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CRASHWORTHY DESIGN AND EVALUATION ON THE FRONT-END STRUCTURE OF KOREAN HIGH SPEED TRAIN

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ABSTRACT−An intensive study was conducted for the crashworthy structural design of the recently developed Korean High Speed Train (KHST). Two main design concepts were set up to protect both crews and passengers from serious injury in heavy collision accidents, and to reduce damage to the train itself in light collision accidents. A collision against a movable 15-ton rigid obstacle at 110 kph was selected from train accident investigations as the accident scenario for the heavy collisions. A train-to-train collision at the relative velocity of 16 kph was used for the light collision. The crashworthiness behaviors of KHST were numerically evaluated using FEM. Analysis results using 1-D collision dynamics model of the full rake consist and 3-D shell element model of the front end structure showed good crashworthy responses in a viewpoint of structural design. Occupant analyses and sled tests demonstrated that KHST performed well enough to protect occupants under the considered accident scenarios. Finally our numerical approaches were evaluated by a real scale collision test.

KEY WORDS : Crashworthiness, Finite element method, Railway safety, High speed train, Sled test

1. INTRODUCTION

Historically, the rail transit industry provides the safest means of transportation available all around the world. Especially, the high speed train is advantageous in terms of convenience, fast access, exactness and transportation operation efficiency. However, an unexpected accident may cause serious financial and human losses like the recent train accident that occurred in Eschede, Germany on June 4, 1998. The accident was caused by the derailment of the ICE, which killed 98 people and injured over 200. Thereafter, many countries advanced in railway technology have usually designed rolling stocks for crashworthiness in order to minimize the losses caused by train accidents (Tyrell *et al.*, 2000; Cleon *et al.*, 1997). Since 1999, the USA has required a rule for the design and evaluation of crashworthiness on high speed trains of TIER II (commercial speed of 200−240 kph), and Europe will also issue the crashworthiness in UIC (International Union of Railways) regulations in the near future.

First of all, some accident scenarios were defined to conduct the crashworthy design of the Korean High Speed Train (KHST). In order to improve the safety of KHST, crush energy absorbing sub-structures were designed for protecting the front end of the train. Next, its crashworthiness characteristics, such as the design of the crushable zone, survivable space and impact acceleration levels, were evaluated, solving the one-dimension dynamic model of the train with PAM-CRASH (Tyrell *et al.*, 1997; Marguet *et al.*, 1995). The energy absorption capability of the front structure and the safety of passengers and drivers were analyzed using a 3D-shell model (Kim *et al.*, 2002; Marissal *et al.*, 1992; Tyrell *et al.*, 1999) of KHST. Finally, occupant analyses and sled tests were conducted to evaluate the crashworthiness of KHST with the calculated accelerations. Finally, a collision test was performed using two subway EMU (electric multiple units) vehicles to verify the reliability of our numerical analyses.

2. CONCEPTUAL DESIGN TO IMPROVE CRASHWORTHINESS OF KHST

In this study, the following guidelines were set up for the crashworthy design of KHST to cover the most common accident patterns by investigating some foreign countries (Lombard, 1995; Cleon *et al.*, 1997; Marguet *et al.*, 1995).

- Accident scenario 1: in the collision with a 15-ton rigid obstacle at 110 kph, required no intrusion into survival spaces, no overriding, and passengers' deceleration at less than 5 g.
- Accident scenario 2: in the train-to-train collision at a

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relative velocity of 16 kph, required no permanent deformation in the structure, and passengers' deceleration at less than 3 g.

The first guideline is usually used for a level-crossing safety of TGV in France. The second guideline is applied to minimize damage to vehicle bodies and electric equipments in the event of light collisions in the station compound.

2.1. Crashworth Design Specifications of the Front End Structure

From the conservation laws of momentum and energy, the motions of two bodies are to be mathematically described as shown in Equation (1) and (2).

From the conservation of momentum,

$$m_1v_1+m_2v_2=m_1v_{f1}+m_2v_{f2} \tag{1}$$

and, from the conservation of energy

$$\frac{1}{2}m_1v_1^2+\frac{1}{2}m_2v_2^2=\frac{1}{2}m_1v_{f1}^2+\frac{1}{2}m_2v_{f2}^2+E_d \tag{2}$$

are derived, where

m_1, m_2: masses of the body 1 and 2
v_1, v_2: initial speeds of the body 1 and 2
v_{f1}, v_{f2}: final speeds of the body 1 and 2 after collision
E_d: dissipated energy during collision

If the two bodies are collided in a perfectly plastic fashion, the final speeds of the body 1 and 2 after collision may be defined as follows.

$$v_f = v_{f1} = v_{f2} \tag{3}$$

By plugging Equation (3) into (1), the final speed can be obtained like the equation (4).

$$v_f=\frac{m_1v_1+m_2v_2}{m_1+m_2} \tag{4}$$

From Equation (2) and (3), the dissipated energy E_d is obtained as given.

$$E_d=\frac{m_1m_2(v_1-v_2)^2}{2(m_1+m_2)} \tag{5}$$

It is worthy noting that a collision of a light body to a heavy one needs the same dissipated energy as a collision of a heavy body to a light one.

From Equation (5), 5.74 MJ and 0.168 MJ must be dissipated to satisfy the accident scenario 1 and 2 respectively, if we assume the power car (68 tons) is involved alone in the collision.

Equation (5) doesn't make it clear that how much energy must be dissipated in each body, but it denotes only the total energy to be dissipated during the collision. The total energy may be denoted like Equation (6) about the body 1 and 2.

$$E_d=E_{d1}+E_{d2} \tag{6}$$

where, E_{d1} and E_{d2} denote the energies to be dissipated by the body 1 and 2, respectively. E_{d1} and E_{d2} are expressed in terms of the crush lengths (L) and the mean crush forces (F), if it is assumed that most of the collision energy is dissipated by plastic deformations.

$$E_{d1}=F_1 \cdot L_1 \tag{7a}$$

$$E_{d2}=F_2 \cdot L_2 \tag{7b}$$

The mean crush forces of Equation (7a) and (7b) are expressed in terms of the mean decelerations (a_1, a_2) of the bodies.

$$F_1=m_1 \cdot a_1 \tag{8a}$$

$$F_2=m_2 \cdot a_2 \tag{8b}$$

Since F_2 is the reaction force of F_1, F_2 is equal to F_1. Hence, Equation (9) is obtained as given.

$$a_1=\frac{m_2 \cdot a_2}{m_1} \tag{9}$$

If the body 2 (m_2) collides against the stationary rigid body 1 (m_1) like the accident scenario 1, the crush length (L) is calculated from the mean deceleration (a) and the colliding speed (v) of the body 2 from Equation (5)–(9).

$$L=\frac{m_1}{2a(m_1+m_2)} \cdot v^2 \tag{10}$$

Equation (8) and (10) reveal that the crush length of 1.72 m and the mean crush force of 3332 kN are required to enable the body 2 to keep the mean deceleration of 5g under the scenario 1.

On the other hand, if the body 2 collides against the other body 1 having the same weight (m) like the accident scenario 2, the crush length (L) of each body is calculated using the mean deceleration (a) and its colliding speed ($v = -v_1 = v_2$) from Equations (5)–(9).

$$L=\frac{v^2}{2a} \tag{11}$$

From Equations (8) and (11), the crush length of 0.083 m and the mean crush force of 2000 kN are obtained to get each body to maintain the mean deceleration of 3 g under the scenario 2. But, more energy must be absorbed in the front end for a train-to-train collision due to successive crash when compared with an obstacle-to-train collision. Since the total weight of KHST is 780 tons, 1.926MJ can be absorbed conservatively during the train-to-train collision of 8 kph. If the whole kinetic energy is absorbed in the front end, the crush length of 0.963 m is necessary for the mean crush force of 2000 kN.

It is concluded from the calculations that the front end structure should have structural performances as follows:

For scenario 1,
Energy absorption: more than 5.74 MJ/Power car,
Crush length: more than 1.72 m,
Mean crush force: less than 3332 kN
For scenario 2,
Energy absorption: more than 0.168 MJ/Power car,
Crush length: from 0.083 m to 0.963 m
Mean crush force: less than 2000 kN

2.2. Conceptual Design of the Front End Structure
In order to satisfy these guidelines, it is necessary that the coupler and the replaceable energy absorber in the front end absorb more than 0.168 MJ and, the full front end structure absorbs more than 5.74 MJ.

Taking the results from several trial analyses, a front end structure with structural characteristics as shown in Figure 1 and 2 was designed. In the figure 1, a block-shaped aluminum honeycomb was put on the headstock to absorb some additional impact energy.

In Figure 2, areas I, II, III and IV represent the sequences of energy absorbed at the coupler with hydraulic cartridge, the energy absorber of tube inversion type, the headstock with multi-cell type and the block-shaped aluminum honeycomb, respectively.

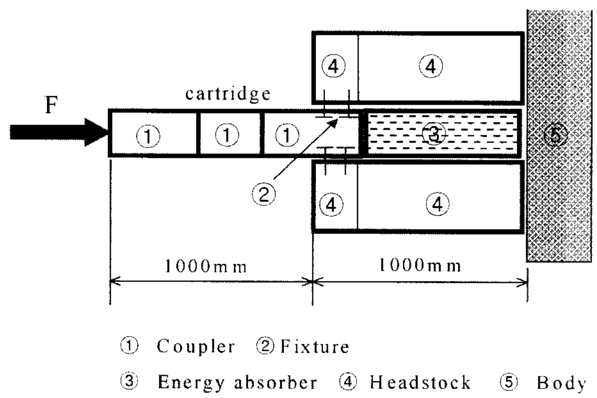


Figure 1. Schematic design of the front end structure.

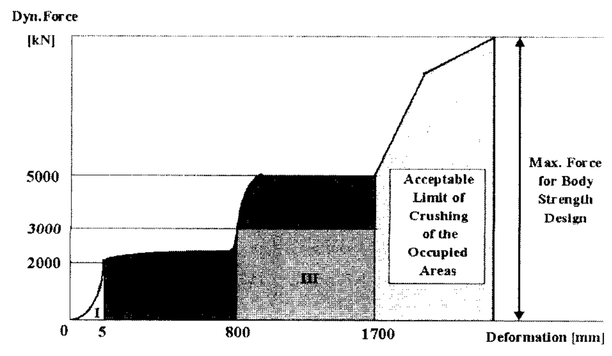


Figure 2. Energy absorption of the front end structure.

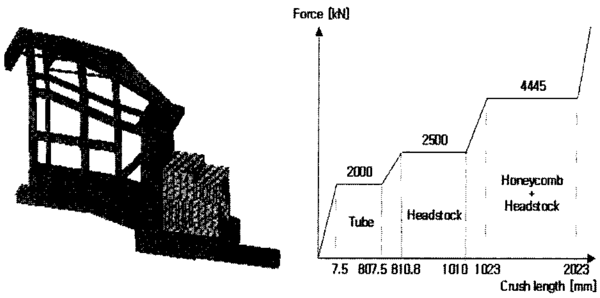


Figure 3. The front end structure of the KHST.

3. ANALYSIS AND EVALUATION OF CRASHWORTHINESS

3.1. Crashworthiness of the Power Car

3.1.1. Design of the front end structure
After many design modifications with the structural layout of Figure 1, a detail design such as shown in Figure 3 were derived. In the process of the detail design, collision analyses were executed to find out the crush characteristics of each structural part, such as the energy absorption tube, the headstock, and the aluminum honeycomb. The detail sizes and physical data of the front end parts may be referred the reference 9. The curve in Figure 3 shows the energy absorption of each structural part in an average sense.

3.1.2. Collision analyses of the front end structures
In order to evaluate the energy absorption of the front end structures when they are crushed, a collision analysis was executed using the accident scenario 1. According to the numerical analysis results, the front end of KHST was crushed in a well-controlled fashion, which would guarantee a good survival space for drivers, as shown in Figure 4.

Figure 5 and 6 show the energy absorption characteristics and the crush forces of the front end. The average crush force of KHST was 3,016 kN, whereas its crush length was up to 2000 mm. And, KHST could absorb 5.8

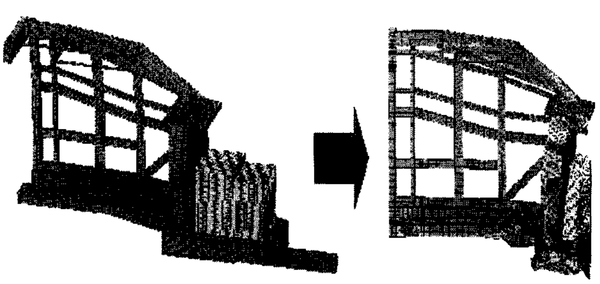


Figure 4. Deformed shape of the front end structure.

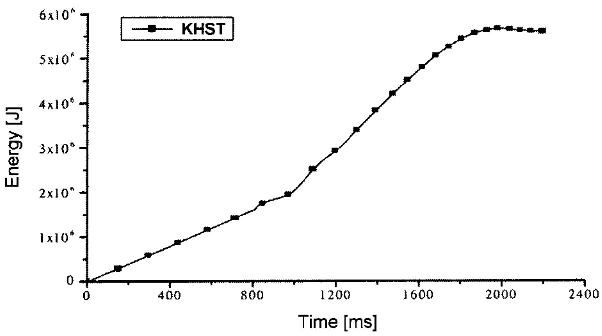


Figure 5. Energy absorption of the front end structure (110 kph).

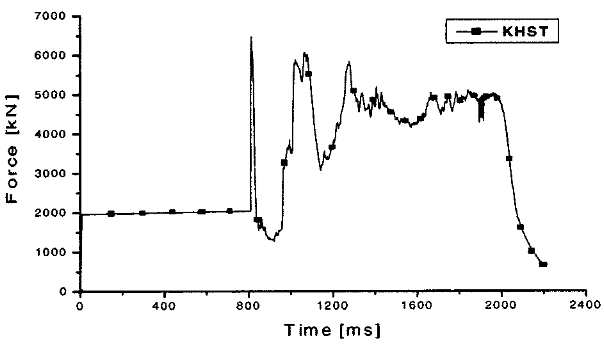


Figure 6. Crush force of the front end structure (110 kph).

MJ of impact energy in the front end. These results showed that the front end of KHST satisfied the design specifications for the accident scenario 1. Furthermore, it is concluded that the design specifications for the accident scenario 2 could be satisified from the numerical results in Figure 5 and 6.

3.1.3. Analysis of driver's safety

To evaluate driver's safety in a level crossing accident, a 50th percentile hybrid III dummy with a seat belt was simulated under the collision condition of accident scenario 1, where a train with a speed of 110 kph collides with a 15-ton rigid obstacle. Figure 7 and Table 1 show the driver's behavior and injury indices, respectively. From the simulation results, it was concluded that the front end structure of KHST would have a good crashworthy performance for a driver.

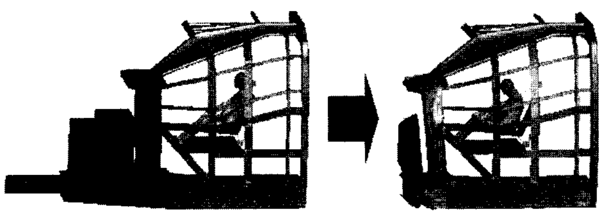


Figure 7. Driver's behavior after collision (KHST).

Table 1. Injury indices under the SNCF scenario (110 kph).

	HIC	Chest [g]	Femur [kN]	Comments
Automotive	1000	60.0	10.0	Safety regulations [FMVSS]
Rolling stock	500	30.0	5.0	Recommendations [Cleon, 1997]
KHST	101.5	22.0	4.0	Recommendations are satisfied

3.1.4. Crashworthiness of the power car

The crashworthiness of the power car of KHST at a level crossing accident was evaluated under a practical situation where it collided against a deformable dump truck of 15 tons at the speed of 110 kph. For the real situations, numerical analyses were conducted using two collision conditions where the train with a speed of 110 kph collided against the 15-ton truck as head-on and offset style. Figure 8 shows the result of the head-on collision analysis, and Figure 9 shows the result of the offset collision analysis. The deformed shapes of its front end structure revealed similar collapse modes as intended in its initial design, and the drivers cab space was not collapsed.

3.2. Evaluation of Crashworthiness for the Full Rake Consist

3.2.1. Evaluation of crashworhiness using 1-D model

In addition to impact energy absorbing capacities, the level of deceleration of passenger's room must be

Figure 8. Deformed shape at head-on collision.

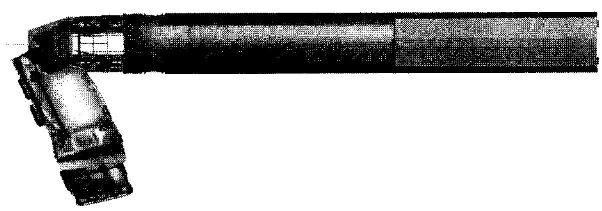


Figure 9. Deformed shape at offset collision.

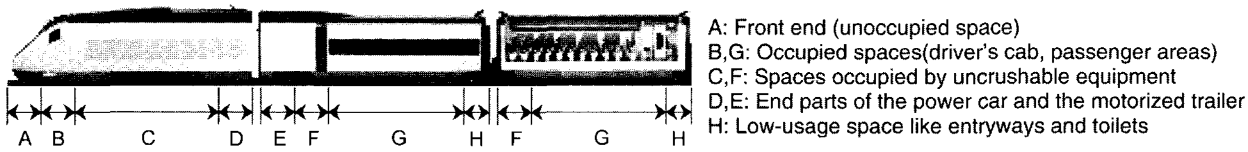


Figure 10. Section definition of the KHST.

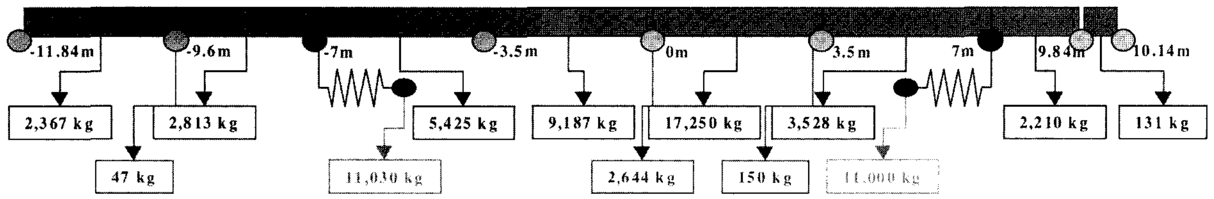


Figure 11. Mass distribution data of the KHST power car.

maintained under 3 g. The crushing characteristic data of each car-body section were calculated by using 3-D shell model analysis, as shown in Table 2 and Figure 10. A dynamic model of the KHST consist composed of 20 vehicles was generated with the mass data of electrical equipment and bogies which calculated using layout of various components. Figure 11 shows a modeling example of the mass distribution (Koo *et al.*, 2002).

The numerical results of 1-D dynamic model were summarized in Table 3. In spite of the heavy collision of the scenario 1, the driver's cab was not deformed plastically. Therefore, the design of the front end guarantees a survival space for drivers. Furthermore, the maximum deceleration of the passengers' room in the first motorized trailer was less than 3 g, which satisfied the design guideline of the scenario 1.

In case of the accident scenario 2, the maximum reaction force was 2000 kN (UIC code: max. 2000 kN), and the maximum deceleration of the passengers' room in the first motorized trailer was 2.4 g (UIC code: max. 3 g). These reaction forces and decelerations satisfy the code of UIC. Furthermore, the structures of the power car except the front end were deformed elastically and not damaged. But the energy absorption reaches up to 1.6 MJ because of the successive collisions by the following trailers. The 1.6 MJ equals to about 83% of the kinetic energy (1.926 MJ) of the full rake consist (780 tons with 8 kph).

Table 2. Crashworth characteristics of each section.

Sectional characteristics	A	B	C	D	E	F	G	H
Mean crush force (kN)	3260	6040	4500	4000	4291	4960	8811	5006
Available crush length (mm)	2023			2060		2762		1712

Table 3. Crash performances of KHST under the two accident scenarios.

	Scenario 1	Scenario 2
Energy absorption in the front end (MJ)	5.712	1.6
Max. reaction force (kN)	4473	2000
Deformation of the front end (mm)	1753/crushed	800/crushed at the coupler and the energy absorber
Deformation of the driver's cab (mm)	4/elastic	1.9/elastic
Deformation of the power car body (mm)	16/plastic	5.5/elastic
Max. deceleration of the power car (g)	7 at the driver's cab	2.2 at the center part
Max. deceleration of the passengers' room in the first motorized trailer (g)	2.9	2.4
Evaluation on safety	Passengers' risks were low	Damage was confined within replaceable parts

It may be concluded that KHST has good crashworthy performances under the scenario 1 and 2, and satisfies the design guidelines.

3.2.2. Evaluation of crashworthiness using 2-D model
The 1-D dynamic analysis can be conveniently used when evaluating the overall performance for crashworthy design of the full rake consist, but it cannot simulate the overriding phenomena. With these design factors in mind, a 2-D dynamic model was generated and analyzed to evaluate the dynamic responses of parts in car-to-car links. Figure 12 shows a 2-D modeling example of the power car (Koo *et al.*, 2002).

Accident scenario 1 was applied to the 2-D dynamic model. The analysis results showed that the vertical displacements between the power car and the first motorized trailer remained within tolerance of the anti-climbing grip (80 mm), as shown in Figure 13. During the accident of the scenario 1, the rear end of the power car has some relative up-down motions to the first motorized trailer within 40 mm. Therefore, the KHST showed no overriding phenomena.

3.3. Evaluation of Passengers' Injury Safety by the Sled Test
The passengers' safety could be numerically assessed with commercial softwares such as LS-DYNA or MADYMO. However, it is impossible to accurately predict passengers' injuries caused by various unknown factors in a collision. To represent passenger's room environment of a real train and to predict their injuries, a sled test with appropriate dummies is a more realistic and reliable method. Figure 14 shows a test example of the HYGE Sled Test that were used to assess passengers' injuries.

The testing conditions were decided using the impact acceleration data of passengers' compartment, which were obtained through 1D dynamic model analyses. Table 4 shows the passengers' injuries under each collision condition. Since 3.2 g of the first test in Table 4 is similar to the maximum deceleration of the passengers' room (2.9 g) in Table 3, it is concluded from the first test

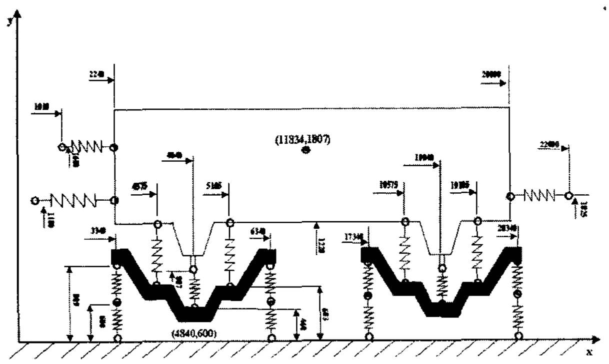


Figure 12. 2-D dynamic model of the KHST power car.

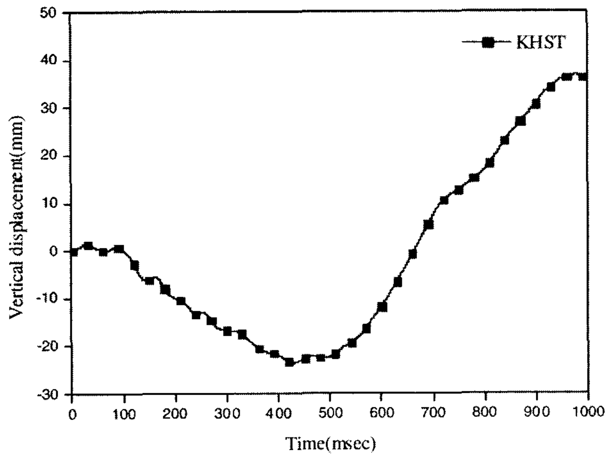


Figure 13. Relative vertical displacements between the power car and the motorized trailer (110 kph).

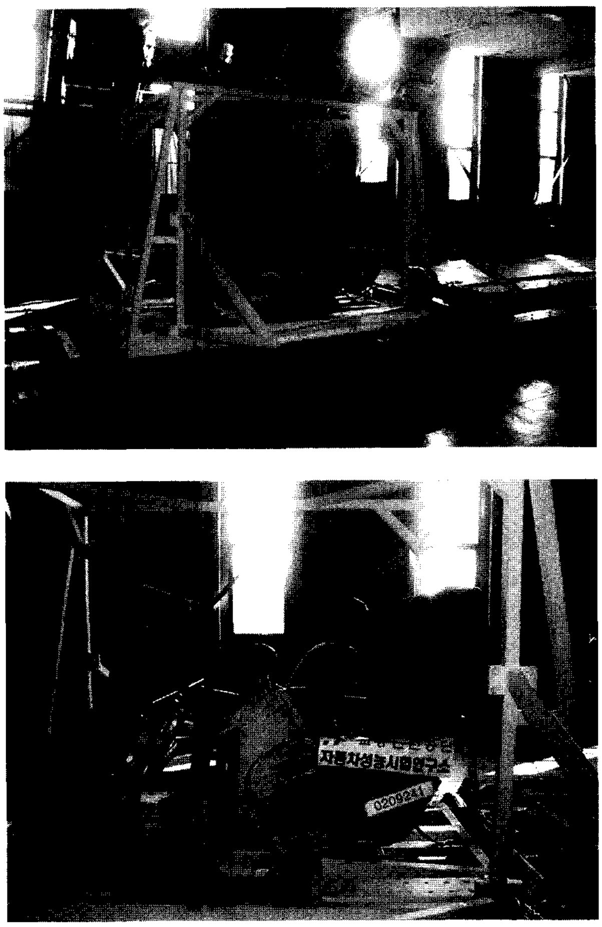


Figure 14. The pre and post of the first sled test (3.2 g).

Table 4. Results of the sled test (Triangular waveform at 250 ms, 50^{th} % Hybrid III, First class seat).

Peak acceleration	HIC	Chest [g]	Femur [kN]	Neck	Evaluation
3.2 g	58.8	9.7	4.3	0.89	Low passengers' risk
5 g	80.9	11.8	4.7	1.02	Serious neck injury
8 g	96.2	12.24	5.4	0.41	The injury indices are low but the seats completely failed: very dangerous for FRA regulations
Automotive	1000.0	60.0	10.0	1.0	Serious injuries (Fatality rate is more than 20%)
Rolling stock	500.0	30.0	5.0	NA	Recommendations for train-passengers

results that the whole passengers' risks are low but their neck injuries are relatively high.

3.4. Real Collision Test of EMU Vehicles

For the evaluation of crashworthiness and the validation of its safety, it was essential to go through collision tests using real train vehicles, but there were practical limitations, such as the financial problem and the test facility. Evaluation using the numerical analysis method may be the easiest approach, but it can cause fatal influences in the safety of passengers if the numerical error is not negligible at the design stage. Therefore, it was necessary to validate the reliability of our numerical analysis technology through the comparison of real scale tests and numerical analyses.

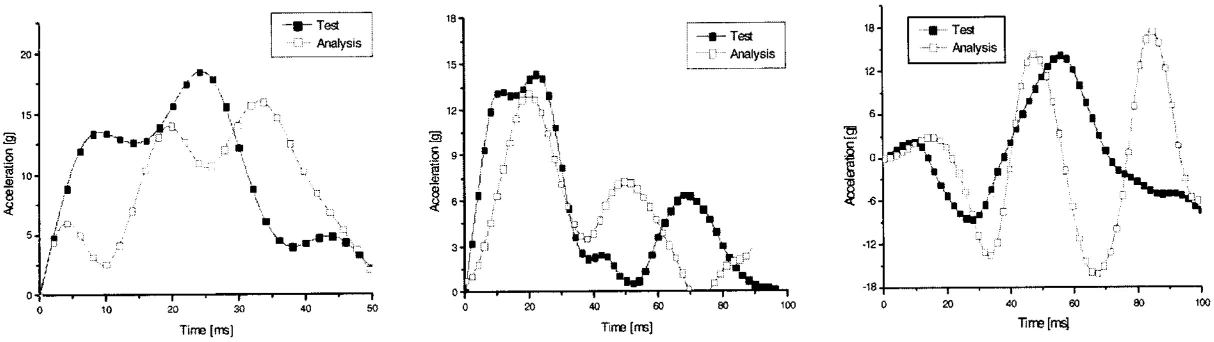
Since the KHST train body was not available for a collision test, the EMU vehicles which were provided by ROTEM Co., a train manufacturer in Korea, were used for this experimental study to validate the reliability of numerical analyses. The vehicles in the experiment were an EMU passenger car was made of stainless steel materials. The test condition was the collision of a vehicle at 25 kph against the same type of vehicle in a station compound. The specifications of the test vehicle are shown in Table 5, and the layout of measurement devices in the test vehicle and vehicle interior is shown in Figure 15.

The experimental results showed a maximum error of 13.4% in horizontal accelerations at the driver's cabin and an maximum error of 23.3% in vertical accelerations at the passenger compartment compared with those from numerical simulations. Figure 16 shows the acceleration graphs comparing the experimental results with the analysis ones.

Table 5. Specifications of the test cars.

	Moving car	Stationary car
Length of a vehicle	21,640 mm	21,640 mm
Width of a vehicle	3,082 mm	3,082 mm
Height of a vehicle	3,868 mm	3,868 mm
Weight of a vehicle	12 ton (empty)	42 ton (payload)
Bogie weight	8 ton	8 ton
Others	-	Parking brake (100 kN)

Figure 15. Test cars and data acquisition systems.



(a) Position 1 (horizontal) (b) Position 2 (horizontal) (c) Position 3 (vertical)

Figure 16. Comparison of accelerations between the test and the FEA results.

4. CONCLUSION

This paper develops the design and evaluation method for crashworthiness on the front end of the high speed train. The crashworthy design concepts were evaluated through the dynamic models, detailed 3-D finite element crash analysis model, a series of sled tests and train crash test. Through this study on the crashworthy design and evaluation of the front end of the KHST power car, the following results have been obtained:

(1) When the leading power car of KHST collides with a 15-ton rigid obstacle at speed of 110 kph, driver's survival space and low injury indices can be ensured.

(2) From the result of the 1-D collision analyses, it was found that KHST had good performances in terms of driver's protection, passengers' safety, and protection of the car bodies.

(3) Through the 2-D collision analyses, the overriding phenomena were evaluated. The overriding displacement was so small as to cause no safety problem.

(4) The passengers' injuries were evaluated through the sled tests, and the result showed that the whole passengers' risks are low but their neck injuries are relatively high under the heavy accident scenario. A serious injury to the neck is expected under the test condition of higher than 5 g. In the test condition of 8 g, a fatal injury could occur because the fixtures of the seat frame were completely failed.

(5) In order to evaluate the reliability of our analyses, an experimental study was conducted with real scale vehicles. When the collision accelerations of the test vehicle were compared with those of the numerical ones, the results were in good agreement by a maximum difference of 20%.

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