튜브형 트라이빔과 합성 지주를 사용한 교량난간의 충격거동

Impact Performance of Bridge Rail Composed of Composite Post and Tubular Thrie Beam

고 만 기[1] · 김 기 동[2]

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요 약 : 14TON 밴 형식의 트럭에 대응할 수 있는 튜브형 트라이빔 교량난간을 제안하였다. 이 교량난간은 합성형 지주에 연결된 튜브형 트라이빔과 철재 가드빔으로 구성되어 있는데, 튜브형 트라이빔은 다양한 범퍼 높이를 갖는 차량에 대응할 수 있고 기존의 교량 난간에 비해서 교량난간의 시종점부와 가드레일 사이를 보다 완벽하게 연결할 수 있는 장점이 있다. 가드레일 지주로 사용되는 것과 동일한 크기의 철재 파이프에 콘크리트를 충전한 합성형지주가 단순히 철재 파이프의 크기를 키운 것보다 강성 및 극한강도를 증대시키는데 효율적임을 확인하였다. 개발된 시스템에 대하여 14Ton-80km/h-15° 의 충돌조건으로 실차 충돌실험을 실시하였는데 NCHRP Report 350의 실험레벨 4의 평가항목을 모두 만족하였다. 컴퓨터 시뮬레이션을 통하여 이 시스템이 국내의 S2 등급으로 분류될 수 있음을 보여주었다.

ABSTRACT : Tubular bridge rail was developed to restrain and redirect a 14ton van-type truck. The developed bridge rail permits better visibility than concrete safety-shape bridge rail, and it has better structural adequacy than the existing steel and aluminum bridge rails in Korea. The new bridge rail consists of a tubular thrie beam(TTB) rail and a steel guard rail, which are connected to composite posts. The TTB shape provides both better containment of diverse bumper heights and more tight fit between the ends of bridge rail and roadside guardrails than the existing bridge rail sections currently used in Korea. Making composite post by filling concrete inside the steel pipe of the same size as are used for the roadside guardrail post was found to be more efficient in increasing the stiffness and ultimate strength than simply increasing the size of the steel pipe. The system was crash-tested for the impact condition of 14ton-80km/h-15° , and it satisfied all evaluation criteria set forth in NCHRP Report 350 for a Test Level 4 safety appurtenance. Acceptable performances were obtained in computer simulations for the impact condition of S2.

핵 심 용 어 : 튜브형 트라이빔, 교량난간, 합성형 지주, 충돌실험, 충격조건

KEYWORDS : Tubulr Thrie Beam(TTB), Bridge Rail, Composite Post, Crash Test, Impact Condition

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본 논문에 대한 토의를 2001년 12월 31일까지 학회로 보내주시면 토의 회답을 게재하겠습니다.

1. Introduction

There had been no guideline in Korea on the bridge rail design until the Ministry of Construction and Transportation (MOCT) issued Bridge Rail Design Guide in 1999(1). Before the design guide was made, the design criteria were adopted from the design guide for the longitudinal barriers made by MOCT in 1997(2). But engineering practice was to adopt the foreign design and to construct it. Concrete safety-shape barrier, steel and aluminum bridge rails were the most popular type. In many bridges, steel or aluminum bridge rails were preferred to ensure a better visibility.

But the members of steel or aluminum bridge rails were manufactured without strict quality control and heavy casualties were caused at many impact accidents. It could have been avoided, had a well designed and verified system been installed. Recently, a falling accident of chemical tanker into a reservoir alerted the public to the importance of the bridge rail structure. Government started to realize that improperly designed rail would be a threat not only to driver but also to the neighboring environment. This study was intended to develop a high performance bridge rail system that would be strong enough to contain large trucks and to resolve the problems of current bridge rail systems. Most of the bridges have their name column made of concrete or granite installed at the entrance of the bridges. This column itself not only causes great danger to impacting vehicle but also interrupts the smooth continuation of a bridge rail and a guardrail which is normally installed at the beginning and end of the bridges for topographic reasons. So the bridge rail to be developed was intended to have the following design characteristics:

1) Have sufficient strength and stiffness against the impact of 14Ton-80km/h-15°
2) Be simple and economical
3) Make the continuation possible between the bridge rail and the guardrail next to the bridge
4) Have proper geometry to prevent rolling over of the vehicle having high center of gravity
5) Ensure a good visibility and be esthetic.

2. Design of the Bridge Rail System

To satisfy the conditions above, a TTB was selected as a main rail. By using the TTB shape diverse bumper height could be effectively contained(3) and the strength requirement could be met simultaneously. Further it could make the transition to the guardrails at the end of the bridge rail to be smooth and continuous because the guardrails can be attached tight fit to the TTB face which was not possible for the normal bridge rails with circular or rectangular section. Tubular shape section of a main rail will also increase the energy absorbing capacity as compared to open sections. TTB Bridge Rail consists of a TTB rail element bolted to 140mm diameter steel posts and a steel guard beam rail mounted above the tubular rail.

In designing a post, economy and strength were the main issue. To make it economical it must be simple in shape and easy to construct. It was decided to use steel pipes with a 140mm diameter and a thickness of 4.5mm, which were the same posts as used for guardrail posts in Korea. The length of posts was 1140mm. The posts were constructed with 300mm × 350mm × 12mm base plate.

The post was attached to the base plate by welding and was stiffened by four rib stiffeners. Stiffeners were also attached to the post barrel by welding. The posts were anchored with four 22mm diameter adhesive anchor bolts located on the front face (traffic side) of posts and two 16mm diameter adhesive anchor bolts located on the back face (field side) of posts.

During static load tests, it was found that the region around the top of rib stiffeners was prone to crack. To improve the lateral stiffness and strength it was necessary to take measures to delay the occurrence of crack near the tip of rib stiffener on the tension side and local buckling at the tip of rib stiffener on the compression side. This was fulfilled by filling concrete inside the post. Before placing the concrete, four 16 mm diameter adhesive anchors were placed into the curb and projected up to 200mm above the curb surface. After the posts were secured, concrete was placed inside each post up to a height of approximately 250mm above the post mounting surface.

Preliminary design was made based on the impact force by Olson Model(4), and the ultimate strength of the section was estimated by plastic failure mechanism procedure. Static tests for both beams and posts were performed and the test results were incorporated into the ultimate strength evaluation and computer simulation by BarrierⅦ(5). Simulations and a crash test were performed to evaluate the impact performance of the system for the impact condition of 14ton-80km/h-15° . Finally, the maximum service level according to Korea bridge rail design guide was investigated by simulations.

Table 1 is the summary of the service

Table 1. Service Level and Impact Conditions for Bridge Rail

Impact Designation	Impact Severity, IS (KJ)**	Impact*	Weight (ton)	Speed (km/h)	Angle (deg)	Limit of Deceleration Level (G)	Maximum Deflection Allowed (cm)	Limit of Exit Angle (deg)
B	60	I	25	30	15	12	30	9
		Ⅱ	1	60	20	12	30	12
A	130	I	25	45	15	18	30	9
		Ⅱ	1	100	20	18	30	12
S1	160	I	25	50	15	20	30	9
		Ⅱ	1	100	20	20	30	12
S2	280	I	25	65	15	20	30	9
		Ⅱ	1	100	20	20	30	12
S3	420	I	25	80	15	20	30	9
		Ⅱ	1	100	20	20	30	12
SS	650	I	25	100	5	20	30	9
		Ⅱ	1	100	20	20	30	12

* Impact 'I' : Truck Test for Strength of Barrier, Impact 'Ⅱ' : Small Car Test for Occupant Safety
** Kilo-Joule

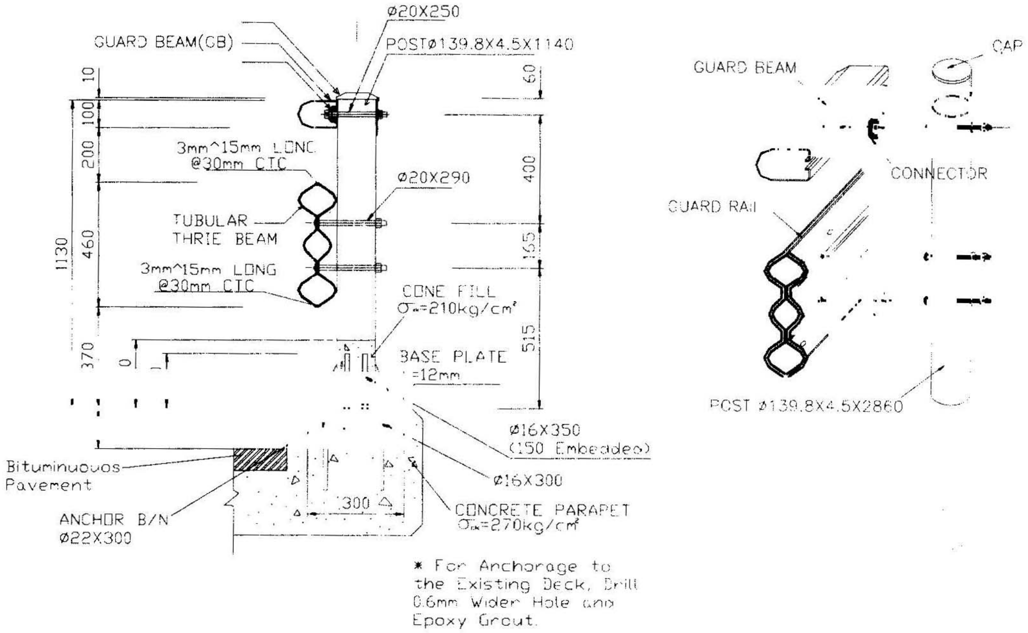


Fig. 1 Tubular Thrie Beam Bridge Rail

level and impact conditions of the bridge rail design guide by MOCT. Despite the impact conditions were established, it was not feasible to use 25ton single unit truck as a design truck since there was no facility to test such a large truck and of course no experience of crash testing such a big truck for the bridge rail design. Crash test environment would not be improved in the near future. In this situation, the design criteria seemed to be too severe to be followed in the actual field. Thus, it was decided to design a system for the impact condition of 14ton-80km/h-15° and to crash test the resulting system for that condition, and then to find the maximum capacity of it by computer simulations. Figure 1 shows the design section of the bridge rail explained above.

3. Static Test and Ultimate Strength Evaluation

For the design above, the ultimate strength was calculated using plastic failure mechanism procedure, then was compared with the impact force calculated by using the Olson model, which was a simple mathematical model for a vehicle impacting a longitudinal barrier. The model estimates the average force acting on the vehicle during the phase of impact. To estimate the strength of the system more accurately, static tests were performed.

From the tests, posts without stiffeners were found to be too weak to be used for bridge rail posts. Posts with stiffeners were prone to crack at the tip of rib stiffener, and after the occurrence of the crack they

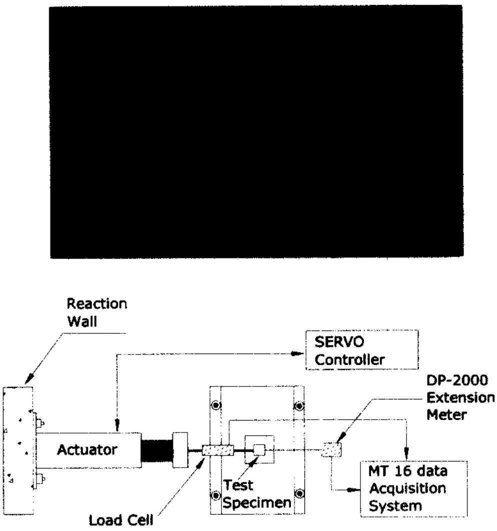
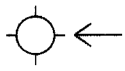
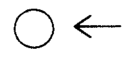
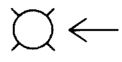
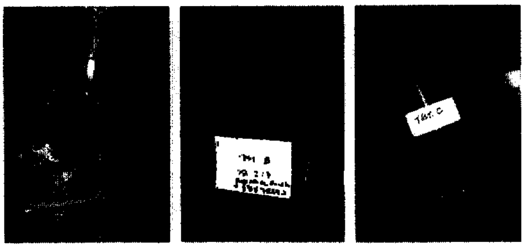


Fig. 2 Test Setup

Table 2. Summary of Post Static Test.

	Test A	Test B	Test C
Orientation of stiffener			
Ultimate Load, PP	9・4 Ton	5・8 Ton	9・5 Ton

* ← : Loading Direction



(a) Test A (b) Test B (c) Test C

Fig. 3 Failure Mode of Posts.

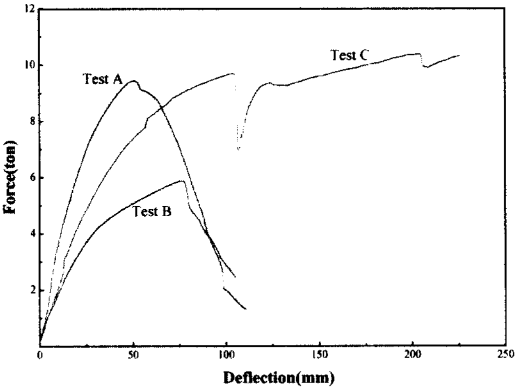
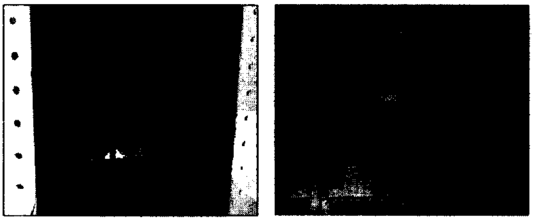


Fig. 4 Force-Deflection Curve of Posts

suddenly failed. To resolve the problem, it was decided to fill the inside of the post with concrete whose compressive strength was 210kg/cm^2.

The length, diameter, and thickness of the posts were 1140mm, 140mm, and 4.5mm, respectively. The posts were SM 490 steel. Figure 2 shows the test setup.

Figures 3 and 4 show the results of representative cases and Table 2 summarizes the test results. Figure 3 shows failure mode of three different type posts. Test A shows the crack failure of the pipe barrel at the tip of the rib stiffener. Test B shows the crack failure around the welding between the post and base plate. Test C shows the bending failure of base plate which develops in a much slower fashion than the crack failures of Test A and Test B. From Table 2, it can be seen that the ultimate strength of Test C is 9.5ton and is larger than that of the other specimens. This may be attributed to the orientation of the rib stiffeners. For Test C, the direction of rib stiffeners is oriented 45 degrees from the loading direction to avoid the welding at the region subjected to the highest tension. And four 16mm× 350mm rebars, which are embedded into concrete mortar to resist flexural action after the occurrence of horizontal crack on the post, seem to delay the local buckling on the compression side of barrel near the top of the stiffener. Therefore, the post



(a) Thrie Beam (b) Guard Beam

Fig. 5 Beam Static Test

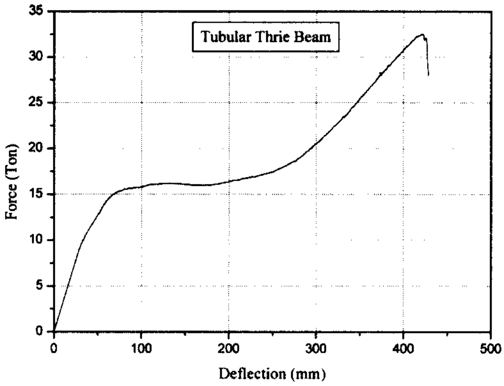


Fig. 6 Force-Deflection Curve for Tubular Thrie Beam

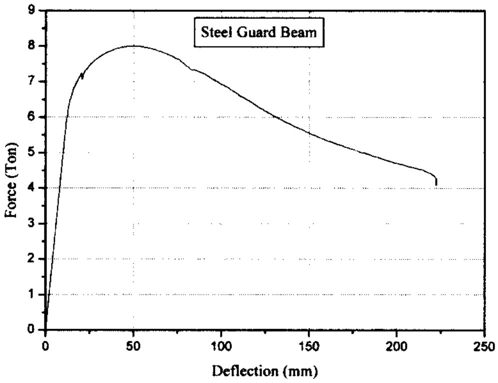


Fig. 7 Force-Deflection Curve for Guard Beam

details of Test C are considered in the system design.

To evaluate the plastic moment M_P of the beam sections, static tests were performed. The test specimens with the length of 2m were hinge supported at the ends. Figure 5 shows the tubular thrie and guard beams being tested.

Figures 6 and 7 show the force-deflection curve for the tubular thrie beam and the guard beam, respectively. From Fig. 6, it can be seen that after flexural yielding at about 16ton, the tubular thrie beam worked as a tension member. For the guard beam, this tension stiffening effect did not occur due to bolt failure at the support of guard beam after about 8ton.

From the test results M_P was found to be about 8t · m for the tubular thrie beam and about 4t · m for the guard beam. These values are used to evaluate the strength of the system and used for computer simulations.

4. Strength Evaluation of the Design and Computer Simulation

By the Olson model$^{(4)}$, the average lateral deceleration G_{lat} and the maximum impact force F_{max} were estimated for the imapct condition of 14ton-80km/h-15° as follows : $G_{lat} = 1.6g$ and $F_{max} = 1.6g \times \pi/2 \times 14ton = 35.4ton$.

The failure load for each rail element based on the palstic failure mechanism procedure$^{(6)}$ can be expressed by

$$W = wl = 8M_P / (L-l/2)$$

,where

W : total applied load
w : load intensity
l : length over which the impact load is distributed
M_P : plastic bending moment capacity of rail
L : total length of each failure mechanism.

Table 3. Ultimate Strength of Each Possible Mechanism

Mechanism	Load Capacity of Rail and Post (Ton)		Ultimate Capacity (Ton)
	Rail*	Post**	
1 SPAN (L=2m)	64	0	64
2 SPAN (L=4m)	27.43	9.5×1	36.9
3 SPAN (L=6m)	17.45	9.5×2	36.5
4 SPAN (L=8m)	12.8	9.5×3	49.8

* Load capacity of the rail :
$W = wl = 8M_P / (L-l/2)$
$M_P = 12$ t · m (=8+4 t · m)
** Load capacity of the post :
$P_p \times$ n(number of post hinge), $P_p = 9.5$t

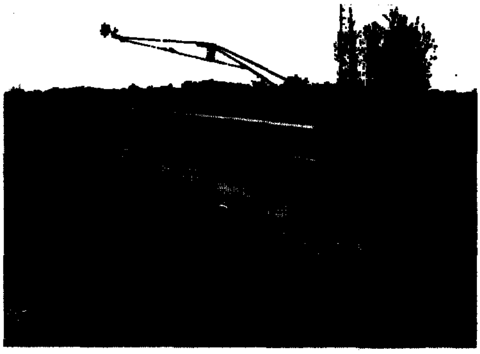
In this study, it is assumed that the length of $l=1$m is reasonable. Based on the above formula and test result the ultimate strength of each failure mechanism was calculated as in Table 3.

From Table 3, it can be seen that the three span failure mechanism is the critical mechanism which produces a load capacity of 36.5ton which is greater than the maximum impact force 35.4ton calculated by Olson model. This indicates that if strength is concerned, the TTB system has enough strength for the impact condition of 14ton-80km/h-15° .

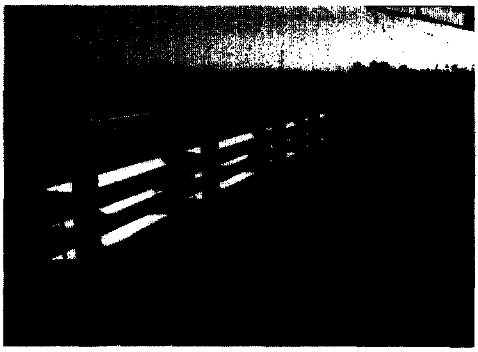
To investigate the impact performance of the system, computer analyses were made using Barrier VII program(5) for the impact condition of 14ton-80km/h-15° . Maximum deflection of the system from the simulation was 23.3cm which was less than the limit value of 30cm in the design guide. The other impact performances were also satisfied.

5. Crash Test

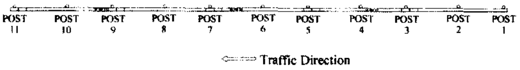
The developed Tubular TTB Rail consists of a TTB rail element bolted to 140mm diameter steel posts and a steel guard beam rail mounted above the tubular rail. The bridge rail system was mounted on an existing 150mm high curb at the TTI testing facility(7). The total length of the installation was approximately 22.5 meters. The spacing between posts alternated 2.0 meters and 2.33 meters. The height of the bridge rail was approximately 1280mm from the pavement surface to the top of the steel guard beam rail. The installation of the bridge rail is shown in Fig. 8.



(a) Frontal View of Installation



(b) Rear View of Installation



(c) Plan of Installation

Fig. 8. Installation of Tubular Thrie Beam

5.1 Test Conditions

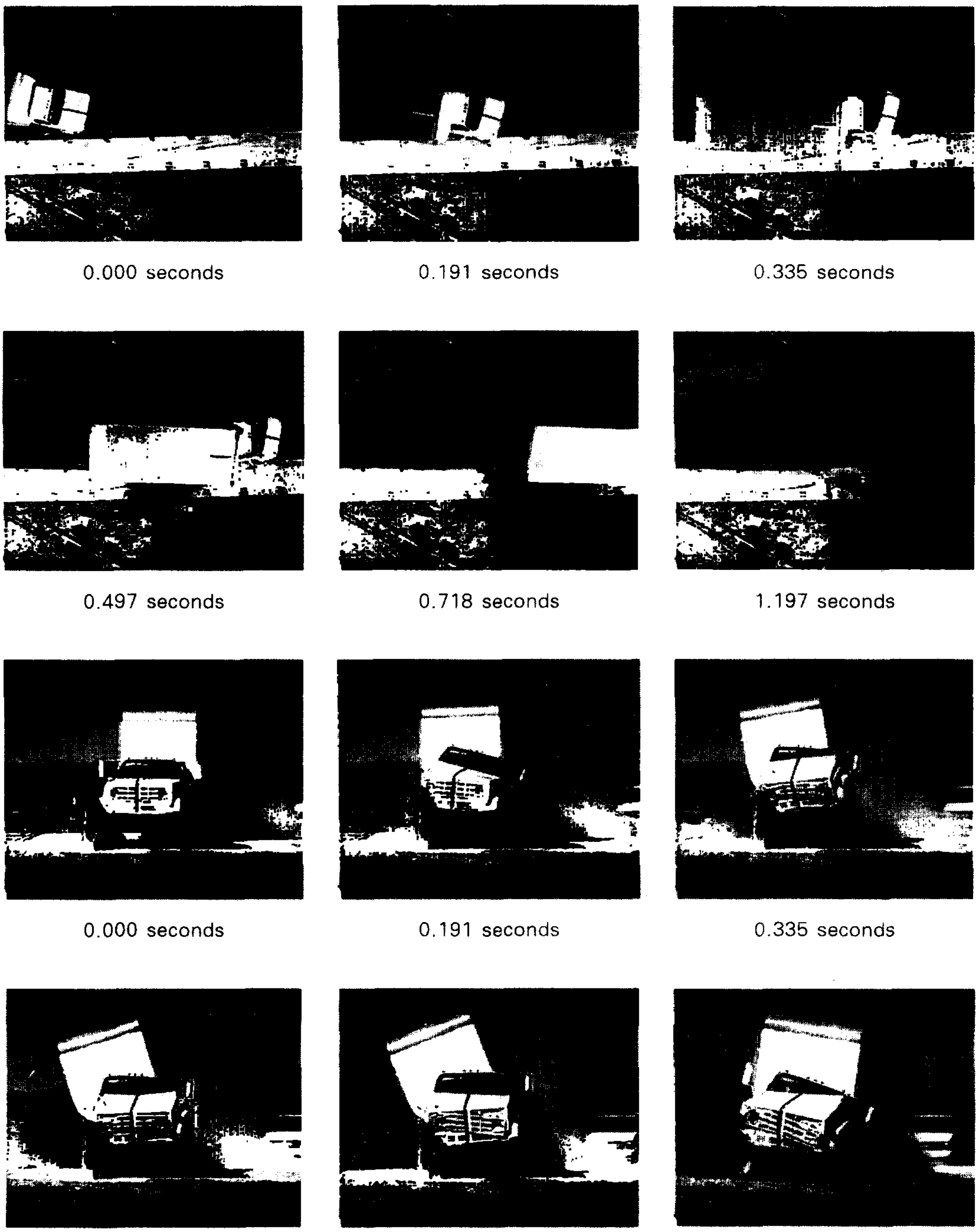
The crash test performed on the developed TTB Bridge Rail is comparable to *NCHRP Report 350* test designation 4-12(8). This *NCHRP Report 350* test involves an 8000kg single-unit truck impacting the critical impact point (CIP) of the bridge rail at a nominal speed and angle of 80km/h and 15 degrees. However, for the test on the TTB Bridge Rail the vehicle used was a 14ton single-unit truck. The purpose of the test is to evaluate whether the bridge rail system can contain and redirect the heavy vehicle. The CIP was determined using information and guidance in *NCHRP Report 350.*

5.2 Impact Description

The single-unit truck impacted the bridge railing at 0.6m downstream from post 5. The vehicle was traveling at a speed of 77.7km/h and impacted the bridge rail at an angle of 14.3 degrees. Shortly after impact the right front tire contacted the concrete curb. Posts 5 and 6 moved at 0.022sec and 0.024sec, respectively. At 0.045sec, the right front tire lost contact with the ground surface and rode up on the curb, and at 0.054sec, post 7 moved. The vehicle began to redirect at 0.055sec. At 0.062sec, the left front wheel began to steer toward the rail, and at 0.103sec, the box-van contacted the top rail at post 5, and at 0.173sec, post 8 moved. The box-van contacted post 6 at 0.180sec, and at 0.187sec, the box support on the box-van began to tear after contact with post 6. At 0.211sec, the left front tire lost contact with the ground and at 0.250sec, the right front tire deflated. At 0.289sec, the right rear tire contacted the curb, and at 0.309sec, post 4 moved. The right rear tire contacted the bridge rail at 0.331sec. The vehicle was traveling parallel with the installation at 0.340sec at a speed of 70.0km/h. At 0.348sec, the right rear tire contacted the rail at post 6, and at 0.349sec, the left rear tires lost contact with the ground. At 0.367sec, the right rear tire deflated, and at 0.404sec, the left front tire returned to the ground surface. The front of the vehicle began to exit at the end of the rail at 0.696sec. The vehicle lost contact with the test installation at 0.957sec, and was traveling at a speed of 63.2km/h and exit angle of approximately 0.4 degrees. The left rear tire returned to the ground surface at 0.969sec. Brakes on the vehicle were applied at 2.4sec and the vehicle subsequently came to rest at 69.3m down from impact and 4.6m toward the field side of the installation. Sequential photographs of the test period are in Fig. 9.

5.3 Damage to Test Article

Minimal damage was sustained by the bridge rail as shown in Fig. 10. There were no cracks in the concrete deck. The deformation of the rail element at post 4 was 16mm. Tire marks were on the face of the curb beginning at post 5, a small tear was in the rail element at impact, The displacement of post 5 was 10mm toward the field side, and The deformation of the rail element was 10mm. The bolt in the bottom rail element



0.000 seconds 0.191 seconds 0.335 seconds

0.497 seconds 0.718 seconds 1.197 seconds

0.000 seconds 0.191 seconds 0.335 seconds

0.497 seconds 0.718 seconds 1.197 seconds

Fig. 9 Sequential Photographs of Test Period at post 6 was deformed and the base plate was pulled upward 30mm from the concrete deck. At the splice near to post 7 the rear rail element was deformed upward, the base plate was pulled up 25mm from the concrete deck, and the displacement the post was 15mm. The displacement of Post 8 was 15mm at the bottom of the post, 10mm at the top of the post. Maximum dynamic deformation of the rail element during the test was 246mm. Maximum permanent deformation to the rail occurred between posts 6 and 7 and it was 40mm, and maximum permanent deformation of the post was 20mm. The damage to the concrete inside a post after the test is shown in Fig. 11.

Fig. 10 Bridge Rail After Test

Fig. 11 Concrete Inside the Post After Test

5.4 Vehicle Damage

The right side of the vehicle received the majority of the damage. Damage to the right side included the door, front tire, rear outside tire and rim, and the box-van and box supports. Structural damage was sustained by the right front U-bolts and the spindle and shock mounts. The bumper, hood, fan, radiator, fuel tank and mounts were also damaged. No deformation or penetration of the windshield occurred, and visibility was not restricted. No deformation or intrusion of the occupant compartment occurred.

5.5 Occupant Risk Factors

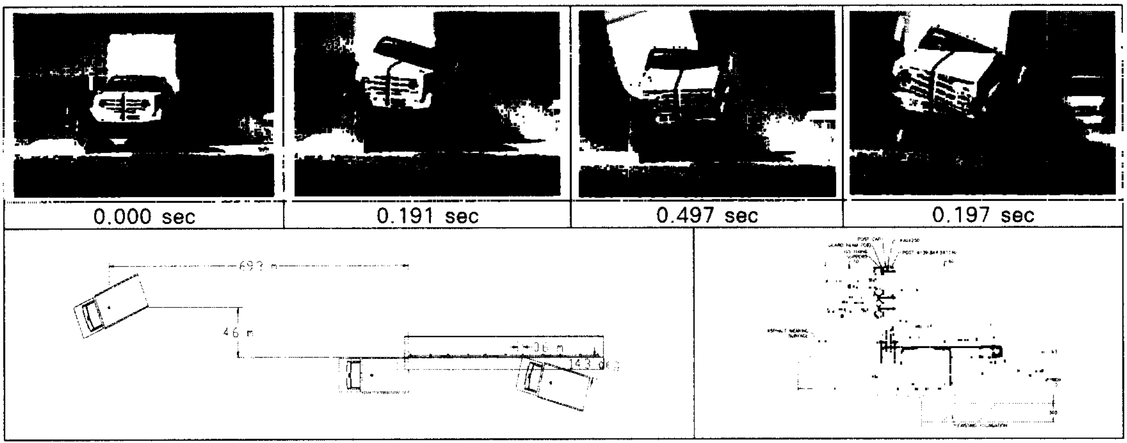
Data from the accelerometer located at the center of gravity of the vehicle were digitized for evaluation of occupant risk and were computed as follows. In the longitudinal direction, the occupant impact velocity was 3.1m/s at 0.311sec, the highest 0.01sec occupant ridedown acceleration was -4.9g from 0.369sec to 0.379sec, and the maximum 0.050sec average acceleration was -4.2g between 0.151sec and 0.201sec. In the lateral direction, the occupant impact velocity was 2.7m/s at 0.311sec, the highest 0.01sec occupant ridedown acceleration was 6.3g from 0.368sec to 0.378sec, and the maximum 0.05sec average acceleration was 3.6g between 0.344sec and 0.394sec. These data and other pertinent information from the test are summarized in Fig. 12.

Conclusively, as Table 4 shows, the developed bridge rail did perform acceptably, according to the safety performance evaluation criteria presented in *NCHRP Report* 350 for a Test Level 4 safety appurtenance.

It was verified that the system satisfactorily performed as a bridge rail for the impact condition of 14ton-80km/h-15° . Impact Severity (IS) for this condition is 231.56KJ (Kilo-Joule). By the Korea bridge rail design guide the grade of the system is between S1(IS=160KJ) and S2(IS=280KJ). To evaluate the highest possible grade of

Table 4. Performance evaluation summary for test

NCHRP Report 350 Evaluation Criteria	Test Results	Assessment
Structural Adequacy		
A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable	The Korean Bridge Railing contained and redirected the vehicle. The vehicle did not penetrate, underride, or override the bridge railing. Maximum dynamic deflection of the rail was 246mm.	Pass
Occupant Risk		
D. Detached elements, fragments or other debris form the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	No detached elements, fragments, or other debris were present to penetrate nor to show potential for penetrating the occupant compartment, nor to present undue hazard to others in the area. No occupant compartment damage occurred.	Pass
G. It is preferable, although not essential, that the vehicle remain upright during and after collision.	The vehicle remained upright during and after the collision period.	Pass
Vehicle Trajectory		
K. After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	The vehicle came to rest 69.3m down from impact and 4.6m behind the bridge rail.	Pass
M. The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle of contact with test device.	Exit angle at loss of contact was 0.4 degrees which was 3 percent of the impact angle.	Pass



General Information
Test Agency------------------ Texas Transportation Institute
Test No. --------------------- 400001-KBR1
Date ------------------------- 02/04/00

Test Article
Type ------------------------- Bridge Rail
Name ------------------------- Korean Tubular Thrie Beam Bridge Rail
Installation Length (m)----- 22.5
Material or Key Elements -- Tubular Thrie Beam mounted on steel posts w/250 mm concrete inside posts
Soil Type and Condition -- Concrete Deck, Dry

Test Vehicle
Type ------------------------- Production
Designation ------------------ N/A
Model ------------------------ 1983 GMC 7000
Mass (kg)
Curb ------------------------- 5 928
Test Inertial ---------------- 14 000
Dummy ------------------------ No Dummy
Gross Static ----------------- 14 000

Impact Conditions
Speed (km/h) --------------- 77.7
Angle (deg) ----------------- 14.3
Exit Conditions
Speed (km/h) --------------- 63.2
Angle (deg) ----------------- 0.4
Occupant Risk Values
Impact Velocity (m/s)
x-direction --------------- 3.1
y-direction --------------- 2.7
THIV (km/h) ---------------- 17.4
Ridedown Accelerations(g's)
x-direction --------------- -4.9
y-direction --------------- 6.3
PHD (g=s) ------------------ 13.9
ASI ------------------------ 0.43
Max. 0.050-s Average (g's)
x-direction --------------- -4.2
y-direction --------------- 3.6
z-direction --------------- 1.6

Test Article Deflections (m)
Dynamic -------------------- 0.246
Permanent to post --------- 0.020
Permanent to W-beam ------ 0.040
Vehicle Damage
Exterior
VDS ----------------------- N/A
CDC ----------------------- N/A
Maximum Exterior
Vehicle Crush (mm)----- nil
Interior
OCDI----------------------- N/A
Max. Occ. Compart
Deformation (mm) --------- nil
Post-Impact Behavior
(during 1.0 s after impact)
Max. Yaw Angle (deg)------ -14
Max. Pitch Angle (deg)----- 7
Max. Roll Angle (deg)------ -10

Fig. 12 Summary of Test Results

the system according to the classification of the design guide, simulations by Barrer Ⅶ program were performed for the impact conditions of S1, S2, and S3. From the viewpoint of structural adequacy which can be evaluated by the maximum deflection, the system satisfies the impact condition of S1 and S2 but does not satisfy the condition of S3. For the impact condition of S3, the maximum deflection is 40cm which is 10cm larger than the limit value of the design guide. The system satisfied the occupant safety and exit angle criteria for the S1, S2 and S3 impact conditions. Therefore, it can be recommended the system be classified as the S2 grade of the design guide.

6. CONCLUSIONS

TTB rail was developed to restrain and redirect a 14ton van-type truck. The developed bridge rail permits better visibility than concrete safety-shape bridge rail, and it has better structural adequacy than the existing steel and aluminum bridge rails in Korea. The new bridge rail consists of a TTB shape rail and a steel guard rail, which are connected to composite posts. The TTB shape provides both better containment of diverse bumper heights and more tight fit between the ends of bridge rail and roadside guardrails than the existing section shapes used as bridge rails in Korea.

Even though the same steel pipes as used for roadside guardrails are used, composite posts are much more efficient in increasing the stiffness and ultimate strength than the larger size of steel post, which are made by filling concrete mortar inside the steel pipe and rib-stiffening it.

The system was crash-tested for the impact condition of 14ton-80km/h-15deg, and it satisfied all evaluation criteria set forth in NCHRP 350 for a Test Level 4 safety appurtenance.

To evaluate the system grade according to the classification of Korea design guide, simulations were performed for the impact conditions of S1, S2, and S3. The simulation results showed that the system could meet the evaluation criteria for the impact condition of S2.

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