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Rollover Analysis of a Bus Using Beam and Nonlinear Spring Elements

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Abstract: - In case of bus rollover, the body structure of a bus should be designed to ensure the survival space for passengers. So, this study focused on evaluating the rollover strength through a computer simulation using the commercial code, LS-DYNA3D at the initial stage of vehicle development. For this purpose, section structure of the bus frame was first modeled using simple beam elements, and the impact boundary conditions required by ECE regulation No. 66 were applied. In order to validate the beam element model, the simulation results were compared to those of shell element model. Since the analysis error with beam element model was mainly caused by the difference in strain energy at the T-shaped connecting joint, the joint connection was modified with nonlinear springs to account for the local buckling. With the improved beam model, the results were in a good agreement to shell element model, but the simulation times were much reduced.

Key-Words: - Rollover strength, Survival space, Beam element, Nonlinear spring, Collapse theory

1 Introduction

Many types of buses have been used for commercial traffic transportation, and life span of a bus is longer than that of a passenger car. Also, a bus have been operated with much more passengers than a small passenger car, however, the research and interest related on its safety seemed relatively low. Since there are many seriously wounded passengers in traffic accidents of buses, more careful analysis and simulation for impact accidents should be investigated. Since the understanding and knowledge of automobile consumers for their safety had been growing up, the related official rules have come into effect. In many bus manufacturers and research institutes, new designs and various researches are in progress to match new regulations.

In Australia, ADR 59 (Australian Design Rule 59) had specified the deformation of bus body in rollover accidents [1], and ECE 66 (Economic Commission for Europe 66) controls the same substance presently [2]. Bus structure designs that ensure the survival space of passengers are indispensable, and for these purposes, the rollover analysis and design by using explicit finite element method are useful [3,4]. Takagi [6] has numerically simulated rollover occurrence and occupant behavior according to the rollover initiation types with commercial computer program. The physical test method for rollover accident has recently developed by Richardson [5] and Larson [7], and Moffatt [8] used the controlled rollover impact system for rollover impact investigation. In this study, the commercial code LS-DYNA3D [11] was used for the rollover analysis of bus structure, and the beam analysis model was modified with nonlinear spring characteristics for the advanced exactness of its solution.

2 Rollover Test

The rollover test of real section structure was executed by a bus manufacturer [15] according to the conditions which were defined by ECE. The body section was located on a rotational platform, and the platform was lifted up by a crane as shown in Fig. 1. The body section structure has the weight of 830 kgf, and the free dropping begins after the center of gravity moves out of the hinge point.

As the results of rollover test, a deformed body section is shown in Fig. 2. Plastic deformation occurred near the welding point of side body beams, and also the local break-down appeared on the open section of the beams. The bending collapse took place at the joining area of lower part of window frame and side beams as shown in Fig. 3. The strength of this area dominates deformation of the whole body, and this connection is the most important to ensure the survival space of passengers in rollover accidents.

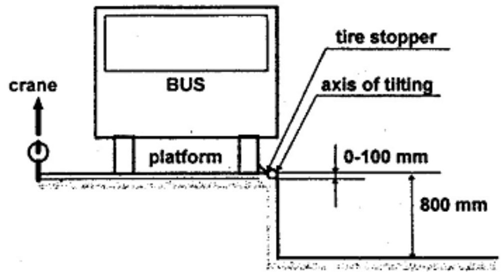

Fig. 1 Rollover test apparatus

Fig. 2 Rollover test of the body section structure

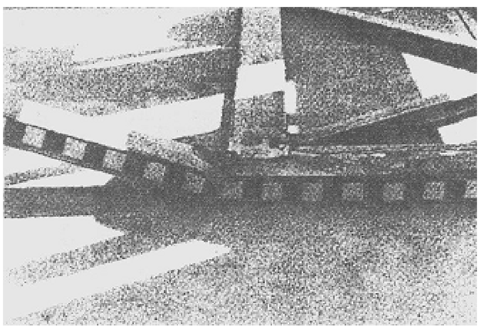

Fig. 3 Side pillar frame under bending collapse

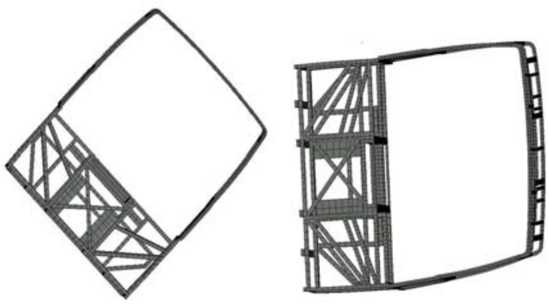

Fig. 4 Rollover analysis of shell element model

3 Numerical Rollover Simulation

3.1 Analysis with Shell Element Model

The body section structure is a skeleton set which is composed of frame-type pillars. This structure is a framework of the whole body which absorbs 60~70 % of the impact energy when impact takes place [9,10]. The exterior panels and leads were neglected for their small capacity of impact energy absorption. Shell elements were used to establish the body section structure as shown in Fig. 4, and concentrated mass elements were arranged to adjust the weight of the structure. The material properties of elasto-plastic steel were employed, and the nonlinear region of material property curve was piece-wise linearly approximated.

3.2 Analysis with Beam Element Model

In the design stage of a bus, the numerical evaluation of rollover features with a simple beam model has the advantages of its low cost and quick response [12]. Moreover, the reduction of effort to generate the analysis model is also possible. The Belytschko-Schwer beam elements [11] with the material properties of resultant plasticity, which was adequate for box-tube type structures, were selected as shown in Fig. 5. The cross-sectional area, moment of inertia, torsional modulus, and the properties of shear area were considered without discrimination with the previous shell model [11]. Also, the concentrated mass elements and the same boundary conditions were applied.

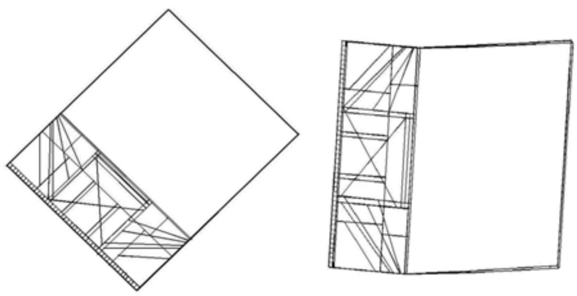

Fig. 5 Rollover analysis of beam element model

3.2 Comparison of the Two Results

It was cleared that the survival space for passengers was secured via computer simulations. Deformation of window pillars were similar to the results of body section test, and the survival spaces were obtained during rollover procedures as shown in Fig. 4 and Fig. 5.

The displacement of window pillars measured from the rain rails and deformation angles from the waist rails are summarized in Table 1. The displacement and deformed angle in beam element model were smaller than those of shell element model, and the differences were 9 % and 12 % of the results in shell element model, respectively.

The strain energy absorbed by the body section in deformation processes is shown in Fig. 6. The absorbed energy of beam element model was higher than that of shell element model. These differences come from the over-estimated stiffness of beam element model. In the beam element model, no local buckling at the area of plastic hinge was considered, and as the result, plastic deformation was not sufficiently estimated. Therefore the beam element modeling with the consideration of the stiffness of pillar joint area is needed to obtain more exact simulation results.

Table 1 Comparison of displacements and deformed angles measured at window pillar

Displacement	Test		392 mm
	Simulation	Shell element model	397 mm
		Beam element model	363 mm
Deformed Angle	Test		24.9 °
	Simulation	Shell element model	25.6 °
		Beam element model	22.5 °

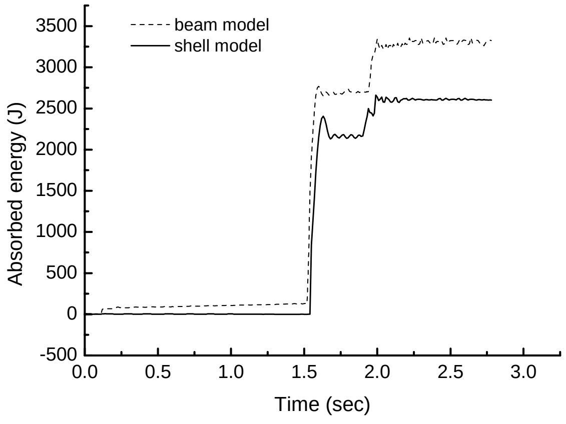

Fig. 6 Comparison of absorbed energy

4 Simulation with Modified Models

Nonlinear spring elements were supplemented to improve the disadvantages of beam element bus model. Nonlinear spring elements were added at the joining area of beam elements to consider the local buckling and the adequate structural stiffness.

4.1 Collapse Theories

The scheme for nonlinear spring input is described in Fig. 7. The characteristics for axial crush, bending collapse, and torsional collapse are required to import nonlinear spring elements, and the curves of force-displacement, moment-rotational angle, and torsion-twisting angle should be computed in advance to the simulations, respectively. The following equations were adopted to represent the axial crush and the average crush force [13].

$$P_{asm} = 16\,\pi\, m_p \left(\frac{a+b}{2t}\right)^{\frac{1}{3}} , \tag{1}$$

$$m_p = \frac{\sigma_y\, t^2}{4} , \tag{2}$$

$$P_{adm} = f_d\, P_{asm} , \tag{3}$$

$$f_d = 1 + 0.03\, v_0^{\,0.256} . \tag{4}$$

The maximum bending moment and post-buckling behavior are important factors to describe the bending collapse of structural frames. The relations on the bending collapse defined by Kecman and Wierzbicki were used as followings [14,17].

$$\begin{aligned} M(\alpha) = \frac{M_0 b}{\sin\alpha} \Bigg\{ & 8 I_1 \frac{r_b}{t} + 2 I_2 \frac{H_b}{r_b} + 2\frac{b}{H_b} \\ & + \frac{\sqrt{2}}{2}\frac{b}{H_b}\left[1 + \left(\frac{H_b}{b/2-\eta}\right)^2\right] \\ & + 4\frac{b\eta}{t(b-\eta)} \sin\alpha + \left(2-\sqrt{2}\right)\frac{H_b}{b} \Bigg\} , \end{aligned} \tag{5}$$

$$H_b = 1.276\, b^{\frac{2}{3}}\, t^{\frac{1}{3}} , \tag{6}$$

$$r_b = 0.795\, b^{\frac{1}{3}}\, t^{\frac{2}{3}} , \tag{7}$$

$$I_1 = \cos\alpha \int_0^{\beta} \frac{1}{\sqrt{1+\cos^2\phi}}\, d\phi \ , \tag{8}$$

$$I_2 = \cos\alpha \sqrt{1+\sin^2\alpha} \ , \tag{9}$$

$$\tan\beta = \tan\left(\sqrt{2}\,\alpha\right) . \tag{10}$$

In the joint area, the eccentric loading is applied, and torsional deformation occurs. The behavior of thin-walled beams under the torsional loading is effectively treated using initial twisting moment T_i, twisting moment in steady-state T_s, critical twisting angle θ_c, and the final twisting angle θ_f as shown in Fig. 8, and the following equations were used to calculate the torsional energy EA [16].

$$\theta_c = \frac{EA - T_s\theta_f}{T_i - T_s} \ , \tag{11}$$

$$T_i = 3.72\,\sigma_y\, t^{1.25}\, b^{1.75} \ , \tag{12}$$

$$T_s = 5.58\,\sigma_0\, t^{1.4}\, b^{2.2}\, l^{-0.6} \ , \tag{13}$$

where σ_0 denotes the stress value that corresponds to the average strain.

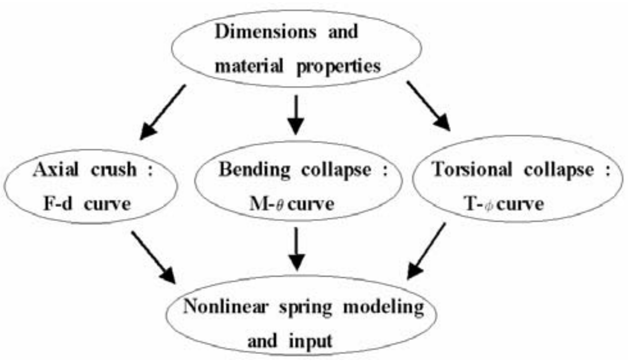

Fig. 7 Scheme for nonlinear spring input

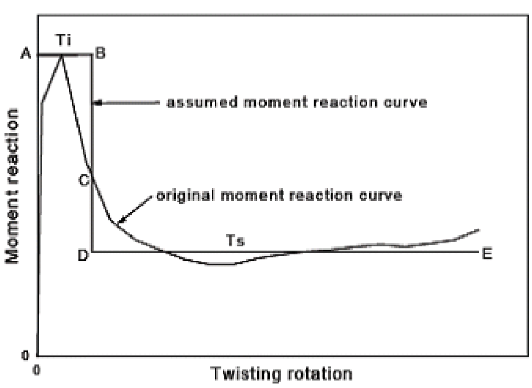

Fig. 8 Torsion-twisting angle curve

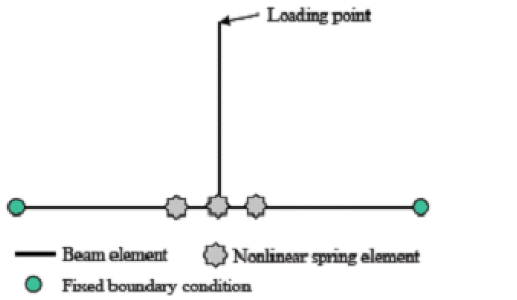

Fig. 9 Modified model for T-shaped joint

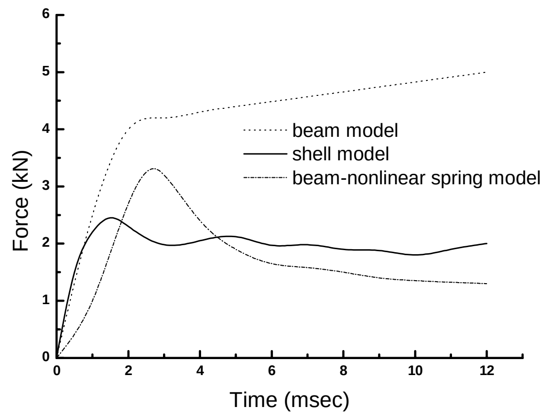

Fig. 10 Reaction force curves against bending

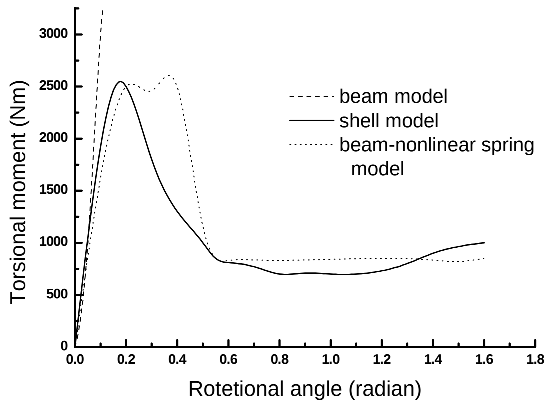

Fig. 11 Reaction torsion curves against twisting

4.2 Verification with Simple Joint Model

To verify the effect of nonlinear spring attachment, T-shaped simple joint model was investigated as shown in Fig. 9. Nonlinear springs were located on the joining point and its both sides. As previously mentioned, the collapse conditions by Wierzbicki and Santosa were applied to activate the added spring elements [13,16].

Reaction properties against the bending and torsional load are plotted in Fig. 10 and Fig. 11, and the absorbed energy curves are in Fig. 12 and Fig. 13, respectively. It was verified that the modified model represented well the nonlinear characteristics of joint area.

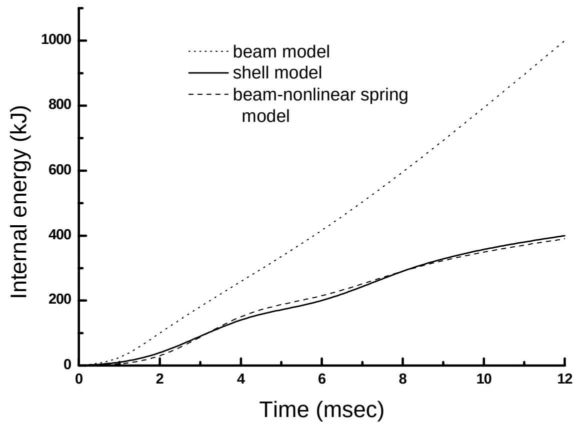

Fig. 12 Absorbed bending energy curves

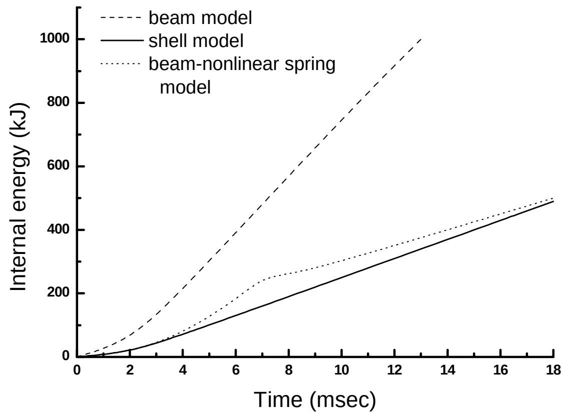

Fig. 13 Absorbed twisting energy curves

4.3 Modified Bus Model and Improved Results

The beam element bus model was modified with the nonlinear spring elements which were verified to be reasonable in the previous section. The joining areas between window pillars and side beams, at which the local buckling and plastic hinge had originated in the previous test and simulations, were remodeled as shown in Fig. 14.

The resultant deformed shape from the rollover simulation with the modified bus model is in Fig. 15. Bending at the modified joint area was increased, and the resultant difference was reduced to 3 % of shell element bus model. The absorbed energies are plotted in Fig. 16, and this comparison shows the improved result which contains the difference of 1.2 % in their energy values.

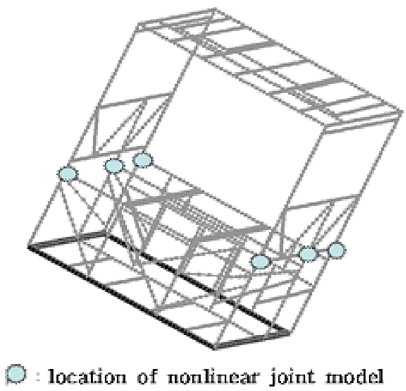

Fig. 14 The locations of modified joints

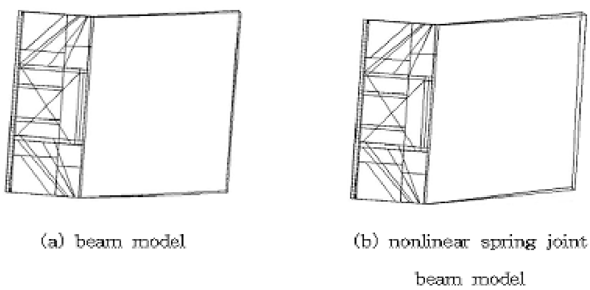

Fig. 15 Deformed shape of modified bus model

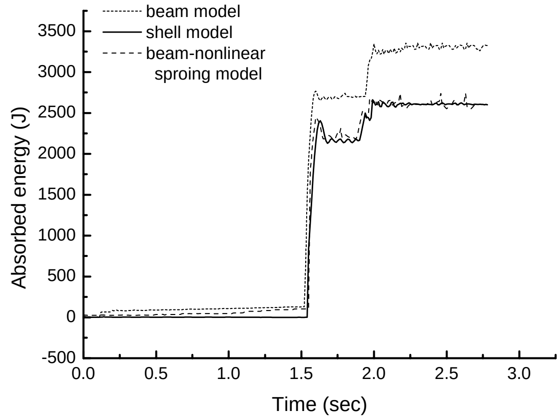

Fig. 16 The comparison of absorbed energy

5 Conclusion

In the rollover simulation of a finite element bus model, a beam element model was successfully modified to save the analysis cost with little loss of its accuracy in comparison with a shell element model. The stiffness of simple beam elements was overestimated, and the local plastic deformation was partially out of consideration. However, the modified model, to which spring elements and its nonlinear characteristics were applied, estimated the structural stiffness properly, and showed the improved results of reaction forces and internal energy. The stability and effectiveness of joint modification technique was confirmed, and the approach was proved to be useful and advantageous in the vehicle rollover investigation and its development.

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References:

[1] ADR 59, Australian Design Rule 59/00, Omnibus Rollover Strength.

[2] United Nation, Addendum 65: Regulation No.66, Uniform Provision Concerning the Approval of Large Passenger Vehicles with regard to the Strength of their Superstructure, 1996.

[3] T. E. Chung, Rollover Analysis and Measurement of a Large-sized Bus, *Transaction of KSAE*, Vol.5, No.6, 1997, pp. 148-154.

[4] H. D. Kim, J. H. Song, C. Y. Oh, Development of a Finite Element Model for Crashworthiness Analysis of a Small-Sized Bus, *Transaction of KSAE*, Vol.10, No.1, 2002, pp. 153-161.

[5] S. Richardson, R. H. Grzebieta, G. Rechnitzer, Proposal for a Dynamic Rollover Protective System Test, *International Journal of Crashworthiness*, Vol. 8, No. 2, 2003, pp. 133-142.

[6] H. Takagi, A. Maruyama, J. Dix, K. Kawaguchi, MADYMO Modeling Method of Rollover Event and Occupant Behavior in Each Rollover Initiation Type, SAE 2003-06-0071, Nagoya, Japan, 2003.

[7] R. E. Larson, J. W. Smith, S. M. Werner, G. F. Fowler, Vehicle Rollover Testing, Methodologies in Recreating Rollover Collisions, SAE 2000-01-1641, Troy, Michigan, 2000.

[8] E. A. Moffatt, E. R. Cooper, J. J. Crotean, K. F. Orlowski, D. R. Marth, J. W. Carter, Matched-Pair Rollover Impacts of Rollcaged and Production Roof Cars Using the Controlled Rollover Impact System, SAE 2003-01-0172, *SAE World Congress*, Detroit, Michigan, 2003.

[9] H. W. Lee, H. W. Shin, A Study on the Characteristics of Frontal and Oblique Impact of a 4WD Vehicle, *Autumn conference proceeding of KSAE*, 1997, pp. 441-446.

[10] C. S. Hong, C. Y. Oh, D. C. Lee, Development of a Finite Element Model for Frontal Crash Analysis of a Mid-Size Truck, *Journal of KSPE*, Vol. 17, No. 4, 2000, pp. 226-232.

[11] Livemore Software, *LS-DYNA THEORETICAL MANUAL*, 1998.

[12] H. K. Min, T. Kim, An Analysis for Rollover Strength of a Medium Bus, *SAE NO.99370235*, 1999, pp. 195-201.

[13] T. Wierzbicki and W. Abramowicz, On the Crushing Mechanics of Thin-Walled Structures, *ASME Journal of Applied Mechanics*, Vol. 50, 1983, pp. 720-739.

[14] D. Kecman, Bending Collapse of Rectangular and Square Section Tubes, *Int. J. of Mech.*, Vol. 25, No. 9-10, 1983, pp. 623-636.

[15] Technical Report, E 130, The Analysis and Experiment on the Rollover Accident of a Bus, Daewoo Bus Corporation.

[16] S. Santosa and T. Wierzbicki, Effect of an Ultralight Metal Fillar on the Torsional Crushing Behavior of Thin-Walled Prismatic column, *Int. J. Crashworthiness*, Vol. 2, No. 4, 1997, pp. 305-331.

[17] S. H. Park, S. Y. Kang, H. Y. Kim, D. K. Min, D. C. Han, Development of Nonlinear Spring Element and Vehicle Crashworthiness Analysis, *Proceedings of KSME Conference, 97380165*, 1997, pp. 407-412.