STUDY ON THE CONCEPT DESIGN PROCESS FOR THE CRASHWORTHINESS IMPROVEMENT OF AN AUTOMOTIVE BODY STRUCTURE USING A KNOWLEDGE-BASED DATABASE

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Abstract— **The purpose of this study is to propose a concept design process for crashworthiness improvement of automotive body structure using technical information on the major joints and members of vehicles. First, in order to collect the technical information on major joints and members, 43 vehicles were selected using benchmark data. The collected technical information for the selected vehicles was the cross sectional shapes of each joint and member which were used for the analysis of joint stiffness, crashworthiness and static stiffness of the member to make a database along with cross section properties. This study applied a statistical technique to perform a concept design of an automotive body using the analyzed information and selected cross section meeting the design objectives. The criteria for the selection of the cross section were defined by subdividing the defined design objectives of an automotive body structure and constraints into members and joints. In order to configure an analysis model of an automotive body structure using the selected cross section, a shape parametric model was used and crashworthiness was assessed to evaluate the configured automotive body structure. The evaluation result showed that the crashworthiness was improved by 15% and 12% respectively compared to an existing body structure. In addition, the weight of the body structure was reduced by 4.2%. Through this study, the process that can rapidly and effectively derive and evaluate the concept design of an automotive body structure was defined. It is expected that, henceforth, this process will be helpful for the study of automotive body structures.**

Keyword- Body structure design, Knowledge based design, Conceptual design, Crashworthiness, Cross-section database

I. INTRODUCTION

Due to the development of new crashworthiness techniques, vehicle safety has greatly improved over the past 30 years. Fig. 1 shows the development in crashworthiness since the 1980s as the risk of permanent medical impairment and the risk of fatality. The risk of permanent medical impairment can be seen to have been halved when comparing car models introduced in the early 1980s with models introduced within the last 5 years, while the risk of fatality has dropped 85 % during the same time period. (e.g. [1])

Though automakers have added many features to help drivers avoid collisions, such as anti-lock braking systems and traction control devices, vehicles also include many other crashworthiness features such as rigid steel occupant-cells surrounded by strategically placed, energy absorbing components. Nevertheless, demand for crashworthiness technology development remains strong. In view of this, higher demands have been advocated to ensure higher standards of safety in vehicles. This has lead to continuous research in the design of efficient energy absorbers to dissipate energy during an accident while protecting the occupants of the vehicle.
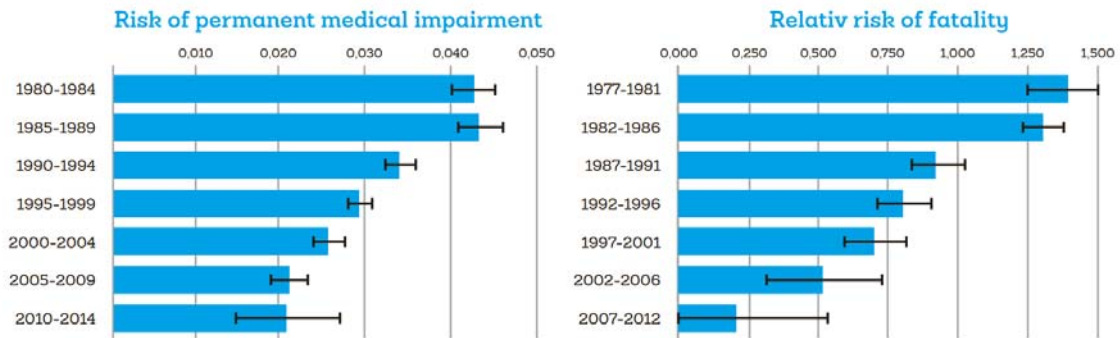
Fig. 1. Development in crashworthiness since the 80s as risk of permanent medical impairment and risk of fatality (e.g. [1])

Most automobile companies apply this process in the very early phase of the project at a point where the ability to influence the direction of development is high and the cost to judge the feasibility of implementation is relatively low [2]. As can be seen in Fig. 2, the design freedom at the concept design phase is higher than in other design phases. Therefore, various design ideas can be applied at the concept design phase and a design meeting various requirements can be derived by examining the performance of each application plan. If the design accuracy increases at the concept design phase, the number of design changes can be reduced at the detail design phase, leading to reduced time of design development and cost savings. This study describes the difference between a new design methodology and the existing design methodology by investigating a design methodology to improve accuracy at the proposed concept design phase and by proposing a new design methodology.
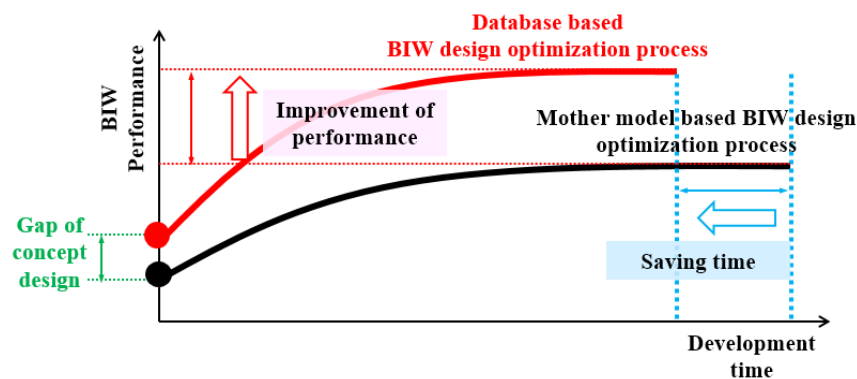

Fig. 2. Status of product knowledge level, degree of freedom for decision and cost responsibility at vehicle development process

A. *Investigation of Documents Related to the Concept Design Process of an Automotive Body Structure*

In current prevalent concept design theories, a high fidelity concept model is constructed using three design methods: methods based on the predecessor model, and methods "from scratch". (e.g. [3]) Methods based on predecessor models could achieve higher design efficiency compared with other methods since predecessor models include essential design factors such as load path information of the load case. Duddeck used the SFE CONCEPT, an engineering tool using an implicit parameterization technique, for his concept model construction. The parameterized model was based on the reference model, and the design target was crashworthiness improvement. (e.g. [4]) The "from scratch" method is used at the very beginning of the design process. It could be classified as topology optimization and the functional layout design of load-carrying components. Topology design optimization is shape and size optimization by eliminating material from the admissible design space. World Auto Steel, the automotive group of the World Steel Association, used topology optimization for skeleton structure design in an FSV program (e.g. [5], [6]). The FSV program developed this initial structure by considering three longitudinal load cases, two lateral load cases and one vertical load case, as well as investigations about bending and torsional static stiffness. Though the topology optimization was able to provide an initial starting point for the FSV's geometry, it is limited by its static approximation of dynamic crash loads and does not consider grade variations of the sheet metal within the structure. Linli Tian used a topology optimization method based on an equivalent static loads method (ESL) for optimization of automotive body-in-white subjected to representative crash loads. (e.g. [7] Also, the functional layout design used a simple geometric description of functional elements such as beam, joint and panel. F. Tarlochan describes a computationally aided design process of a thin wall structure subject to dynamic compression in both axial and oblique directions. The performance parameters used are the absorbed crash energy, crush force efficiency, ease

of manufacture, and cost (e.g. [8]). G. H. Bae suggested a simplified side impact analysis method for improvement of side crash performance. (e.g. [9]) Hidekazu Nishigaki predicted the collapse behavior of the frame member using First Order Analysis (FOA) as a method, which engineering designers can use easily in an initial design stage. (e.g. [10])

B. Methodology

The design methodology proposed by this study involves deriving a design that is close as possible to the design objectives by examining various design problems at the initial design phase with high design freedom. To do this will require information on each phase of the automotive body structure design including information on the design problems related to the parts and subsystem of the body structure, as well as information on the relationship between the phases. It is expected that the higher the accuracy of such information, the higher the accuracy of the design defined at the initial design stage. In order to do this, this study attempted to obtain the information necessary for design through the information on the development of the existing automotive body structure. That is, this study built a database of the shapes of automotive body structures by benchmarking them, converted the shape information of key joints and members of the automotive body structures into CAD data to establish analysis models, and established a database of the information on the design stage of the body structure subsystem. In order to utilize this database, the design problems were defined first, and the design process configuring the automotive body structure was defined as shown in figure 3 by selecting those cross sections suitable for the design problems from the defined relational formula. This study describes the method to establish a database for each phase in Chapter 2, the method to carry out the design using the database in Chapter 3, and the conclusions of this study in Chapter 4.
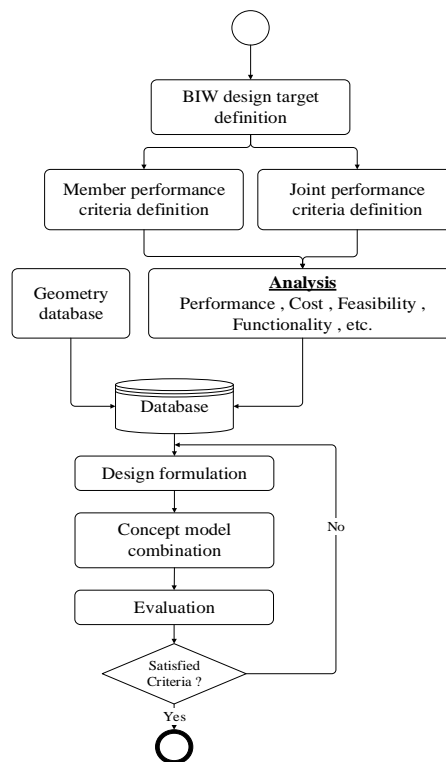

Fig. 3. Evaluation and decision activities in the design process.

II. HOW TO ESTABLISH THE DATABASE

This study used the benchmark data of automotive body structures in order to establish a database which was the core of the proposed design methodology. From the benchmark date, cross section shape information of key joints and members is collected. Then, using the cross section shape information, performance analysis of joints and members for database establishment is progressed.

A. Benchmark Data Collection for Database Establishment

The benchmark data on a total of 43 types of vehicles was used for each vehicle segment. TABLE I shows these vehicle segments. Since the vehicle to be designed in this study was a B-segment vehicle, data was collected focusing on the B-segment.

TABLE I. Vehicle segment distribution of knowledge-based database

Vehicle segment	Vehicle number
A	3
B	17
C	13
D	3
M	7

In general, the subsystem is divided into bisections vertically (upper / under) or trisections (front / middle / rear) horizontally. However, this study defined the subsystem as the key joints and members (A pillar upper joint, A pillar middle joint, A pillar lower joint, B pillar upper joint, B pillar lower joint, C pillar upper joint, front member, and rear member) as shown in Fig. 4.
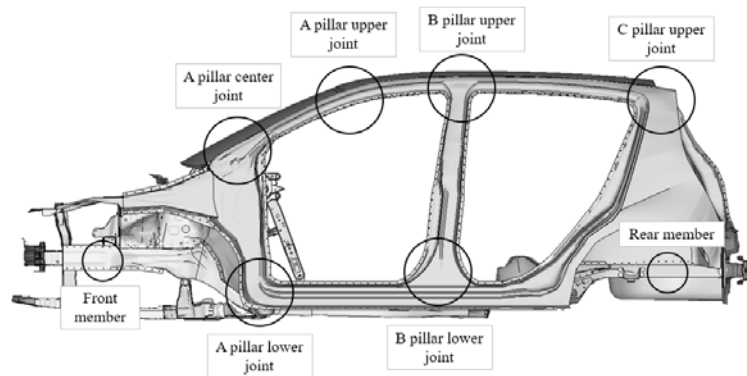
Fig. 4. Selected body joint part and member for cross section shape database generation

Fig. 5 is example of cross section shape information of key joints and members in benchmark data. In this study, 314 cross section shape information is collected.
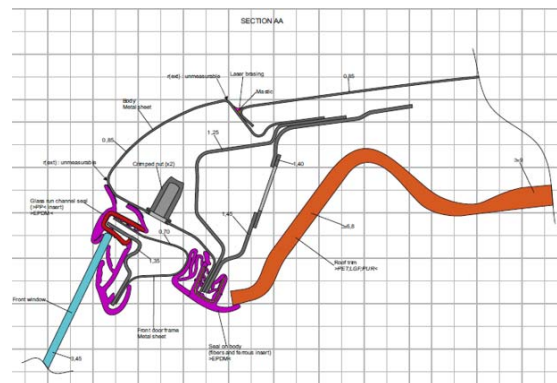

Fig. 5. Example of cross section shape information of key joints and members in benchmark data

B. Performance Analysis of Joints and Members for Database Establishment

The performance index related to the performance of an automotive body structure was defined in order to analyze the performance of each joint and member. This study evaluated the axial compression characteristics and bending collapse characteristics related to the crashworthiness of a vehicle, as well as the static stiffness (bending stiffness, torsional stiffness) and joint stiffness, which were related to the body structure stiffness, and made a database of these values. In addition, the manufacturing cost was estimated when applying each material as well as its performance in order to analyze the difference in the performance of mild steel and advanced high strength steel.

1) *Axial compression characteristics*: In this study, buckling load (peak load) is used for axial compression characteristics of members. For more detail analysis, as shown Fig. 6, eigenvalue analysis was performed to predict the point at which buckling occurs in order to analyze the structural behavior due to structural instability. By performing post buckling analysis applying only up to the tertiary mode as the resultant value of the mode shape for which eigenvalue analysis was completed, it was possible to predict the geometric characteristic and position at which buckling occurs (e.g. [11]) .
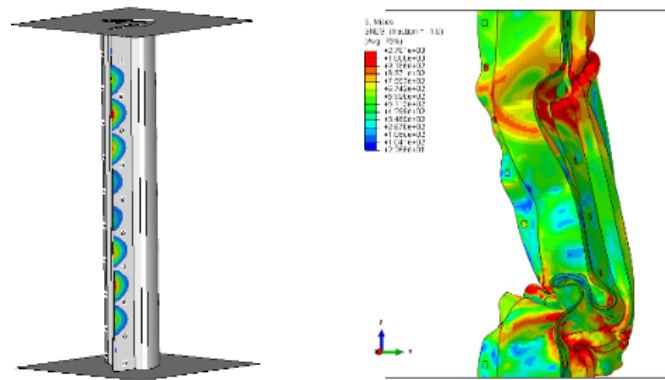
Fig. 6. Example of buckling analysis

2) Bending collapse characteristics: And this study analyzed the bending collapse characteristics of the key members in order to evaluate the bending stress of the key members which occurs due to a collision of the automotive body structure. The Kecman's analysis has mainly been used for the analysis of the bending collapse characteristics. Kecman performed experiments with cantilever beam bending by completely fixing one end of a beam. Since the bending collapse equation derived by him has coefficients that must be determined through experiments, it can be called a semi-empirical formula. (e.g. [12]) Therefore, this study made an experimental device the same as the one used for the experiment proposed by Kecman to evaluate the bending collapse characteristics of each member.

3) Static stiffness: Furthermore, it is important to define the boundary condition in order to evaluate the static stiffness of each member since a simple evaluation of the static stiffness of a cantilever with one end being completely fixed may derive a result different to the actual behavior of an automotive body structure. Therefore, this study analyzed the bending characteristics by establishing an analysis model in the shape of a beam with both ends being simply supported. Also, in the case of the torsional stiffness, the static torsional characteristics were analyzed by defining the boundary condition with the same condition (e.g. [13]).

4) Joint Stiffness: And the rotational stiffness of a joint has a significant influence on the natural frequency of a vehicle due to local deformation. Therefore, various studies have been performed concerning the joint stiffness, and as a result, various methods to predict joint stiffness using a formula as well as the methods to calculate joint stiffness taking nonlinearity into consideration are presented (e.g. [14], [15]). S. B. LEE suggested numerical approximation of joint stiffness using the response surface method in terms of beam section properties (e.g. [16]) Nicklas Bylund is used dynamic stiffness for joint stiffness estimation. For this he defined Dynamic equation governing the joints. (e.g. [17]). This study built key joint models and derived the joint stiffness through linear static analysis and nonlinear quasi-static analysis using the tip moment method. The analysis conditions were derived as shown in Fig. 7 by extracting joints from the vehicle model and constraining the six degrees of freedom at one end of a joint branch.
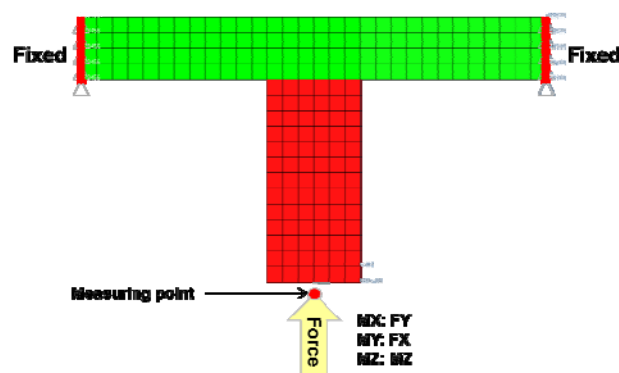

Fig. 7. Boundary condition for joint stiffness analysis

In addition, the load was defined according to the length of each joint branch and the defined load and moment were applied in the direction of the set local coordinate respectively, and then the rotation angle of each direction was measured at the point to which the load is applied.

III. AUTOMOTIVE BODY STRUCTURE CONCEPT DESIGN USING THE DATABASE

The object of this study is the improvement of crashworthiness (side impact and roof crush) and lightweight design using a database which is constructed in Chapter 2. For this, the design criteria was first defined by the body structure requirement of side impact and roof crush. And then, cross sections for concept design were selected by the defined design criteria.

A. Design Criteria Definition

To define the design criteria, load path analysis of side impact and roof crush was progressed. In this study, the crash performance evaluation was carried out for two test conditions, i.e., FMVSS 214 side impact and FMVSS 216 quasi-static roof strength. The body design requirement of side impact is that the body side crush load should be high, because increased side crush force decelerates the barrier quickly before impact with the occupant. Physically, this high side crush force can be achieved with rigid side-to-side structural members aligned at the barrier face height as shown in Fig. 8. (e.g. [18]) Therefore, the cross section of the B pillar beam and rocker panel, which satisfy such constraints as a 10% improvement of maximum bending moment and buckling load compared with the reference model, are determined as design targets.
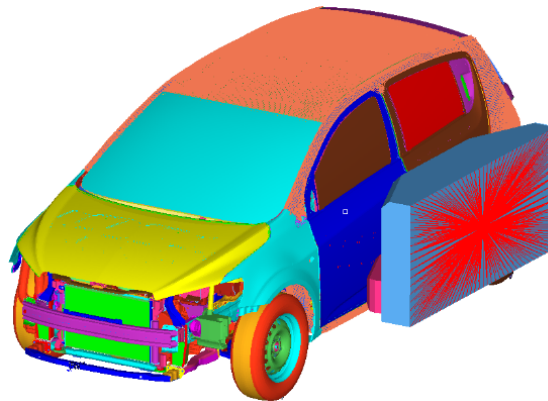

Fig. 8. Side structural members aligned at the barrier face height

For the stick model used to understand the sectional loading conditions of a roof crush such as shown in Fig.9, the FMVSS 216 condition was considered. As a result of calculation using NASTRAN, the A pillar and B pillar, and roof rail would carry approximately 85% of the total necessary roof strength load. Therefore, the cross section of the A pillar joint, roof rail beam and B pillar beam, which satisfy constraints such as 10% improvement of maximum bending moment and buckling load compared with the reference model, are determined as design targets.
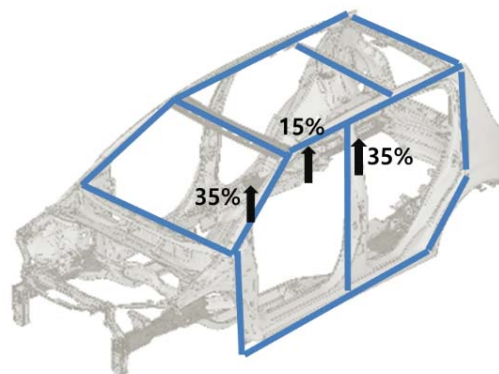

Fig. 9. Distribution of the reaction forces estimation using first order model

B. Result of Concept Design and Establishment of Analysis Evaluation Model

First of all, performance of the reference model's key joint and members (beams) was analyzed for concept design and information retrieved from the database. The first step, the candidates, which satisfy the constraints, are picked out, and then the lightest cross section is selected as the optimal model. Fig. 10 ~ Fig. 13 show the performance of the member and joint to which each selected cross section is applied. From the results of the performance comparison, it was found that another model was selected in the A pillar upper joint, front roof cross member, side roof rail beam and rocker panel beam. The performance of the reference model is optimal in

the A pillar middle joint, A pillar lower joint, B pillar upper joint, B pillar lower joint, C pillar upper joint and rear member.
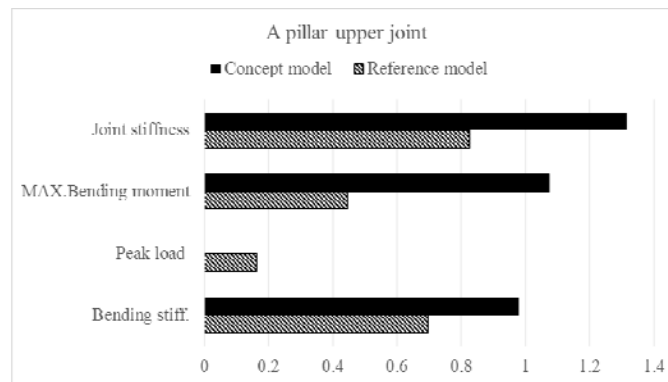

Fig. 10. Performance comparison of A-pillar upper joint to which selected cross section
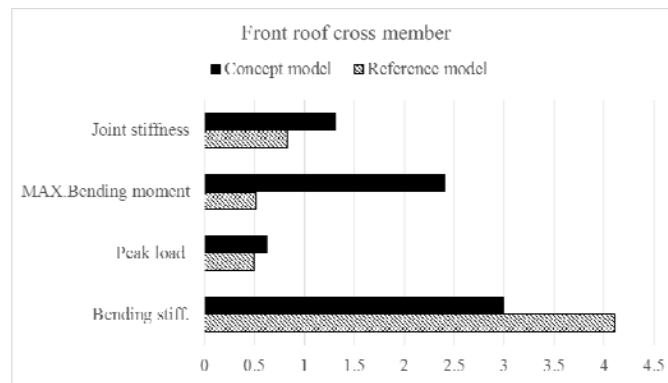

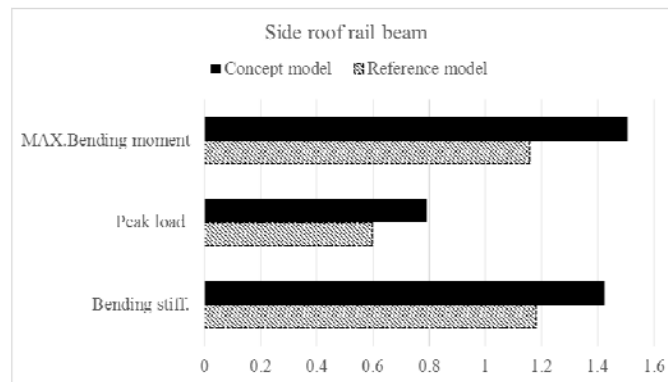Fig. 11. Performance comparison front roof cross member to which selected cross section

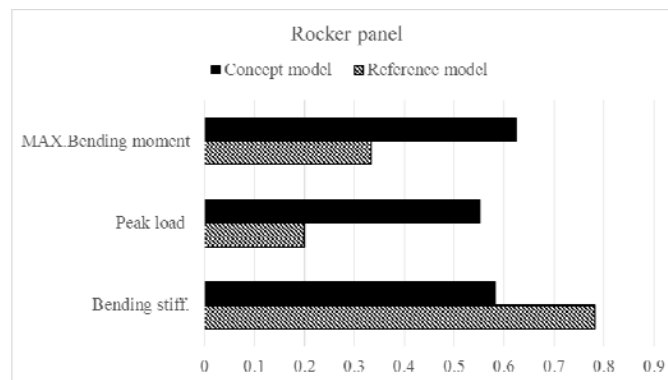Fig. 12. Performance comparison side roof rail beam to which selected cross section

Fig. 13. Performance comparison rocker panel to which selected cross section

An analysis model was established to evaluate the performance for the body structure concept design by applying the selected joints and member to the body structure. In order to establish the analysis model, a parametric model was established using the SFE CONCEPT, which is an engineering tool using implicit parameterization technique. The parametric model signifies a model with the design parameter and model shape directly connected. Fig. 14 shows the established model.
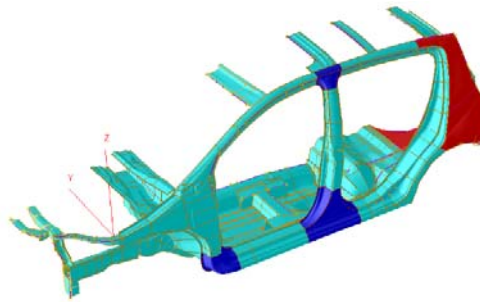

Fig. 14. Construction of automotive body structure conceptual design using SFE CONCEPT

C. Automotive Body Structure Concept Design Evaluation Result

For the evaluation of the body structure, this study evaluated crashworthiness and checked the performance changes compared to the reference body structure. For this, side crash and roof crush analysis were performed using LS-dyna. Fig. 15 ~ Fig. 17 are result of side impact and roof crush. TABLE II shows the evaluation result summary.
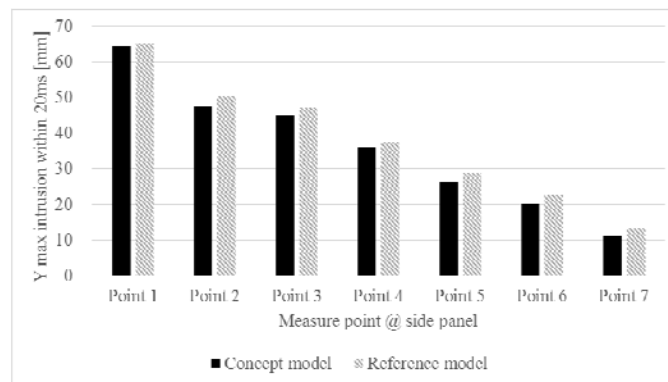

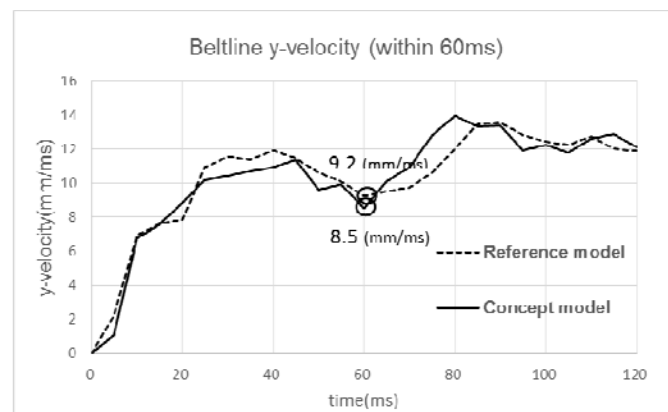Fig. 15. Side crash analysis result: Y max intrusion within 20ms

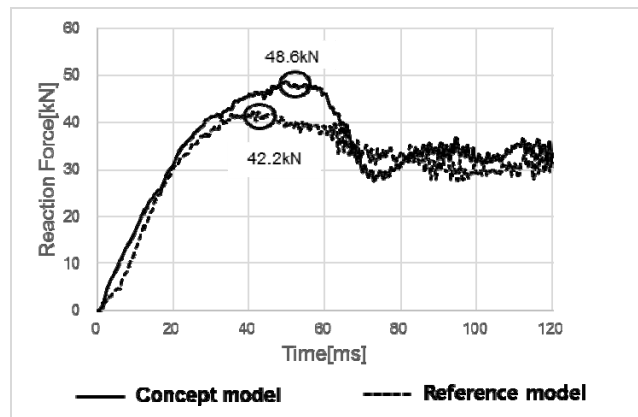Fig. 16. Side crash analysis result: Belt line y velocity

Fig. 17. Roof crush analysis result

TABLE II. Performance evaluation result

Performance index		Concept model
Crashworthiness	Side crash	15% improved
	Roof crush	12% improved

It was found from the evaluation result that crashworthiness, side crash and roof crush increased by 15% and 12%, respectively. The reason for the significant increase in crashworthiness compared to static/dynamic stiffness is that the selected cross sections include the cross section to which advanced high strength steel (AHSS) was applied. Fig. 18 shows the properties applied to the concept design.
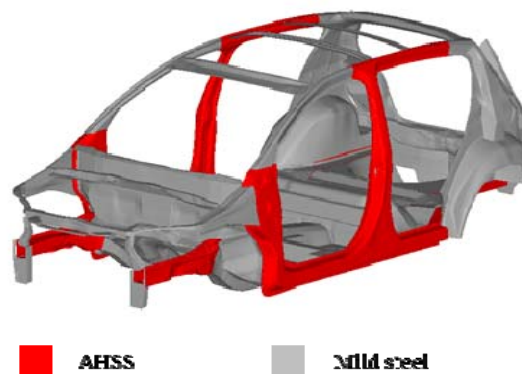

Fig. 18. Material distribution of concept model

IV. CONCLUSION

This study proposed a concept design methodology using a database for the structural performance and shape of the key joints and members configuring an automotive body structure in order to improve design accuracy at the concept design phase. This study used the information on cross sections of 43 produced vehicles. In addition, this study defined the key joints and members as a subsystem of an automotive body structure, and analyzed the crashworthiness and static stiffness of each joint and member to make a database. Lastly, it was made possible to predict the performance of an automotive body structure for cross sections by establishing the relationship between the subsystem and body structure. In order to perform the concept design of an automotive body structure using the database established as such, the design problems that defined the purpose of body structure design and constraints were formulated, and a What-If study technique was applied to select an optimal model, which is a design parameter, according to the defined design problems. A model meeting the design purpose was then selected and in order to configure an automotive body structure with the selected model, a shape parameter model was used. In order to evaluate the performance of the configured body structure, the crashworthiness was evaluated and by comparing the results with the reference automotive body structure, the reliability of the body structure established by the design methodology proposed by this study was secured.

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