Carbody-side Strengthening Effects of an Inner Sub-frame Ring Structure

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When a railway vehicle overturns in an accident, the carbody cross section is likely to take on a parallelogram shape as a result of side impact, and the survival space for passengers and crew is reduced as a result. To secure the survival space available, an inner-ring structure can be formed by uniting sub-frames attached to the inside of the carbody as non-structural members. The authors performed strength tests and FE analysis to verify the possibility of improving carbody strength against loads from the side by creating such a ring structure.

Keywords: carbody strength, non-structural members, inner frames, strength test, finite element method

1. Introduction

Despite ongoing efforts to reduce accident risk and ensure the safety of railways, it is a fact that fatal accidents sometimes occur. When a railway vehicle overturns due to natural phenomena such as strong winds or as a result of derailment, the carbody cross section is likely to take on a parallelogram shape from the side impact, and the survival space for passengers and crew may be reduced by such deformation.

Takigami et al. proposed improvement for the rigidity of commuter vehicle carbodies using sub-frames attached to the inside as non-structural members without modification to the main (outer) shell of the carbody [1]. A ring formation (referred to as an inner-ring structure in this paper) made by joining sub-frames together is considered capable of improving carbody strength to combat transformation of the cross section into a parallelogram shape due to loading from the carbody side.

The authors therefore performed strength tests and FE analysis to verify the possibility of improving carbody strength against loads from the side by adopting an inner-ring structure.

2. Static strength tests

No crashworthiness requirements for railway vehicle bodies against side impact are established either in Japan or in Europe. In the United States, there is not a standard for the design and construction of body structures against impact loads from the side but a standard against only static loads [2]. The authors therefore carried out static strength tests on actual-size partial carbodies to verify the effects of adopting the inner-ring structure on improving carbody side strength after studying the test method through FE analysis.

2.1 Study of the test method through FE analysis

Fig. 1 FE model

The authors constructed a numerical model (see Fig. 1) for the carbody portion in the vicinity of the door pocket of a standard stainless steel carbody structure of the type mass-produced since 1980s. This model was used for the structure in which the inner ring was adopted, the carbody’s outer shell was the same as that of the conventional body structure, and the inner sub-frames of the ceiling and the door pocket were strengthened and connected using reinforcing components (the details will be described later). The model was obtained by dividing an FE mesh based on a size of 25 mm, and two-dimensional shell elements were used for it. The number of nodes was about 120,000, and the number of elements was about 100,000. An explicit FE code ‘PAMCRASH’ was used for the analysis.

From the results of study through FE analysis, the strength test method was determined in such a way that the bottom of the specimen’s side beam was fixed, and a rigid beam of 200 mm in width was translated horizontally to press the vicinity of the frieze board statically in order to transform the cross-section shape of the specimen into a parallelogram as shown in Fig. 2.

According to numerical analysis under these test conditions, buckling occurred at the floor joist and floor panel as shown in Fig. 3. This indicated that improving the strength of the door pocket post panel was not sufficiently effective to strengthen the whole carbody. Ac-
Accordingly, further improvement was conducted by reinforcing the floor with stiffening ribs added to the inside of the side beam as shown in Fig. 4.

2.2 Specimen

Two kinds of partial car bodies were used as specimens for static strength tests in the vicinity of the door pocket of actual-size stainless steel car body structures. One is a conventional body structure with sub-frames attached to the inside of the car body as shown in Fig. 5 (referred to as the normal specimen in this paper). The other is a body in which the inner-ring structure is adopted, the outer shell is the same as that of the conventional body structure, the inner sub-frames of the ceiling and the door pocket are strengthened and connected using reinforcing components, and the floor is reinforced by adding stiffening ribs to the inside of the side beam as shown in Fig. 6 (referred to as the inner-ring specimen in this paper). The details of reinforcements and the added inner frames in this specimen are listed in Table 1. The specimen was about 2,000 mm long, 3,000 mm wide and 3,000 mm high. Braces were attached to prevent local deformation in the specimen end during transportation and preparation for the tests, and these were removed before testing was carried out.
Table 1 Reinforcing components

<table>
<thead>
<tr>
<th>Item</th>
<th>Description (compared with the normal specimen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frames for light units</td>
<td>• No holes for weight reduction</td>
</tr>
<tr>
<td></td>
<td>• Thickened (3.2 mm → 4.5 mm)</td>
</tr>
<tr>
<td>Frames for frieze boards</td>
<td>• Thickened (2.3 mm → 4.5 mm)</td>
</tr>
<tr>
<td>Door pocket post panels</td>
<td>• Post thickened (2 mm → 4.5 mm)</td>
</tr>
<tr>
<td></td>
<td>• Extra post added (thickness: 4.5 mm)</td>
</tr>
<tr>
<td>Ceiling frames</td>
<td>• Attached between frames for light units (thickness: 4.2 mm)</td>
</tr>
<tr>
<td></td>
<td>• Attached between frame for light units and frame for frieze board (thickness: 4.2 mm)</td>
</tr>
<tr>
<td>Floor joists</td>
<td>• Added to floor</td>
</tr>
<tr>
<td>Connecting brackets</td>
<td>• Door pocket post and floor joist connected (thickness: 4.5 mm)</td>
</tr>
<tr>
<td>Stiffening ribs</td>
<td>• Added to side beam (thickness: 4.5 mm)</td>
</tr>
</tbody>
</table>

2.3 Test method

The strength test setup is shown in Fig. 7. The bottom of the specimen’s side beam was fixed, and a rigid beam of 200 mm in width was translated horizontally at a rate of 5 mm/min to press the vicinity of the frieze board statically using two hydraulic jacks so that the shape of the specimen’s cross section was transformed into a parallelogram. The load was measured using two load cells mounted on each jack, and the deformation (defined as the translated distance of the rigid beam) was measured with two displacement transducers.

2.4 Test results

The shape at the maximum deformation (about 800 mm) of the inner-ring specimen is shown in Fig. 8, and the relationship between the load and the deformation for each specimen is shown in Fig. 9. The shape of the cross section for each specimen was transformed into a parallelogram shape as shown in Fig. 8. As can be seen from Fig. 9, the rate of loading increase fell gradually in the early stages of deformation for each specimen, and the load became almost constant (about 10 kN in the normal specimen and about 40 kN in the inner-ring specimen) when the deformation reached about 400 mm. After the deformation reached 700 mm, the load decreased gradually for the inner-ring specimen.

3. Discussion

Figure 10 shows the relationship between energy and deformation as calculated from the test results for the relationship between load and deformation shown in Fig. 9. The ratio of the energy of the inner-ring specimen (Ei) to that of the normal specimen (En) is also shown in Fig. 10.

The results show that the energy absorption increases by a factor of about four from the adoption of the inner-ring structure. Moreover, when 5 kJ of kinetic energy, for instance, is absorbed, the carbody deformation is about 600 mm in the normal specimen and about 230 mm in the inner-ring specimen; this indicates that
the adoption of the inner-ring structure reduces deformation by about 62% of what it would otherwise be.

Accordingly, in regard to carbody cross section transformation to a parallelogram shape in accidents such as trains overturning, a reduction of such deformation can be expected by adopting an inner-ring structure as opposed to the conventional body structure. However, because the amount of energy that can be absorbed is limited to a few tens of kJ as shown in Fig. 10, energy absorption may be insufficient depending on the accident situation.

The numerical results obtained from FE analysis showed a close correlation with the test results for each specimen. However, the load-deformation curve from FE analysis exhibited a wave form because the translation speed of the rigid beam was calculated as 250 mm/s to shorten the calculation time, and the load did not decrease after deformation reached 700 mm because weld and bolt rupture were not modeled. It is therefore considered that the FE analysis method reported here is effective for the evaluation of carbody strength, and that it can be used to examine the influence of individual inner-ring members for appropriate modification of their specifications as required.

4. Conclusion

In this study, the authors examined the effect of an inner-ring structure created by joining together sub-frames attached to the inside of the carbody as non-structural members without modifying the main shell of the body as a measure to reduce injury to passengers and crew when the carbody cross section is transformed into a parallelogram shape due to side impact in the event of trains overturning, railroad crossing accidents, etc.

Static strength tests using partial carbodies were carried out for the vicinity of the door pocket of an actual-size standard stainless steel carbody structure, and FE analysis was performed under the same conditions as the tests. It was verified that the numerical analysis results were consistent with the test results, and that the carbody strength against loading from the body side was improved by adopting the inner-ring structure compared with the conventional body structure.

Reduced carbody deformation can therefore be expected by adopting the inner-ring structure compared with the conventional body structure when the carbody cross section is transformed into a parallelogram shape in accidents such as trains overturning.

In the future, the authors plan to verify whether the inner-ring structure is effective in strengthening the entire carbody by applying the numerical analysis model developed to the whole carbody, and will also examine the effectiveness of the inner-ring structure under various loading conditions (for example, loads applied to the carbody at points other than in the vicinity of the door pocket). Further, it is necessary to verify all these considerations under dynamic loading conditions. In addition, although weight reduction and improvement of practical use for the inner-ring structure have already been studied [3], investigation of their balance with the strength improvement verified in this study will be needed.

References