Development of Crashworthy Structure Composed of Aluminium Alloys for High-speed Railway Vehicle

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Abstract

Passive safety performance is a crucial issue that keeps a survival space when a crash occurs. It is a key to minimize the risk of injury to the crew and passengers. In this paper, we describe the newly developed crashworthy structure composed of aluminium alloys for high-speed railway vehicle and the essential technologies to achieve the performance effectively. The vehicle can absorb 1.2MJ under full-face collision condition and 0.75MJ or more under overriding condition. At the intermediate-end of the vehicle, it absorbs 1.1MJ under full-face collision condition. Further more, the unit train can keep the survival space without any large deformation against the collision scenarios of Technical Specification for Interoperability, such as the collision of two identical units at 10m/s. Meanwhile, the newly developed energy absorption block contributes to achieve good balance and stable energy absorption. In addition, full-scale collision tests using the prototype of the front-end and intermediate-end have been carried out to confirm the fundamental collision characteristics and ensure the accuracy of the analysis method. The verified analysis method was also applied to evaluation of the modified crashworthy structure and contributed to achieve the required performance. The developed crashworthy structure is employed for a car body of UK class395 high-speed train at a maximum speed of 62.5m/s (225km/h).

1 Introduction

A special interest for the collision safety of railway vehicle has emerged with increasing operational speed and interoperation. In particular, passive safety performance is a key to minimize the risk of injury to the crew and passengers [1-4]. Actually, a serious crash accident still happens [5,6]. Thus, the passive safety performance is a crucial issue that keeps a survival space when a crash occurs. The crashworthy structure should be deformed in a well-balanced manner and absorb energy stably. And the carbody shell itself should withstand large deformation. The crashworthy structure also has static strength against the loads that are worked by a low impact accident or normal operation. For high-speed train, it is necessary to take into consideration pressure variations that occur when a train runs through a tunnel. In addition, a number of requirements for the crashworthiness performance of railway vehicle are regulated in Europe [7,8]. To achieve the above requirements, the crashworthy structure should be designed to satisfy both the energy absorption performance and static strength. For now, steel skeleton construction is mainly applied [9, 10]. However the steel skeleton structure is not appropriate to the aluminium airtight carbody against pressure variations, and there are the difficulties in weight saving and speed dependency of steel strength, which is to be considered. In such a background, we have developed the high-speed railway vehicle having the crashworthy structure composed of aluminium alloys on the front-end and intermediate-end of the vehicle [11-13]. The crashworthy structure is mainly composed of aluminium alloy. And the car body shell is composed of aluminium double-skin extrusions and fabricated by low-heat-input joining using Friction Stir Welding (FSW) [14, 15]. In this paper, the outline of development process is described at first. After that, we describe the developed crashworthy structure, crash characteristics and detail of key technologies to achieve goals.
2 Development process and goals

The process of our study is shown in Figure 1. As a first step of study, we set the fundamental specification of crashworthy structure based on the regulation shown in Table 1. A minimum energy absorption of 1.0MJ under full-face collision condition at each end was set as a target. In addition, a minimum energy absorption of 0.5MJ under overriding collision condition at front-end was also set as a target. These targets were derived from the structural requirement of British Railway Group Standard (RGS) [7]. Furthermore, the specific collision scenarios that are defined in Technical Specification for Interoperability (TSI) [8] were also set as a development goal. It was set to ensure the integrity of survival space of car body. In the applied TSI, there are the following collision scenarios; 1) the collision of two identical units at 10m/s, 2) the collision with 15x10^3kg mass buffered wagon at 10m/s, and 3) the collision with 50x10^3kg mass obstacle at 30m/s. At a next step, we made the concept of the structure. The energy absorption scenario to control collision behavior and performance is built. In the scenario, the coupler, frames of car end structure and energy absorption blocks were taken into consideration. The relationship between the displacement from the edge of the car body and its collision load was estimated to satisfy the required performance. At this step, we decided the rough layout of the crashworthy structure based on the energy absorption scenario. The energy absorption block was also employed to achieve stable and efficient energy absorption. At a next step, materials for the structure are selected as listed in Table 2. Aluminium plate and extrusions are employed. The component of the main structure is design and developed at a next stage. The energy absorption block was also developed as aluminum hollow extrusions. After the component design, we decided the more detailed shape of the structure. Then, we manufactured the full-scale crashworthy structures of front-end and intermediate-end respectively by way of trial. Quasi-static collision tests using the full-scale prototype crashworthy structure were carried out. The purpose of each test was to confirm the fundamental collision characteristics and ensure the accuracy of the analysis method. After the test and validation, we modified the crashworthy structure to apply to the actual carbody and evaluated the required performance by analysis that was validated. On the analysis of this step, the carbody shell built by FSW was included in the model to evaluate the integrity of the survival space. The result of each step is described in the following sections.

<table>
<thead>
<tr>
<th>End type</th>
<th>Crash mode</th>
<th>Min. Energy Absorption (MJ)</th>
<th>Max. Force (kN)</th>
<th>Max. length of the structure (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cab</td>
<td>Full face</td>
<td>1.0</td>
<td>3000</td>
<td>1.0</td>
</tr>
<tr>
<td>Override</td>
<td>0.5</td>
<td>3000</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Intermediate</td>
<td>Full face</td>
<td>1.0</td>
<td>3000</td>
<td>1.0</td>
</tr>
</tbody>
</table>

(a) Crash scenario regulated in RGS

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Crash mode</th>
<th>Acceleration</th>
<th>Other</th>
<th>Stiffening of the survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5m/s</td>
<td>5m/s</td>
<td>Below</td>
<td>5.0g</td>
</tr>
<tr>
<td>2</td>
<td>820m Wagon</td>
<td>10m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>150m Lorry</td>
<td>30.4m/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Crash scenario regulated in TSI

Figure 1: Development process of crashworthy structure

Table 1: Regulations on crash condition
### Crashworthy structure

The exterior appearance of developed crashworthy structure of each end, front and intermediate, is shown in Figure 2. To satisfy the specifications listed in Table 1, it is necessary to absorb a great deal of energy generated during collision and reduce the acceleration. On top of that, it is necessary to make a measurement for weight saving and pressure variations that occur when a train passes through a tunnel at high speed. At the front-end structure, energy absorbing structure is placed at the forward part of cab end wall. It is designed to fit to a streamlined shape. And it is fixed by bolts to ease repair when it works. Furthermore, the blocks are covered by an aluminium box structure to withstand the static load. Stiffeners are placed above the aluminium box structure to prevent overriding. These support the smooth energy absorption without unexpected deformation of the principle structure. The anti-climber and its support box are placed at the lower part. These structures are only made of steel to withstand 1500kN compressive force as a proof load that is regulated in RGS. At the intermediate-end, the structure is designed as an airtight body by using aluminium plates and extrusions. The energy absorption block is placed under the floor. The crashworthy structure itself is also fixed by bolts to the carbody shell for ease of repair. The structure of crushable space at each end will be absorbed by plastic deformation of materials during collision. On the other hand, that of survival space will be kept without large infringement.

![Diagram](image)

**Figure 2: Developed crashworthy structure composed of aluminium alloys**

### Energy absorption block

In regard to absorbance of energy, energy absorption blocks that can efficiently absorb energy in compact and lightweight structures have been developed. Aluminium alloys are employed to consider the following items; 1) the carbody shell is made of aluminium alloys, 2) stability of the collision mode, 3) comparing with steel, a gap between peak and average collision load is smaller. In addition, hollow extrusions, A6063S-T5 (JIS H4100), are employed to improve the productivity of fabrication process and reduce the strength variance by heat affection of welding. As the shape of block, a 2-layered octagonal section is employed to fit to

<table>
<thead>
<tr>
<th>JIS</th>
<th>Designation</th>
<th>BS EN</th>
<th>Designation</th>
<th>Product form</th>
<th>Application part</th>
</tr>
</thead>
<tbody>
<tr>
<td>H4000</td>
<td>A5083P-O</td>
<td>573-3</td>
<td>AW-5083-O</td>
<td>Plate</td>
<td>Body panel, beam and stiffeners</td>
</tr>
<tr>
<td>H4100</td>
<td>A6063S-T5</td>
<td>573-3</td>
<td>AW-6063-T5</td>
<td>Extrusion</td>
<td>Energy absorption block</td>
</tr>
<tr>
<td>H4100</td>
<td>A6N01S-T5</td>
<td>573-3</td>
<td>AW-6005-T6</td>
<td>Extrusion</td>
<td>Floor and beam</td>
</tr>
<tr>
<td>H4100</td>
<td>A7N01S-T5</td>
<td>573-3</td>
<td>AW-7005-T6</td>
<td>Extrusion</td>
<td>Collision pillar and corner frame</td>
</tr>
</tbody>
</table>

Table 2: Aluminium alloys for crashworthy structure
the streamlined shape of front-end. Ribs are placed symmetrically to collapse in a straight-line and not to interfere with each other when collapsed. The collapse behavior of developed block as an example is described in Figure 3. The outside dimension of testing block is 210mm. The length before testing is 440mm. The figure clearly shows that while collapse continues, regular smooth buckling and creasing occur as energy is absorbed. Moreover, the analysis results successfully express the same behavior, so the predictive accuracy can be considered high enough. The absorbing energy of this test specimen is 144kJ by 276mm displacement. It is adequate performance as the component of crashworthy structure to achieve the design target.

![Figure 3: Collapse behavior of the energy absorption block](image)

### 5 Fundamental crash characteristics and accuracy of analysis

The quasi-static full-face collision test was carried out to verify the fundamental crash characteristics under the condition of RGS. In addition, the calibration of crash analysis in comparison with testing was carried out to assess accuracy. Figure 4 shows the overview of the test specimen under collapsing. As a result of the test, a prototype structure was stably deformed in a well-balanced manner. And collision mode is well matched between testing and analysis. It shows that no deformation has been observed at cab main structure. In other words, the crew and passenger survival space has been preserved in this collision condition. As a representative case, the force-displacement characteristics at the front-end structure are shown in Figure 5. 1.2MJ energy is absorbed at 440mm stroke and the analysis result of force-displacement characteristic almost matches the test result thereof. However, characteristics from 75mm to 225mm displacement are slightly unmatched. The variance might be caused by the difference in initial geometry and constraint condition between the analysis model and test specimen. Because the test specimen is a welded structure, the range of the heat-affected zone (HAZ) and bead depth will be slightly different from that of theoretical model. The accuracy of analysis in comparison with test result is calculated from the displacement. Here, we defined that a displacement of 1.0MJ energy absorption is an effective “stroke”. The error of stroke is 2.9%. In the case of the overriding collision of front-end, the error of estimation is 3.5%. In the case of the full-face collision of intermediate-end, the error of estimation is 9.9%. In other words, the energy absorption can be estimated by analysis within 10% error. This result shows that the stroke estimation achieving 1.0MJ energy absorption by numerical analysis is well matched between analysis and test results. On the other hand, the collision force has been kept over 3000kN after 250mm displacement. The force should be controlled to be less than 3000kN until required energy absorbing. Thus, we modified the prototype model by using the verified analysis to comply with RGS.
6 Crash performance of the train with modified crashworthy structure

After the testing and verification of analysis, the prototype model was improved to be an actual production model. In this process, a verified analysis method is employed. The carbody shell of saloon area is included in the analysis model and its integrity is evaluated under the condition of RGS and TSI. The unit train set with bogie and coupler model is employed for the evaluation under the condition of TSI. As an example of TSI standard, Figure 6 shows deformation of the cab and intermediate section in accordance with TSI scenario1. It is clear that in either of the front train scenarios, the deformation is limited to the crashworthy structure, and even around the driver’s cab, the survival space for the driver is adequately secured. This result confirms that the passenger sections are protected against deformation during collision. At the intermediate section of the right side train, deformation is also limited to the crashworthy structure. The saloon sections are preserved without large deformation. Force-time characteristics of leading vehicles are shown in Figure 7. For first 0.17s, deformation is generated at the coupler. After that, the crashworthy structure of front-ends as shown in Figure 2(a) starts to deform. In this time, peak 5000kN force is generated, however, lasts for less than 0.005s. Thus, this peak force can be ignored. It cannot make a large impact on the collision mode. The collision load at front-ends keep 3000kN or less and the energy absorption is lasting until 0.4s. At 0.4s, collision between the leading and 2nd vehicle occur. The reversed force value shows that the intermediate-end of 2nd vehicle is deformed at first. However deformation is not continued. The force is reversed again soon and kept less than 1000kN. It means that the intermediate-end structures are not fully deformed. In addition, the acceleration generated during the collision is 0.9g that is significantly below the specified value 5.0g. As a summary of the evaluation, crash performance of the developed structure is described in Table 3. At the front-end of the vehicle, the crashworthy structure absorbs 1.2MJ under full-face collision condition and 0.75MJ or more under overriding collision condition. At the intermediate-end of the vehicle, it absorbs 1.1MJ on full-face collision condition. Further more, the unit train can keep the survival space without any large deformation against the collision scenarios of TSI. The acceleration on each scenario is also below the specified value. In short, developed crashworthy structure is fully complied with requirements of RGS and TSI as shown in Table 3.
7 Application of the crashworthy structure

The developed crashworthy structure is employed for a car body of UK class395 high-speed train at a maximum speed of 62.5m/s (225km/h) as shown in Figure 8.

Figure 8: UK class395 high-speed train having developed crashworthy structure
8 Conclusions

We have developed the crashworthy structure. On the development process and structure, there are the following features.

1) The newly developed energy absorption blocks contribute to achieve good balance and stable energy absorption. These blocks make it easier to control the amount of energy absorption on the various structures.

2) The full-scale collision tests have been carried out to confirm the fundamental collision characteristics and ensure the accuracy of the analysis method. The error of energy absorption estimated by analysis was within 10%.

3) At the front-end of the vehicle, the crashworthy structure absorbs 1.2MJ under full-face collision condition and 0.75MJ or more under overriding collision condition. At the intermediate-end of the vehicle, it absorbs 1.1MJ on full-face collision condition. Furthermore, the unit train can keep the survival space without any large deformation against the collision scenarios of Technical Specification for Interoperability.

4) The developed crashworthy structure is employed to a car body for UK class395 high-speed train.

References