tension loading cases for CTT and UT-CTT were 57% and 72% respectively. The mentioned phenomena can be largely explained from the difference in compressive strength and tensile strength for both of the materials. Unlike steel, which has the same strength in both compression and tension, CTT and UT-CTT materials have significantly lower compressive strength compared to their tensile strengths. Thereby the steel component showed no difference in results.

From the analytical results, both CTT and UT-CTT will promote weight reduction compared to steel. UT-CTT offers a significantly higher weight reduction compared to that of CTT.

### 5.3 Head Injury Criterion and Tsai-Hill Criterion

The majority of the work in this thesis was focused on HIC and Tsai-Hill Criterion multi-constrained optimization. Promotion of pedestrian safety on a bonnet-like plate component was considered necessary according to numerous research conducted in the past. So far, according to U.S. national statistics, no improvement on pedestrian safety in relation to improved bonnet design was observed. As stated by EEVC, redesign of car fronts could lead to pedestrian safety [6], and optimization conducted using CTT and UT-CTT could contribute to that. From research conducted by the Rover Group [12], critical impact load related to skull fracture was noted. Using such load, as well as impactor mass and impact velocity proposed by EEVC, deflection requirement on a bonnet using Work-Energy Theorem was calculated. With considerations mentioned in the method section, it was expected that HIC would decrease using CFRTP. Due to violation of constraint, optimization using CTT material was infeasible, and therefore, numerical simulation of head impact was simulated for steel and UT-CTT comparison only.

In the analytical calculation, indirect approach was taken in order to reduce HIC; HIC was assumed to decrease using CFRTP bonnet by increasing deflection, and therefore increasing the energy absorption. From numerical simulation, it was observed
that HIC did significantly decrease using UT-CTT. Also, the deflection of the CFRTP bonnet upon head impact was higher than that of the steel bonnet as expected. The result could be explained by observing the peak acceleration from the simulations; peak acceleration upon head impact for steel bonnet and CFRTP bonnet was measured to 108 [G] and 80 [G] respectively.

Although the impact time interval slightly increased for the CFRTP bonnet, major reduction in peak acceleration resulted in improved HIC. The deflection calculated analytically was higher than what was measured in numerical simulation. The deflection of steel bonnet differed by 41% and the deflection of CFRTP bonnet differed by 12%. Lower deflection could be partially explained from the fact that the headform mass was slightly lower in the numerical simulation than that of analytical calculation. Therefore the impact load would have been lower in the case of the numerical simulation. Also, even though HIC of 1000 was expected for the steel bonnet, the actual HIC was measured to be lower in the numerical simulation. From cadaver experiments, the Rover Group [11] suggested 4 [kN] as critical impact load for skull fracture, therefore giving HIC of 1000. But according to Bain and Meaney (2000) critical impact load was suggested to be 7 [kN] [25]. Using the critical impact load suggested by Bain and Meaney (2000) in Work-Energy Theorem given in equation [2], analytical calculation of the deflection of steel bonnet becomes 38 [mm] which is much closer to numerical simulation deflection result of 40 [mm].

Even though the critical impact load suggested by Bain and Meaney (2000) seems to more closely relate deflection of bonnet to that of numerical simulation, it is difficult to conclude that their suggestion is better or more realistic than what is suggested by the Rover Group [12] since the experimental method used to calculate the critical impact, HIC and critical impact load, differs between the two researches. There are multiple ways to simulate head impact to the bonnet, such as cadaver experiment, animal experiment, dummy experiments and etc. But none of the mentioned methods are suitable comparison to real vehicle to pedestrian collisions. The only way to most realistically measure HIC and critical impact load would be living human crash experiment to the bonnet, but due to obvious injury risk, such experiments involving living human are only conducted in vehicle to wall frontal collision at relatively low velocities to avoid any kind of injury.

Although there are some deviations between analytical and numerical results regarding deflection, it is meaningful to note that HIC clearly decreases using CFRTP bonnet. The multi-constraint optimization using Head Injury Criterion and Tsai-Hill Criterion definitely seems to motivate CFRTP bonnet for HIC reduction, and promote pedestrian safe design. Optimization conducted also seems to verify and support EEVC’s statement that pedestrian casualties may be reduced by redesign of car fronts [6].

5.4 Comparison between optimizations

Three different types of optimizations were conducted in this thesis. In addition to previous optimization conducted by Ohori [19], a fourth set of results could be included in the comparison. From weight reduction results, UT-CTT seems to promote higher weight reduction compared to that of CTT for most optimization cases. The weight reduction was however 1.5% higher with CTT component in the case of critical buckling optimization. Although the strength in compression is higher for the UT-CTT material, the resulting component thickness is slightly higher for the CTT material; giving larger
cross-sectional area. In addition, the CTT material has a slightly lower density compared to that of the UT-CTT material. This could explain why weight reduction in critical buckling optimization is higher for CTT. In Tsai-Hill Criterion optimization, much higher weight reduction is promoted using UT-CTT. Such results are expected since UT-CTT has higher strength to weight ratio than that of CTT. Multi-constraint optimization seems to also promote UT-CTT as a proper candidate to replace steel. Optimization was infeasible for CTT material since the material fails to jointly fulfill HIC consideration and failure safe design consideration. Optimization conducted by Ohori [19] also suggests higher weight reduction with UT-CTT for stiffest design. Comparing the four optimizations, UT-CTT stably promotes weight reduction of 65% or higher without significant difference between the optimizations. Weight reduction using CTT seems to largely vary depending on the criteria used to optimize.

5.5 Future remarks

There are ways to further improve weight reduction of bonnet components using CFRTP. It would be possible to conduct shape optimization in order to vary the thickness within the bonnet so that thickness is higher at locations with higher stresses, and vice versa. Shape optimization with structural stiffener considerations would provide further improved solutions. For example, when using stiffeners on a component, it would be beneficial to conduct a stiffener location optimization; locating the optimal position and shape of the stiffener aiming for the highest possible weight reduction of an overall component. Such mentioned optimizations, if manufacturing of CFRTP with uneven thickness is possible, and if desirable optima can be found, would definitely enable higher weight reduction. Another possibility of further weight reduction would be to use sandwich materials. Using CFRTP skin and different core material, or CTT/UT-CTT skin and different CFRTP core could provide higher weight reduction. Using different CFRTP materials for skin and core are already being researched at the University of Tokyo in prof. Takahashi’s laboratory.

In order to further improve pedestrian safety in the future, rotational acceleration and straining of the brain must be considered. A great portion of brain damage rises from rotational acceleration such as hematomas and DAI. Multi-constraint optimization formed with various constraints emphasizing both rotational and linear acceleration would provide valuable contribution to pedestrian safety. Currently, no proposed solution exists, but such consideration would be the future of pedestrian safe bonnet design.

6 Conclusion

In the proposed thesis, topology optimization was conducted in order to reduce bonnet component weight by using CFRTP materials. Multiple optimizations were conducted in hopes to provide safety prioritized solution yet maintaining the highest possible weight reduction of CFRTP. Results obtained through optimization were further investigated by FEA. The results indicate that, CFRTP materials could be a valuable candidate to replace steel in mass production of automotive components in strive for human safety. With such indications, further research on CTT and UT-CTT seems worthwhile.

From the results obtained, it is suggested that UT-CTT can further improve human safety yet reach over 65% in weight reduction of bonnet component. From the
two different CFRTPs used in this thesis, the UT-CTT material is recommended over the CTT material since more robust optimized solution was observed using UT-CTT. After preliminary research to raise UT-CTT as a mature material is finalized, initiation of mass production of automotive components using UT-CTT could be the ultimate future of automobiles.
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Sang-Won Lim
Tokyo, June, 2016
Bibliography


