Development of Simplified Truck Chassis Model for Crashworthiness Analysis

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Abstract

In this paper bending resistance of thin-walled channel beam is applied to create simplified model for truck chassis. In the simplified model, beam and nonlinear spring elements are used to model the side-rails, and equivalent beams are applied to represent the cross members. Both detailed and simplified models are used for crashworthiness analyses, and the results are recorded and compared. Relatively good agreement is achieved between these analyses, while the computing time is significantly reduced for the presented modeling method.

1. Introduction

Since last 90's, simplified modeling methodology and simplified finite element (FE) models have been significantly developed and extensively used for crashworthiness analysis. Compare to the detailed FE models that are traditionally used for computer analysis, the simplified models effectively reduce the overall model's size, thereby simplifying the calculations and saving much more computer time and resources while preserving reliability and accuracy. On the other hand, the simplified models can be used in early design stage, which can allow users to easily change design ideas and approximately evaluate different designs.

Most of detailed FE models are composed of beam-type parts and plate-type parts, both of which are traditionally modeled with shell elements. According to this paper, the beam-type parts can be simplified using only beam elements (for solid members), or beam and nonlinear spring elements (for thin-walled members), and some of the plate-type parts can be modeled with "equivalent beam elements". The objective of this paper is to demonstrate and validate the developed simplified modeling methodology.

Particularly, in this paper, the developed nonlinear spring element used to simplify the thin-walled box section channels is applied. Besides that, a new element that can simulate the collapse behavior of thin-walled channel section members is also developed and used for simplifying the structures that contain such members. Also, the equivalent beam element is imported to model the plate-type parts. Therefore, an improved simplified model can be obtained by applying all the simplified elements and modeling technique. To validate this modeling method, a truck chassis model is used as an example and the simplified modeling techniques are applied to simplify it. Crashworthiness analyses are performed on both detailed and simplified models to verify the developed simplified model as well as the modeling techniques, LS-DYNA are used for running such analyses.

2. Create Simplified Model for Side-Rails

As investigating the truck chassis model, it can be found that the entire chassis model is composed of two side-rails and six cross members. Simplified models are developed for each of them. As shown in figure 1, it is seen that the side-rails are composed of thin-walled box and channel section beams, and therefore, they are simplified by directly applying the modeling method and the bending resistance for box section beam which was developed previously, and the derived bending resistance for channel section beam. This section mainly describes how to create the simplified model for the side-rails, and the simplified modeling of the cross members will be introduced next.

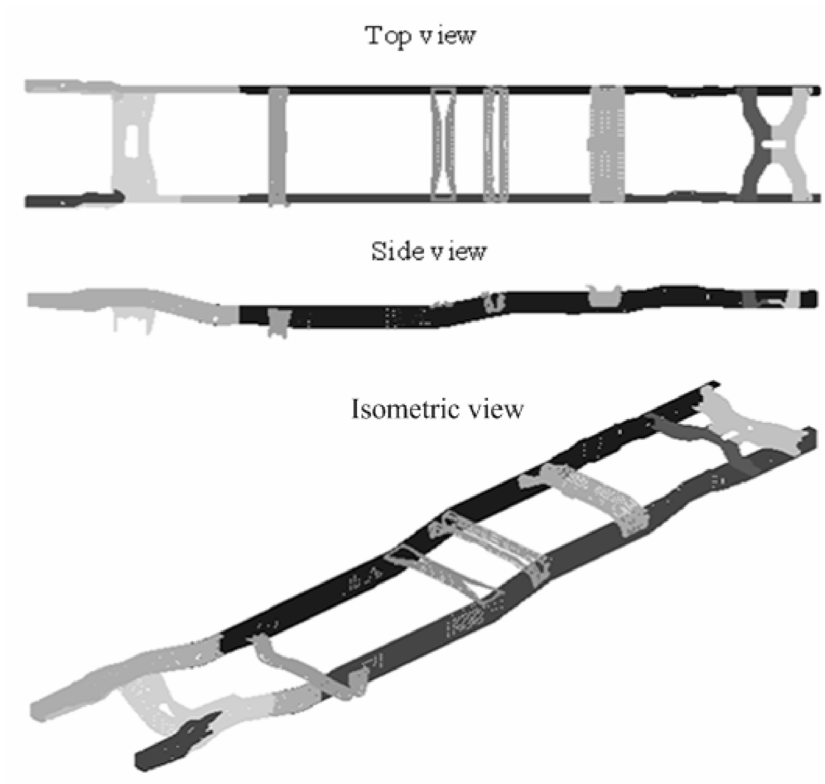

Figure1. Detailed truck chassis model

Detailed Model

Before creating the simplified side-rails model, the structure of detailed model is presented and studied. Figure 2 only plots the left side-rail model, and the right side-rail model has the same characteristics because the two side-rails are symmetric. From this figure, it is found that one side-rail model can be divided into several segments due to the varying geometries and features, and each segment has its own cross section and wall thickness. A concise profile of the detailed model with the related geometries is drawn in figure 3 and the simplified side-rails model is created using this profile.

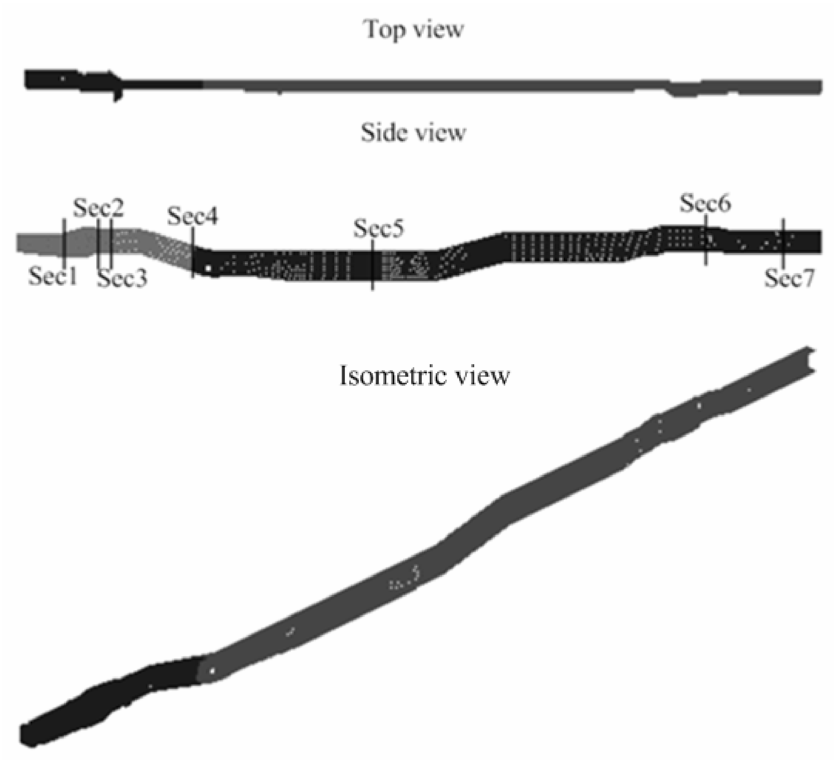

Figure2. Detailed side-rail model

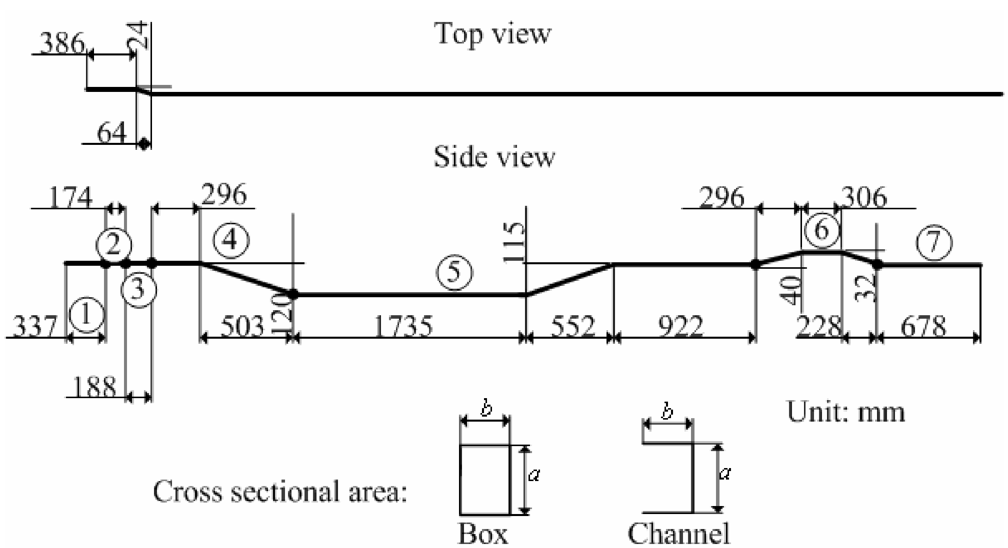

Figure3. Profile of side-rail model

In figure 3, segments 1 through 7 have different cross sections, which are numbered from 1 to 7 in figure 2. Because the cross section in the model changes gradually, a median cross section is extracted from each segment and used as the characteristic cross section of a segment. Table 1 lists the cross sectional geometries.

Table1. Cross sectional geometries of different segments

Segment # (figure 3)	Cross section # (figure 2)	Cross sectional type	Web a (mm)	Flange b (mm)	Thickness t (mm)
1	1	Box	118.7	97.7	5.1
2	2	Box	155	97.7	5.1
3	3	Box	160.5	97.7	5.1
4	4	Channel	147.2	50	5.1
5	5	Channel	174.5	66.5	6.1
6	6	Channel	157.8	50	6.1
7	7	Channel	136.7	68	6.1

Simplified Modeling

Based on the configuration of the detailed side-rail model and the characteristics of each cross section, the simplified side-rail model can be developed. In developing the simplified model, the body of the simplified model is modeled using the Hughes-Liu beam elements based on the plotted profile of the detailed model (as shown in figure 3). On analyzing the structure of the side-rail model, it is found that the simplified model needs 10 plastic hinges to predict the bending behavior. Those plastic hinges are modeled using nonlinear rotational spring elements (as shown and numbered in figure 4), and the dimensions of the cross sections where the plastic hinges are located is measured in order to calculate the nonlinear spring's bending resistance. As listed in table 1, the detailed side-rail model has 7 different cross sections along its length. Table 2 lists all 10 nonlinear springs and their corresponding cross sections. Since the cross sections include both box and channel sections, following equations are applied to calculate the equivalent bending resistances, and some of the results of the calculations are also listed in table 2.

For box cross section 1 – 3:

$$\frac{M(\theta)}{M_0 a} = (A-1)\left[6+\cos\alpha\left(\frac{2}{(2-\sin\alpha)\sqrt{1-\sin\alpha}}+2\phi+26.2\right)\right]+2A(1+\sin\alpha)+2 \quad (1)$$

$$M_0 = (\sigma_0 t^2)/4 \quad (2)$$

$$A = \frac{\lambda\cos(\theta/2)}{\sqrt{\lambda\sin(\theta/2)-\lambda^2\sin^2(\theta/2)}} \quad (3)$$

$$\phi = \arccos\left(1-2\lambda\sin(\theta/2)\right) \quad (4)$$

$$\lambda = \frac{a}{b} \quad (5)$$

$$\alpha = \phi - \theta/2 \quad (6)$$

$$M_p = \sigma_0 t[a(b-t)+\frac{1}{2}(b-2t)^2] \quad (7)$$

$$\theta_J = 2\arcsin\left(\frac{h-0.5t}{b}\right) \quad (8)$$

(Note: equations (1) to (6) come from reference [7] and (7), (8) come from reference [4])

For channel cross section 4 – 6 with $a/b \approx 3$:

$$M(\theta) = 27.78bM_0\left(\frac{b}{t}\right)^{\frac{1}{3}}\left[0.58 + 0.56\left(\frac{t}{b}\right)^{\frac{1}{6}}\frac{1}{\sqrt{\theta}}\right] + M_0 b \qquad (9)$$

For channel cross section 7 with $a/b \approx 2$:

$$M(\theta) = 16.54bM_0\left(\frac{b}{t}\right)^{\frac{1}{3}}\left[0.58 + 0.6\left(\frac{t}{b}\right)^{\frac{1}{6}}\frac{1}{\sqrt{\theta}}\right] + M_0 b \qquad (10)$$

And:

$$M_P = \sigma_0 t\left(b(a-t) + 0.25(a-2t)^2\right) \qquad (11)$$

$$\theta_J = 2arctg\left(\frac{H}{a}\right) \qquad (12)$$

For all the channel cross sections
(Note: equations (9) to (12) are developed by the author)

With the calculated bending resistances of the nonlinear springs, the simplified side rail model then can be created by integrating the beam elements and the nonlinear springs. Figure 4 plots the simplified model, which has the same profiles shown in figures 2 and 3.

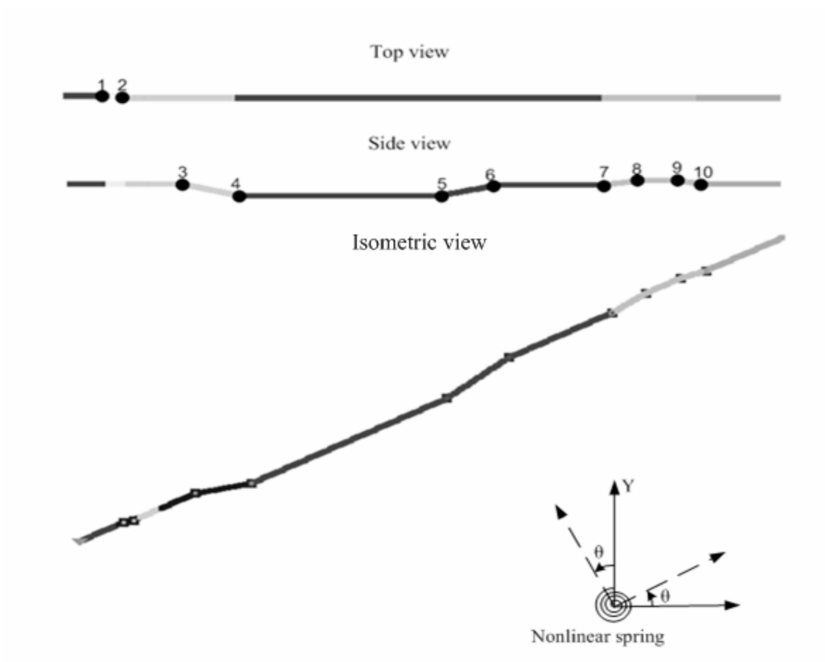

Figure4. Simplified side-rail model

Table2. Characteristics of nonlinear springs used for simplified side-rail model

Nonlinear spring #	Related cross section # (see table 1)	Fully plastic moment M_p (KN*m)	Angle of fully plastic bending θ_P (degree)	Angle of jamming θ_J (degree)
1	2	38.2	1.2	57
2	2	38.2	1.2	57
3	4	24.8	1.3	62
4	4	24.8	1.3	62
5	5	44.7	1.1	59
6	5	44.7	1.1	59
7	5	44.7	1.1	59
8	6	32.4	1.7	61
9	6	32.4	1.7	61
10	7	32.1	1.2	65

Results and Comparisons

After creating the detailed and the simplified side-rail models, they are used for crashworthiness analysis. During the analysis the initial velocity is set as 15m/s and the crash time is set to be 0.1 second. Important crash results are recorded and compared to verify the efficiency of the simplified model. They are plotted and listed in the following figures and table. Meanwhile, the deformed configurations of both models are also presented.

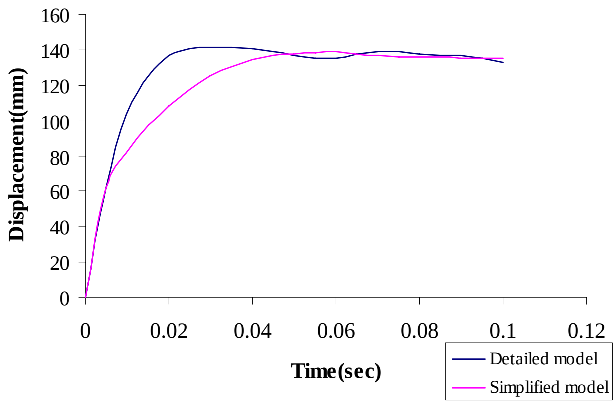

Figure5. Displacements for side-rail models

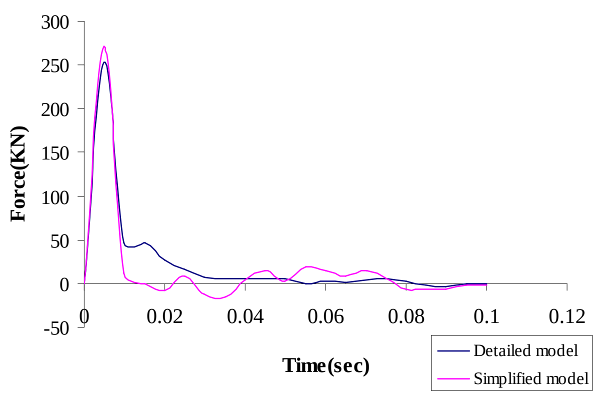

Figure6. Crushing forces for side-rail models

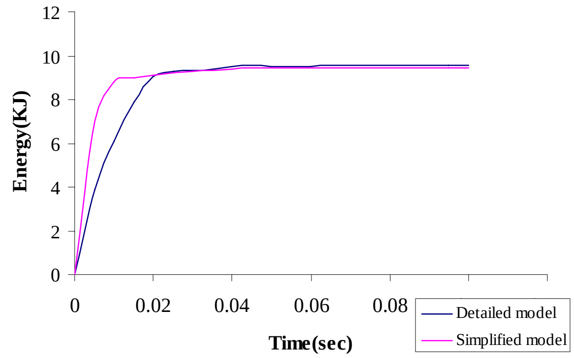

Figure7. Absorbed energies for side-rail models

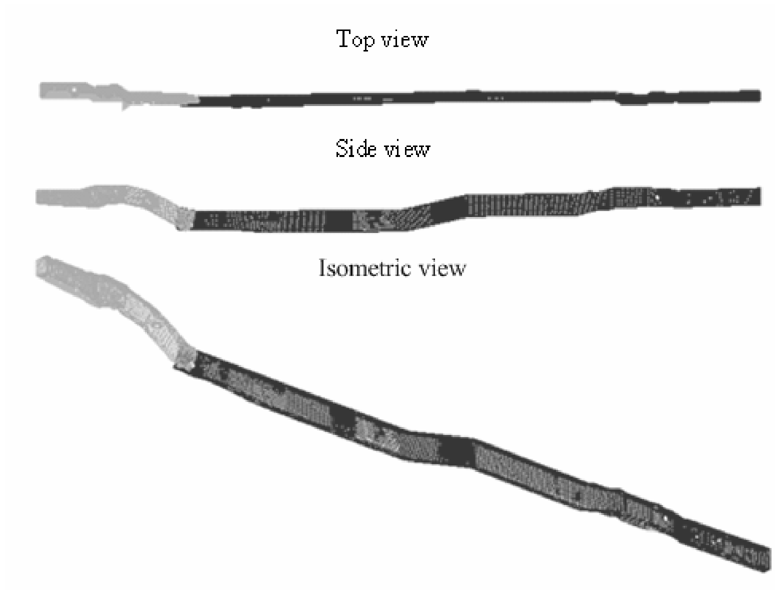

Figure8. Deformed detailed side-rail model

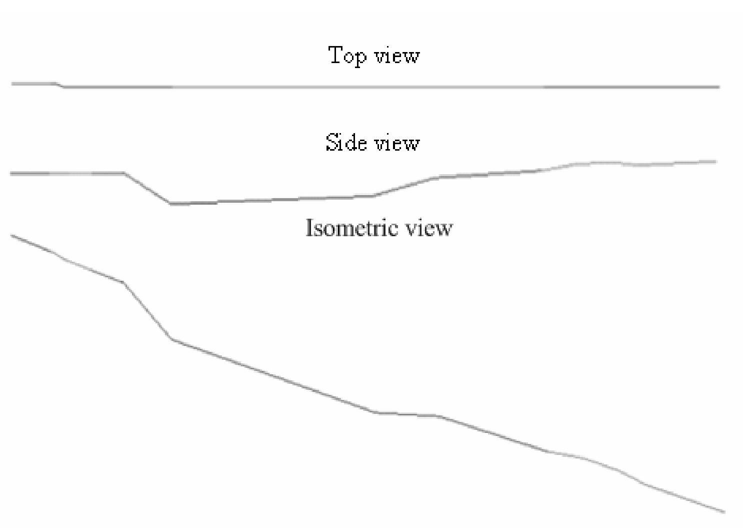

Figure9. Deformed simplified side-rail model

Table3. Comparisons of crash results from detailed and simplified side-rail models

	Detailed model	Simplified model	Difference (%)
Max. global displacement (mm)	141.3	138.8	-1.8
Peak crushing force (KN)	252.8	270.8	7.1
Absorbed energy (KJ)	9.6	9.4	-2
Computer time (sec)	60420	2580	-95.7

From table 3, it is concluded that the developed simplified model can accurately simulate the crash behavior of the detailed model; all of the errors for the important crash results are below 10%. However, the simplified model only takes about 4% computer time as much as the detailed model does. Thus, the efficiency of the simplified model is verified, and the simplified model can be applied directly for the final simplified truck chassis model.

3. Create Simplified Model for Cross Members

Besides the side-rails, the entire chassis model also has six cross members, which are considered as plate-type parts with irregular shapes. A simplified modeling method for generating the simplified cross member models needs to be developed for the final simplified truck chassis model. In this paper, a new modeling method names equivalent beam method is applied to simplify the detailed cross member models. This method is to calculate the original cross members' mass and stiffness and then, create equivalent beams that have the same mass and stiffness as the original cross members. These equivalent beams should have simple configurations, which can be easily represented by beam element models with the specified cross sectional information. Next, the developed beam element models are connected to the simplified side-rails model and replace the original cross member models in the final simplified truck chassis model.

In the truck chassis model, the cross members are mainly used to support the side-rails and to absorb the partial impact energy during the crashworthiness analysis. Therefore, it is possible to calculate these cross members' masses and their moments of inertia and to develop a series of equivalent beam models that have those same masses and moments of inertia. Thus, the equivalent beams have the same masses and stiffness as the original cross members and show similar crash behavior during the crashworthiness analysis. The developed beam models are straight beams with uniform cross sections enabling easy representation by beam elements.

Table 4 lists the cross members' masses and moments of inertia, which are the same as those of the equivalent beams. Since the cross members and the equivalent beams have the same material, the volume of the equivalent beams is calculated by dividing the mass by the density. The length of the equivalent beams is measured as the distance between the two side-rails, which is 897mm. Then, the cross sectional areas of those beams are calculated and assigned as characteristic parameters of the beams to ensure that they have the same masses as the original cross members. The values of the cross sectional areas of the equivalent beams are also listed in table 4.

In table 4, the moments of inertia I_{xx}, I_{yy} and I_{zz} are estimated through a series of static analyses. For example, to find the I_{xx}, a testing moment, M_x, is applied on the ends of the cross members; after the analyses, the final bending angel θ_x is found. Thus, the I_{xx} is calculated using the formula $M_x = \frac{EI_{xx}}{L}\theta_x$, where E is material's Young's modulus and L is the cross member's length, which is 897mm. Similarly, the I_{yy} is found following the same steps. As for the I_{zz}, since it regards the torsional stiffness, in the analysis, one end of the cross member is fixed and a testing torque T_z is applied to the other end. After obtaining the final torsion angle ϕ, the moment of inertia I_{zz} is calculated using the formula $T_z = \frac{GI_{zz}}{L}\phi$, where the G is the material's shear modulus. It is determined using the given material's Young's modulus and Poisson's ratio, which is $G = \frac{E}{2(1+\nu)}$. Figure 10 uses cross member1 as an example and shows how the different testing moments are applied to it.

After obtaining the inertias and cross sectional areas, the equivalent beams are modeled using beam elements with correct input moments of inertia and cross sectional areas. Figure 11 shows the equivalent beams' I_{xx} and I_{yy} with respect to X and Y directions.

On the other hand, some of the cross members buckled from their middle portion during the crashworthiness analysis. To reproduce the buckling in the simplified model, one hinge is applied at the middle of each cross member. The hinge is a spring element whose stiffness is estimated as the bending stiffness $\frac{EI_{yy}}{L}$; thus, the new rotational spring element is defined by inputting the bending stiffness. Figure 12 shows the detailed model for cross member1 and its equivalent beam model with one hinge in the middle.

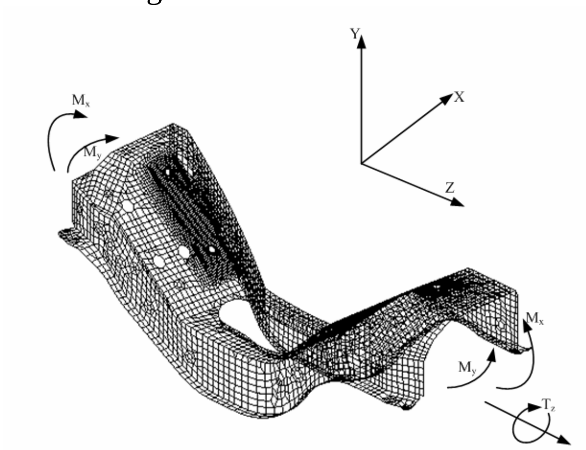

Figure10. Applying testing moments to find moments of inertia

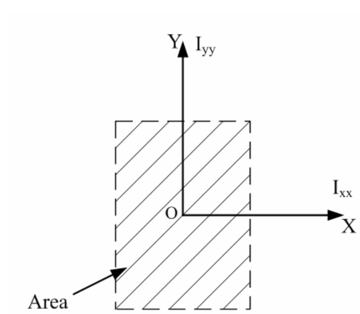

Figure11. Cross sectional information of equivalent beams

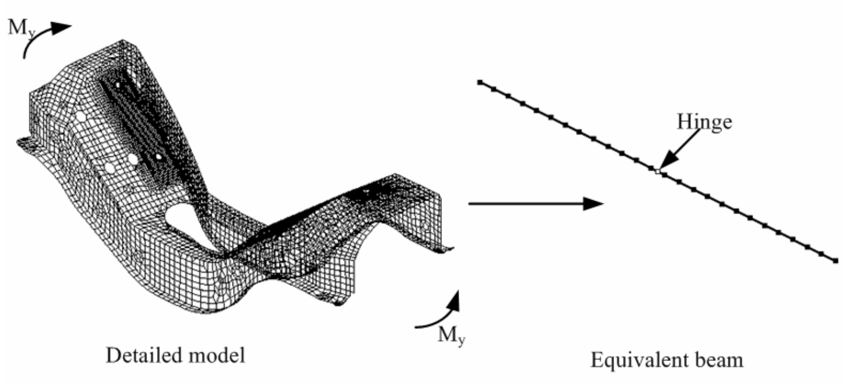

Figure12. Detailed model and equivalent beam model for cross member1

Table4. Characteristic inputs for equivalent beams

	Mass (Kg)	Cross sectional area (mm^2)	I_{xx}(mm^4)	I_{yy}(mm^4)	I_{zz}(mm^4)
Equivalent beam1	23.7	3374	2108	2196	507
Equivalent beam2	8.2	1168	802	799	34
Equivalent beam3	2.8	399	178	187	9
Equivalent beam4	4.2	598	385	391	19
Equivalent beam5	8.7	1239	757	792	64
Equivalent beam6	10	1424	704	730	59

(Note: Original cross members have the same masses and inertias as the equivalent beams)

4. Develop Simplified Model for Truck Chassis

Simplified Modeling

Given the simplified side-rails model and developed equivalent beams, the simplified truck chassis model can be obtained by assembling the equivalent beams onto the simplified side-rails model. The X-positions of connecting points between the equivalent beams and the side-rails are the X-positions of the cross members' centers of gravity (as shown in figure 13).

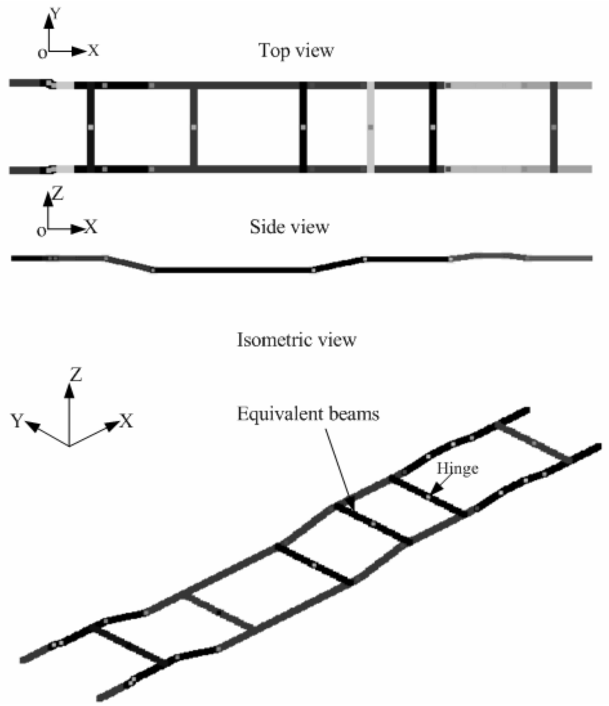

Figure13. Simplified truck chassis model with equivalent beams

Results and Comparisons

The developed simplified chassis model with equivalent beams is used for crashworthiness analyses, and the crash results are compared with the detailed model to validate the developed simplified model and the equivalent beams. Figures 14 and 15 compare the deformed configurations of both detailed and simplified models; the results of the comparisons are plotted in figures 16 through 18 and listed in table 5.

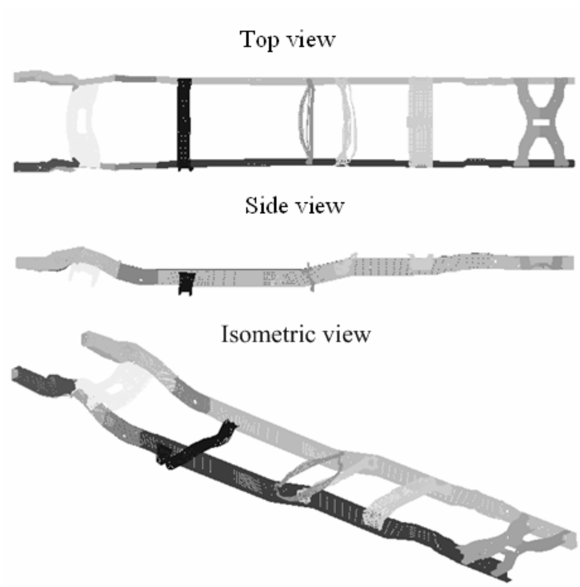

Figure14. Deformed detailed truck chassis model

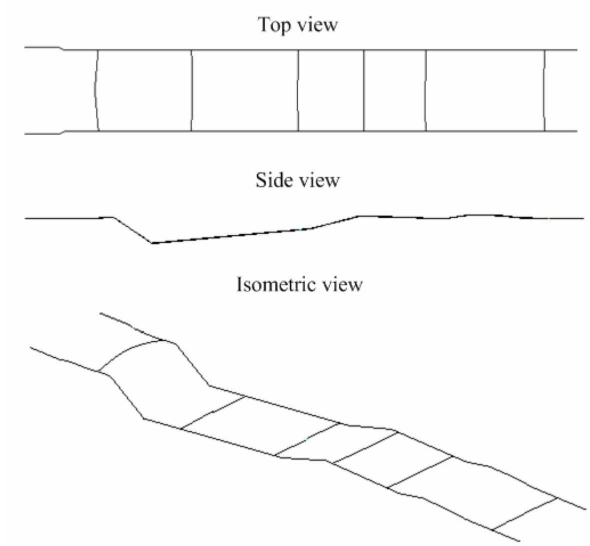

Figure15. Deformed simplified truck chassis model

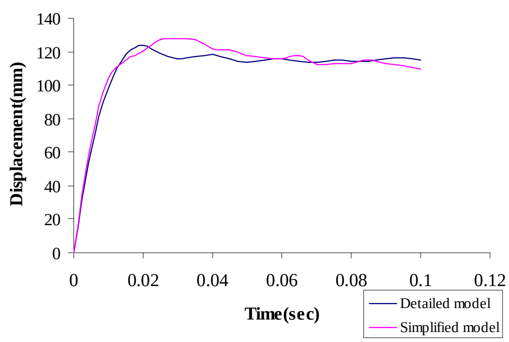

Figure16. Global displacements for simplified chassis model

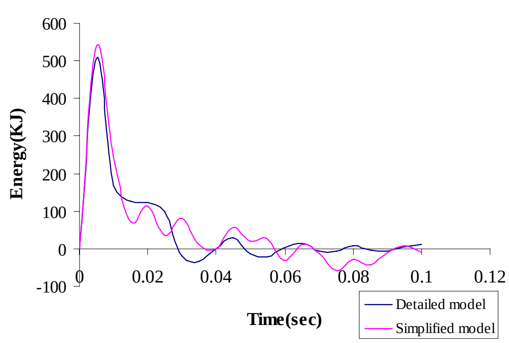

Figure17. Crushing forces for simplified chassis model

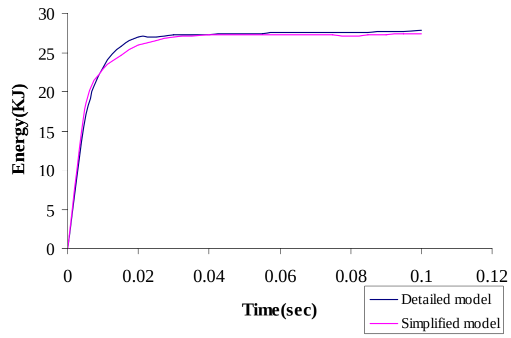

Figure18. Absorbed energies for simplified chassis model

The results of the comparisons show that the developed simplified model and the detailed model reach a close consensus in simulating the chassis's crash response. All the errors are below 10%, and the simplified model only takes 8% of the computer time of the detailed model to finish the analysis. Moreover, when comparing figures 14 to 15, it can be found that with the hinge at the middle of cross members, cross member1 in the simplified model undergoes similar buckling to the detailed cross member model. From the output of the nodes' displacements, it is calculated that in the detailed model the deformation at the center of cross member1 is 62.2mm while, the value in the simplified model is 60.0mm, and they are very close to each other. Therefore, the simplified chassis model with equivalent beams is validated, and the modeling method is verified as capable of creating further simplified crash models.

Table5. Verification of simplified chassis model with equivalent beams

	Detailed model	Simplified model	Difference (%)
Max. global displacement (mm)	123.7	127.6	3.2
Peak crushing force (KN)	505.5	540	6.8
Absorbed energy (KJ)	27.8	27.4	-1.4
Computer time (sec)	126420	10140	-92

Discussion

The results of the comparisons verify that the detailed model and the developed simplified model achieve similar results in simulating the chassis's crash response. All the errors are below 10%, and the simplified models took less than 10% of the computer time necessary for the detailed model to finish the crashworthiness analysis.

5. Conclusions

This paper develops the final simplified model for the truck chassis model. The crash results and the comparisons show that the developed simplified model works very well in simulating low-speed impact problems and is eligible for replacing the existing detailed model to save computer resources. In the simplified model, the bending resistance of the channel section beam derived by the author is applied to the development of the new nonlinear spring elements that model the plastic hinges of the side-rails. Again, the simplified modeling method presented in previous literatures is used to create the simplified model for the side-rails that receive the majority of the impact loads and significantly contribute to the crash. Also, in simplifying the cross members, the equivalent beams are generated and applied to replace the detailed cross member models previously simulated by shell elements. Finally, as shown in the comparison, taking all of the steps can significantly reduce the overall size of the chassis model.

References

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