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Demand Model for Concrete Barriers Subject to Tractor Tanker-Trailer Impact

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Abstract: Test-level-6 (TL-6) barriers are specified for situations that involve a high percentage of truck traffic or unfavorable site conditions, where truck rollover or penetration beyond the railing could result in severe traffic consequences. Previous studies of TL-6 barriers impacted by tractor tanker-trailers (the truck category that creates the highest impact demands) assumed that the barriers behave rigidly. The rigid barrier assumption is investigated in this paper through simulation studies in which validated nonlinear models of the truck and barrier are employed. Parametric simulations are carried out to evaluate the effects of truck velocities, weights, and barrier heights on the impact force demands. The demand model in the current design guideline is critiqued based on the simulation results, and a discrepancy was found between the predicted barrier performance by AASHTO-LRFD loading and the truck impact. A revised demand model is proposed based on the simulation results.

Author keywords: Heavy truck impact; Concrete barriers; Impact design load

Introduction

In the current AASHTO-LRFD's Section 13,[1] TL-6 barriers are specified for situations that involve a high percentage of truck traffic or unfavorable site conditions, where truck rollover or penetration beyond the railing could result in severe traffic consequences. Many state DOTs, such as New York, New Jersey, and Pennsylvania, are currently considering the implementation of TL-6 barriers.[2] According to the,[3] the general impact conditions, truck speed, and weight associated with MASH TL-6 heavy trucks are based on a 360-kN tank-type tractor-trailer traveling at 80 kph. The current AASHTO-LRFD Section 13 specifies a lateral static design force of 778 kN to represent a TL-6 truck impact. This provision stems from limited crash tests and engineering experience.

More recently, numerical simulations using validated finite element (FE) models of heavy trucks were used to assess the impact force demands. Bligh et al.[4] conducted a simulation study on the impact load demands for TL-5 barriers with different heights using the 360-kN MASH van-type tractor-trailer model. Based on their parametric studies, a dynamic demand model for TL-5 barriers was proposed as a function of truck speeds and weights. Compared with the TL-5 barrier, studies on the TL-6 demand model have been rather limited, primarily due to the lack of a well-calibrated tank-type tractor-trailer model.

Whitfield et al. [5] used computational modeling to propose a new MASH TL-6 barrier. In their study, a preliminary TL-6 tank-type tractor-trailer model was developed by modifying an existing TL-5 van-type tractor-trailer. The developed TL-6 truck model was validated against an instrumented wall test by Beason et al.[6]. They noted that the general impact behavior of the modified TL-6 truck model was found to be similar to the test results. However, the forces imparted to the simulated wall, which was assumed to be rigid, as done by Bligh et al.,[4] were much lower than those from the tests. In subsequent phases of their study, the truck model was further refined by Rasmussen et al.,[7] incorporating more detailed chassis components and ballast modeling. Although better simulation results were achieved than that in phase 1,[5] the simulation results still underestimated the peak impact force from the testing by 26%.[7]

A key limitation of previous simulation studies is that the barriers were assumed to behave in a rigid manner. Since the influences of this key assumption are not known, realistic inelastic modeling of the barrier is needed to simulate the impact demand and failure pattern of the barrier more accurately. The simulated barrier behaviors from nonlinear modeling can be used to further validate the static design load specified in the current design guidelines. Moreover, the speed and weight of the MASH TL-6 truck were assumed to be constant, i.e., 80 kph and 360 kN. Further research is needed to develop a more comprehensive understanding of the demand model for the TL-6 barrier by varying the velocity and weight of the tractor-trailer. This study addresses these key limitations in the existing literature, which is quite limited to date. Concrete barriers are more commonly used

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for TL-6 test levels than steel railings. Hence, this study was mainly focused on the impact behaviors of TL-6 concrete barriers. Simulation results from this study could also serve as an important reference for developing new and refining existing design guidelines for barriers and bridge deck overhangs, such as Section 13 of AASHTO-LRFD.[1]

Finite Element Model of The Truck

Currently, there is no well-calibrated TL-6 tank-type tractor-trailer available. Hence, a representative MASH TL-6 tractor-tanker trailer model was developed by modifying a validated TL-5 van-type tractor-trailer. Details about the TL-5 truck can be found in Miele et al.[8]. Similar to the MwRSF study,[5] the van body on the TL-5 vehicle was replaced with an elliptical cylinder (tank) while keeping the original tractor and the rear tandem axle. Fig. 1 shows the developed TL-6 truck model in LS-DYNA,[9] where the tank model was constrained to the railings on top of the trailer bed. The geometry of the truck model was determined based on key requirements by MASH,[3] such as the overall length and location of the center of gravity of the truck.

Whitfield et al.[5] conducted a field survey on the geometry of the TL-6 trucks and provided the dimensions of typical tank-trailers. Based on their report, the tank modeled in this work has an elliptical shape with a dimension of 12.4 m (length) × 2.3 m (width) × 1.6 m (height). Shell elements were used to model the tank, and the shell's thickness was assumed to be 2.3 mm. The nonlinearity of the steel tank was modeled using *MAT_PLASTIC_KINEMATIC in LS-DYNA.[9] The strength of the steel was assumed to be 414 Mpa with a tangent modulus of 600 Mpa. The element size for the tank part is 100 mm in the simulation. The ballast in the tanker was modeled using soft materials to represent a flexible cargo with a Young's modulus of 1.5 Mpa. However, liquid sloshing in the tank was not considered. The center of mass for the ballast is 2,050 mm above the ground, and the

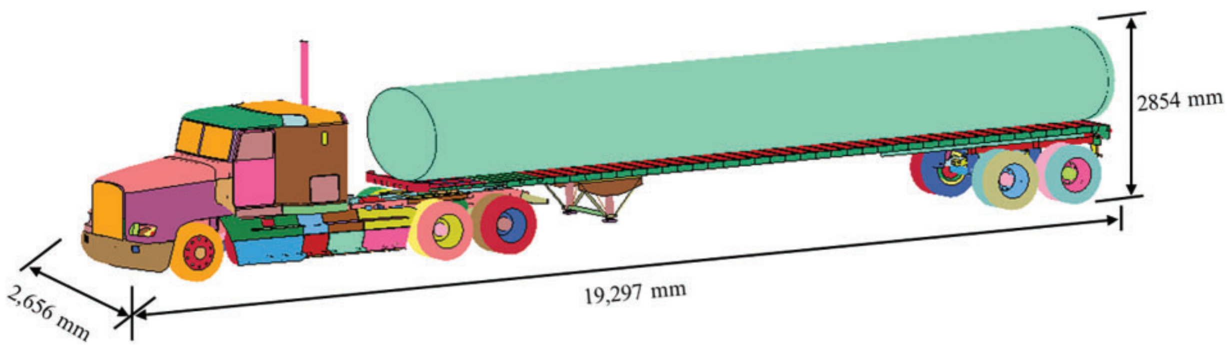

Figure 1. Developed FE model of the TL-6 truck

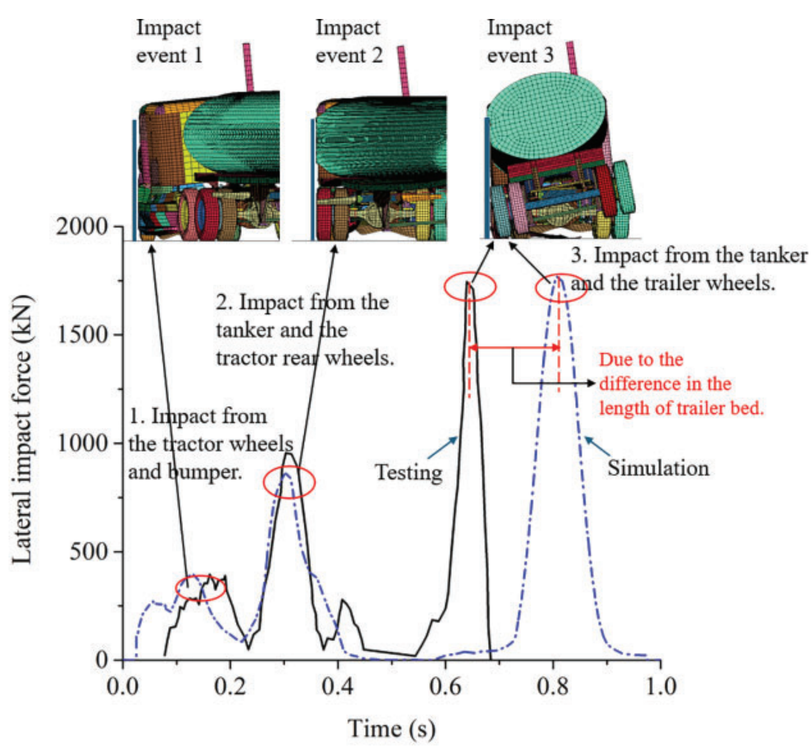

Figure 2. Impact force comparison of testing results and simulation

overall length of the truck model is 19,297 mm, which both matched the requirements of MASH.[3] The total number of elements in the truck model is roughly 272,800.

To validate the developed TL-6 truck model, the 1989 TTI instrumented wall test[6] was simulated to compare the impact behaviors of the truck along with its impact force time histories with those from the test. According to the testing report,[6] the truck weight was 360 kN, the impact speed was 88 kph, and the impact angle was 16 degrees. Based on the testing report, the damage to the barrier was mostly cosmetic, and the detailed rebar drawing of the testing wall was not available. Therefore, the barrier wall was modeled as elastic with its height and length maintained the same as that in the testing.

Considering that the test is very old, the comparison was deemed preliminary. The focus of this validation was to ensure that the crash behavior of the tractor-trailer during the test and simulation were reasonably similar.

Based on the simulation in LS-DYNA,[9] Fig. 2 shows the comparison between the impact force time history from the

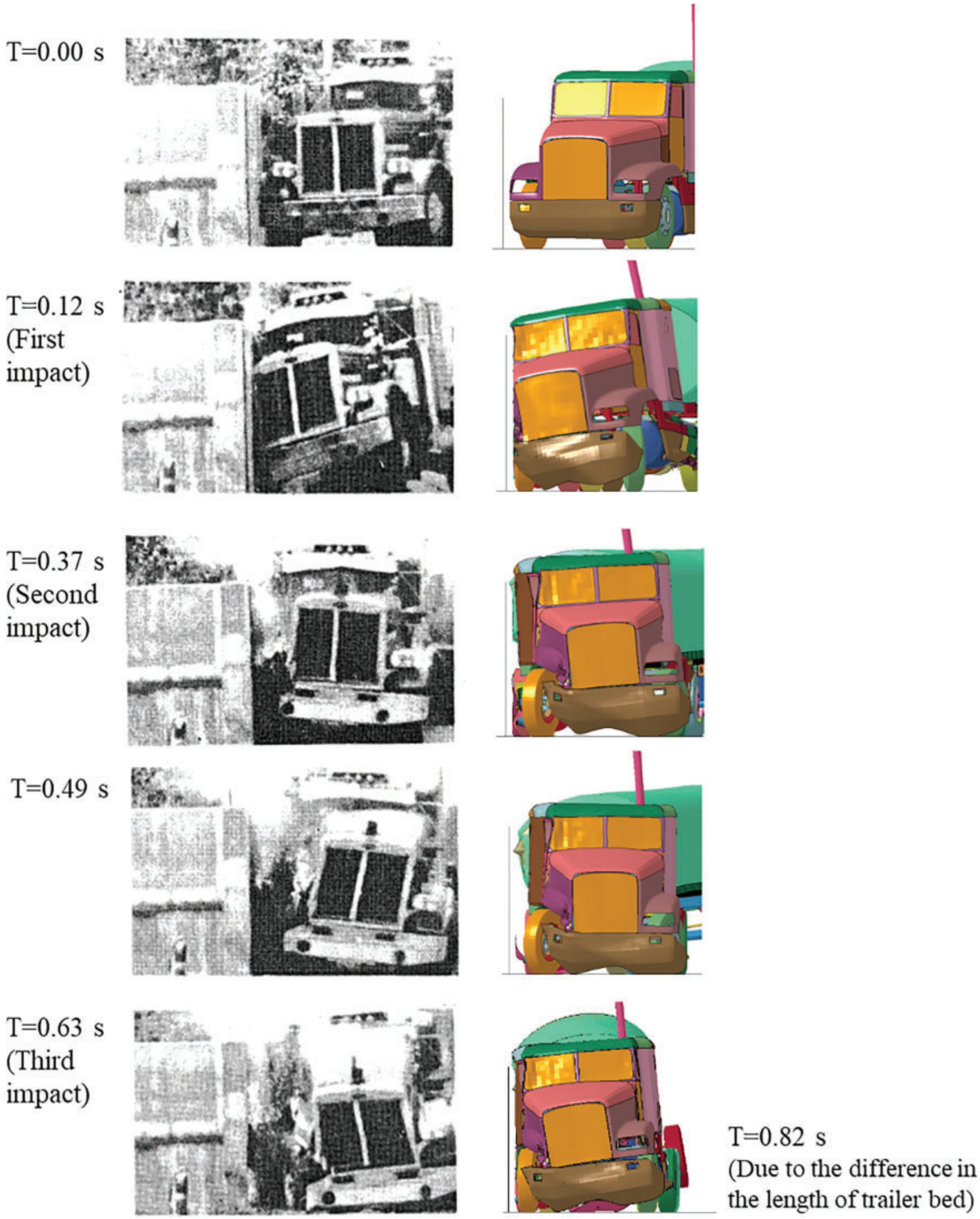

Figure 3. Comparison of truck behaviors between the crash testing and simulations (front view). (T is the time during the impact process.)

simulation and the test. The impact force was obtained by defining the contact between the barrier and the truck from LS-DYNA. It can be observed from Fig. 2 that the simulated force time history matches the one from the impact test reasonably well. In Fig. 2, the crash process for the TL-6 truck consisted of three impact events. The first one was related to the impact from the tractor wheels and bumper; the second one was from the tanker and the tractor rear wheels; the third impact was related to the tanker and the trailer wheels (i.e., the back-slap), which is the most severe one. From Fig. 2, the simulated peak forces for each of the three impact events matched the testing results well.

Detailed comparison of the truck behaviors during the testing and simulations can be seen from Figs. 3 and 4. In the series of photos, the truck was well-directed, and the simulated truck behavior matched the testing results reasonably well. In particular, the inclined angles of the actual tractor and trailer were found to be similar to those from the simulations. It should be noted that a short time lag of 0.19 sec was observed during the third impact, which was due to the difference in the length of the trailer's bed. Given the results shown in Figs. 2–4, the TL-6 truck model was able to represent the MASH TL-6 truck and can be used to investigate the demand models further.

Truck Impact Simulation with MASH TL-6 Concrete Barriers

Fig. 5a shows the TL-6 concrete barrier model based on an actual design drawing from the Texas Department of

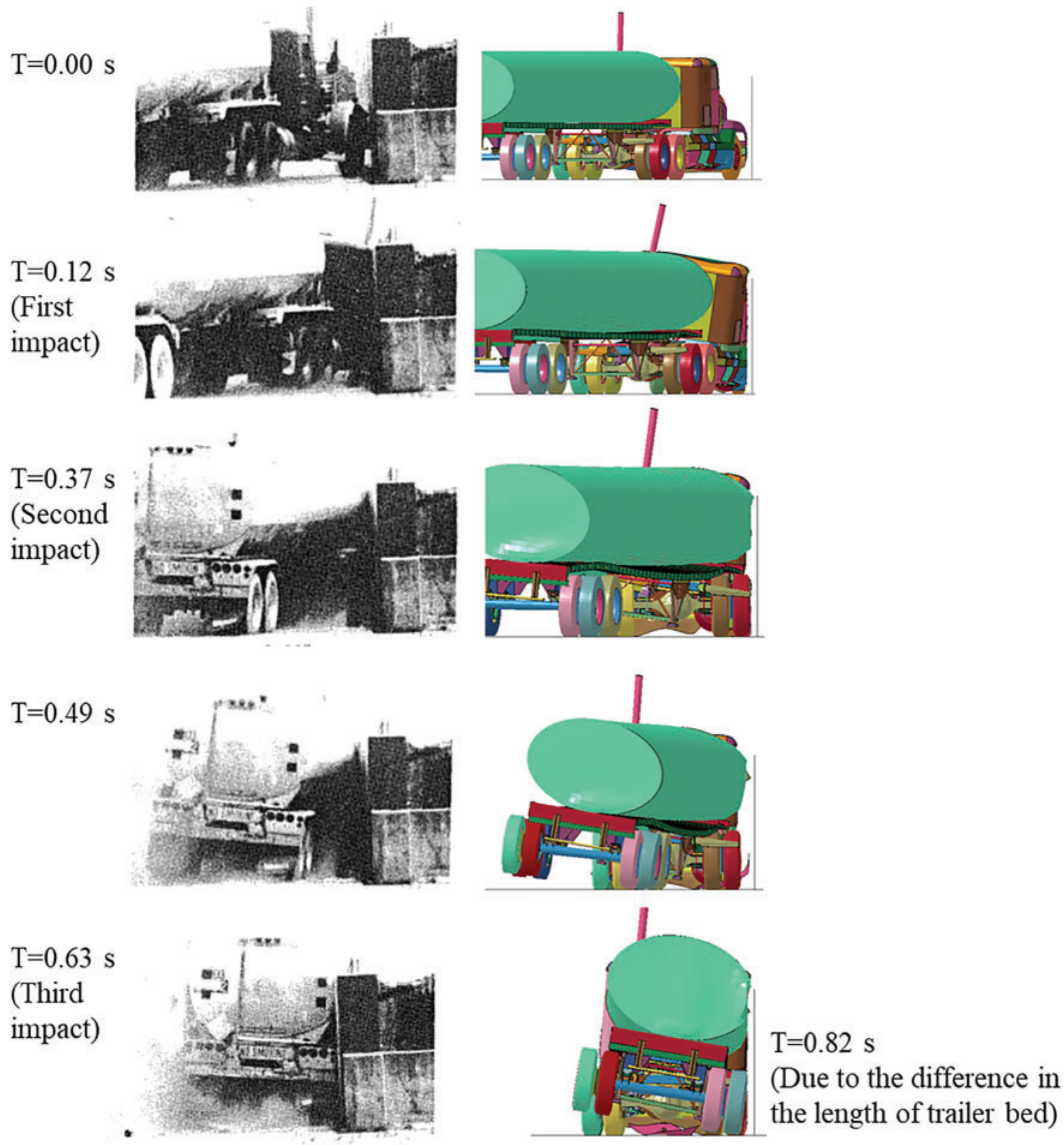

Figure 4. Comparison of truck behaviors between the crash testing and simulations (rear view). (T is the time during the impact process.)

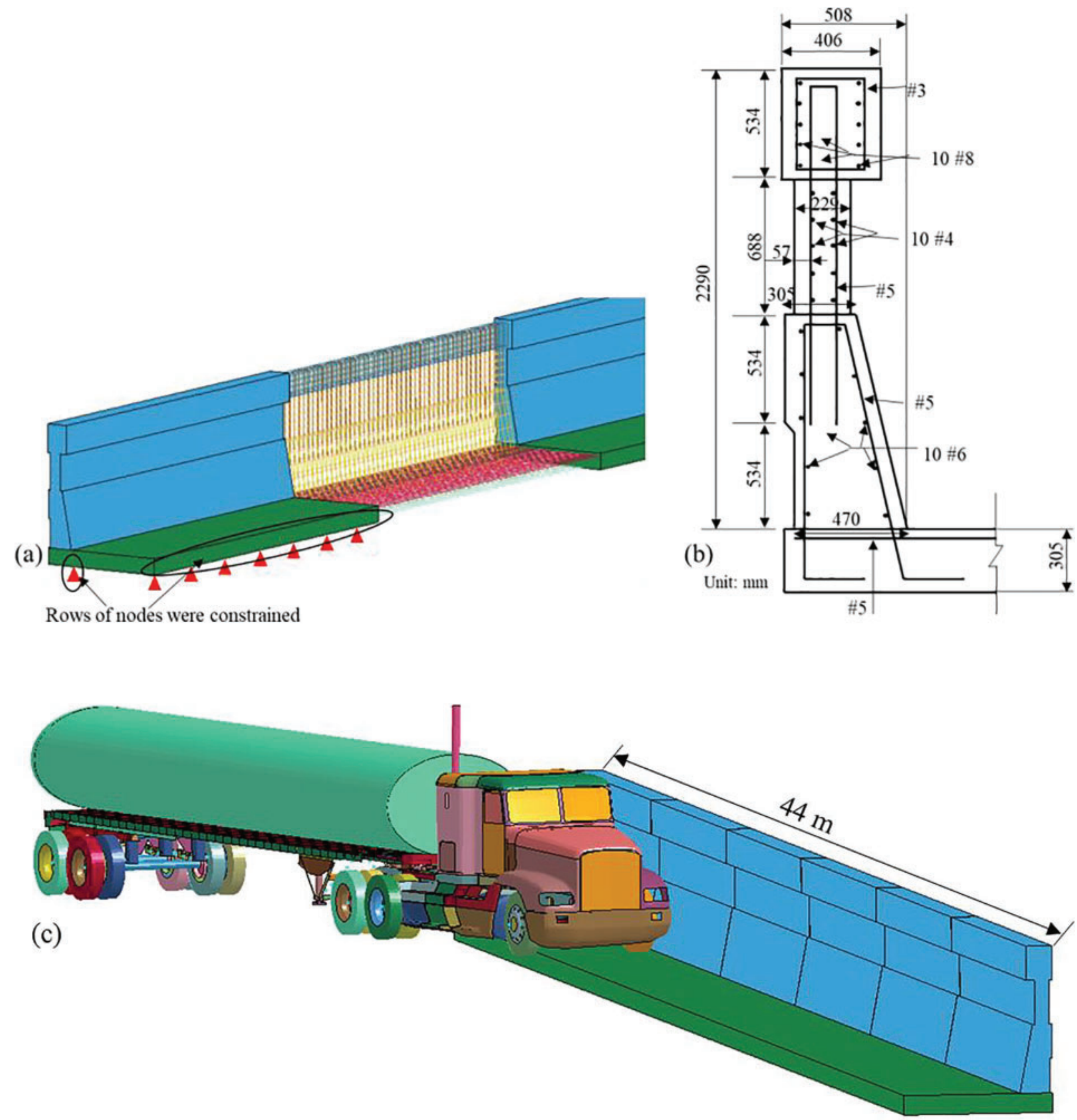

Figure 5. MASH TL-6 concrete barrier: (a) FE model of the barrier; (b) standard drawing; and (c) simulation setup

Transportation (Fig. 5b). Based on a survey by Agrawal et al.,[2] the current TL-6 barrier design is quite standard, and most TL-6 barriers used in the U.S. follow the drawings used in this work. The barrier is 2,290 mm tall, and the thickness of the slab is 305 mm. The behavior of the concrete material under impact loads was represented by the Continuous Surface Cap Model (MAT 159) in LS-DYNA.[9] As shown in Fig. 5a, the steel rebars were explicitly modeled using Hughes-Liu beam elements. The yielding and hardening behavior of the steel bars were modeled using material model MAT 3 in LS-DYNA.[9] The compressive strength of the concrete was assumed to be 25 Mpa and the strength of steel rebars in the parapet and deck was 414 Mpa and 276 Mpa. More details about the reinforced concrete modeling and its validations can be found in Agrawal et al.[10] and Cao et al.[11].

To simulate the overhang of the bridge, the nodes of the deck at the girder stems were modeled as fixed. Fig. 5c shows the simulation setup of the MASH truck impact in LS-DYNA, where the total length of the barrier is 44 m and the impact angle is 15 degrees.

As per MASH,[3] the weight of the TL-6 truck is 360 kN, and the impact velocity is 80 kph. The simulated impact responses of the barrier are shown in Fig. 6, including the time history curves of the impact force and barrier displacement. As shown in Fig. 6a, the peak impact force caused by the back-slap was around 930 kN with an impulse duration of less than 0.2 sec. The observed peak impact force is 20% higher than the prescribed design force for the TL-6 barrier in the current AASHTO-LRFD[1]—although comparing the forces is inappropriate because the former is the peak value

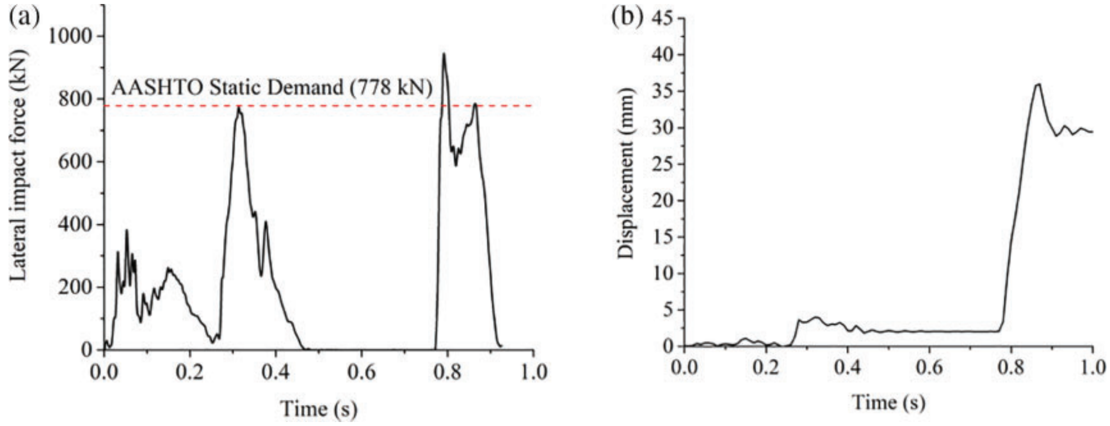

Figure 6. Time history response of TL-6 concrete barrier under MASH truck impact: (a) impact force; (b) lateral displacement of the barrier

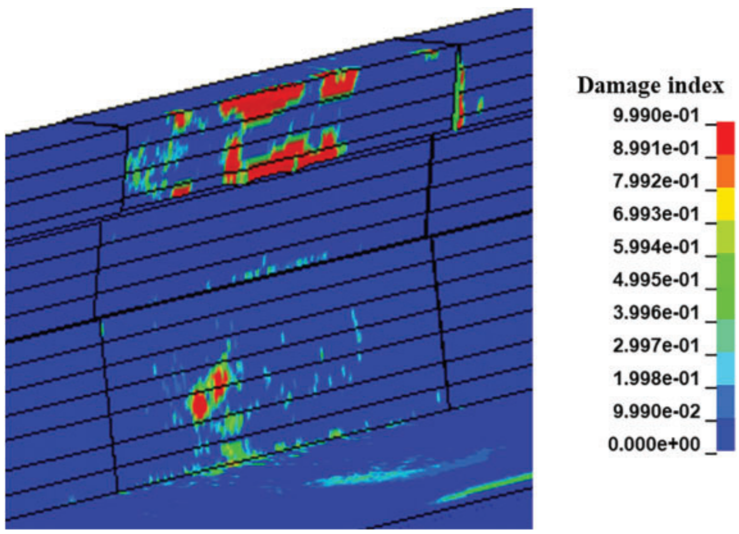

Figure 7. Damage to the barrier caused by MASH TL-6 truck impact

of a time history response, whereas the latter is an equivalent static design load. The peak displacement of the barrier was around 35 mm, as shown in Fig. 6b. The displacement was measured from the top of the barrier and above the impact region from the truck. The damage pattern of the barrier after the back-slap impact is shown in Fig. 7, where minor concrete cracking occurred in the front face of the barrier. The damage index shown in Fig. 7 was defined by Hallquist,[9] where 0.0 means no damage and 1.0 means total damage. Based on the simulation, the truck was successfully redirected and no rollover occurred.

Fig. 8 provides detailed information about the impact locations along the barrier height. The first impact occurred at 508 mm above the ground. The second and third impact events occurred at two different heights, one located at 380 mm above the ground by the wheels' impact and another from 1,780 to 2,286 mm above the ground by the tanker impact. It should be noted that the effective height to apply the TL-6 design load is assumed to be 1,422 mm in the current AASHTO-LRFD.[1] Based on the simulation, the prescribed loading height in AASHTO is between the hit points by the tanker (highest) and the wheels (lowest). It should also be noted that the loading length of the back-slap force was essentially the length of the two wheels and the trailer bed overhang, which was consistent with the prescribed loading length in AASHTO-LRFD.[1]

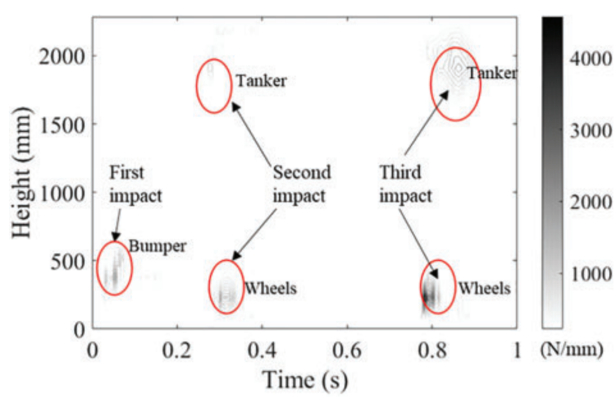

Figure 8. Distribution of impact force on the barrier under MASH TL-6 condition

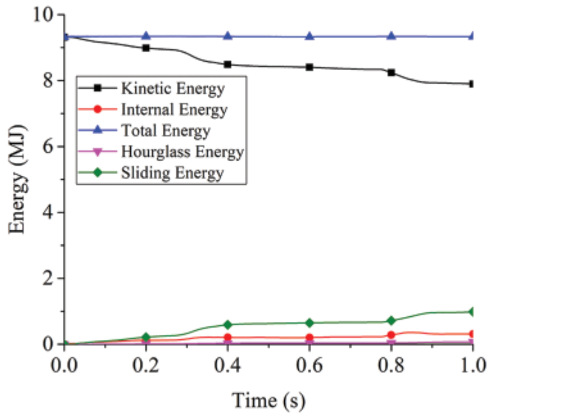

Figure 9. Energy conservation plots from the MASH TL-6 simulation

To further illustrate the validity of the simulation, Fig. 9 shows the energy conservation of the simulation, where the total energy was almost constant and the hourglass energy was effectively controlled. Since the barrier redirected the truck successfully and only showed minor damages, the kinetic energy from the truck did not decrease much and the internal energy of the system was relatively low (only 3% of the total energy).

Parametric Study

MASH [3] guidelines specify a given truck speed and weight for designing TL-6 barriers (i.e., 80-kph speed and 360-kN truck weight). To better understand the barrier's general response to impact and broaden the research space, parametric studies were conducted by varying the truck speed from 64 to 112 kph in increments of 16 kph and changing the truck weight from 180 to 360 kN in increments of 90 kN.

Fig. 10a shows the impact force time history for a 360 kN truck at different impact speeds. As shown in Fig. 10a, the peak impact force increased from 400 to 1,690 kN as the velocity increased from 64 to 112 kph. Fig. 10b shows the impact force time history for an 80-kph truck with different truck weights. In Fig. 10b, the back-slap force increased from 490 to 930 kN as the truck weight increased from 180 to 360 kN. It should be noted that the peak impact demand for the 180 and 270 kN trucks was not from the back-slap impact but from the second impact event by the rear tractor wheels and front of the tanker. The peak impact forces for the 180 and 270 kN trucks at 80 kph were around 890 kN.

The time histories of the lateral deformations of the barrier are shown in Fig. 11. In Fig. 11a, the 112-kph truck caused the highest deformations of 214 mm with only mild damage and a small portion of rebars yielded, while the 64-kph truck caused the least deformation of the barrier,

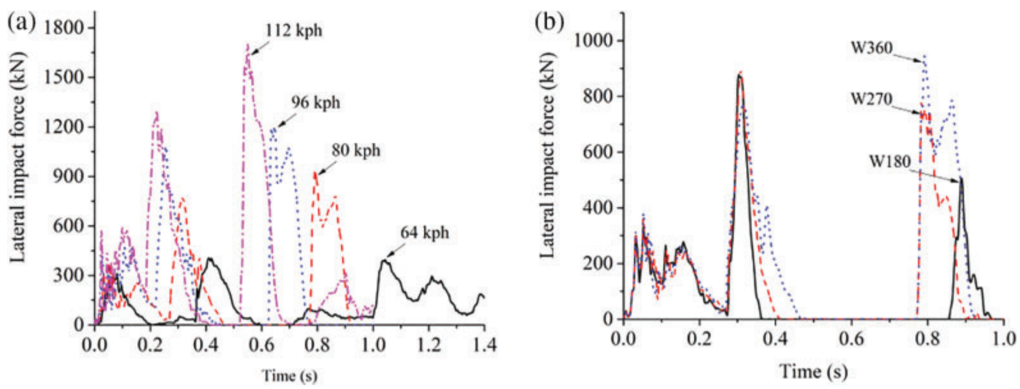

Figure 10. Impact force time histories: (a) truck weight of 360 kN; (b) speed of 80 kph

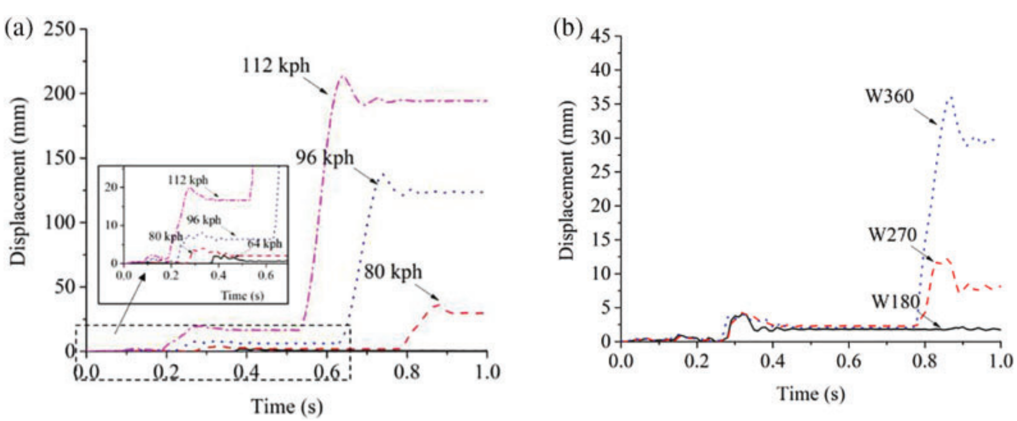

Figure 11. Lateral deformation time histories for truck-tank-trailer colliding with TL-6 concrete barriers: (a) truck weight of 360 kN; (b) truck speed of 80 kph

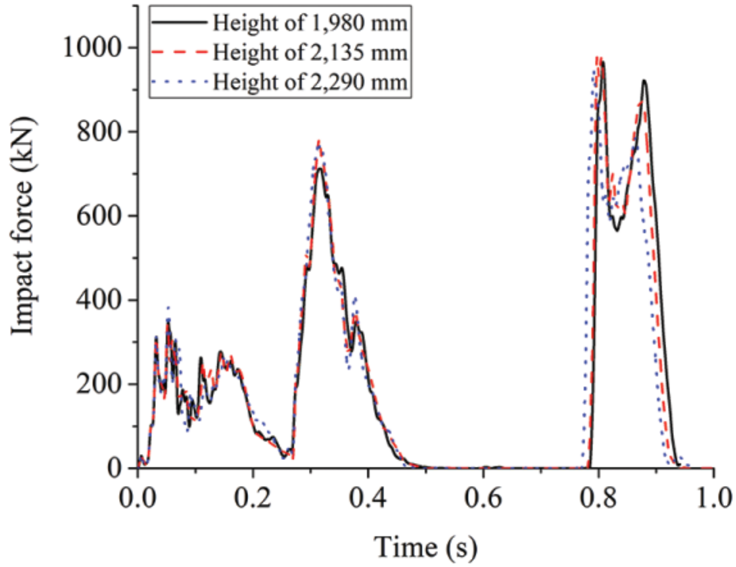

Figure 12. Impact force time-histories of barriers with different heights subjected to MASH conditions

at only 2 mm. It should be noted that the truck was well-redirected in all cases.

In the current AASHTO-LRFD,[1] the minimum barrier height for the MASH TL-6 barrier is 2,290 mm, which is over two times higher than that for TL-5 barriers. To study the influence of barrier height under the MASH condition, i.e., 80-kph speed and 360-kN truck weight, the original barrier height was adjusted in this study to 2,135 and 1,980 mm. In Fig. 12, the simulated impact forces were almost identical for the three different barrier heights. The trucks were also observed to be well-directed based on the simulations and no rollover or penetration occurred. Hence, TL-6 barriers with heights lower than 2,000 mm could be considered for future crash tests and installations.

Critique of AASHTO-LRFD Loading for TL-6 Barrier

As shown in Fig. 6, the dynamic peak impact force by the MASH truck was 20% higher than the 780 kN static design load prescribed by AASHTO-LRFD.[1] It should be noted that a direct comparison between the peak dynamic load and static load is not rigorous. In terms of loading effects, the equivalence of dynamic loads and static design load was validated using nonlinear simulations. To evaluate the accuracy of the AASHTO guidelines, a static load of 780 kN was applied to the barrier as a distributed line loading at a height of 1,422 mm per AASHTO-LRFD. The distribution length was 2,438 mm, as prescribed in the design guidelines.

Fig. 13 shows the simulated barrier deformations subject to truck impact and static loading, in which the AASHTO load predicted a significantly higher deformation than that caused by the MASH truck impact (nearly 6 times higher). Based on the simulation, a reduced static demand at 585 kN is proposed. As shown in Fig. 13 and Table 1, this load is selected to cause a similar deformation as that from truck simulations, which could be considered a more reasonable demand for TL-6 barrier design.

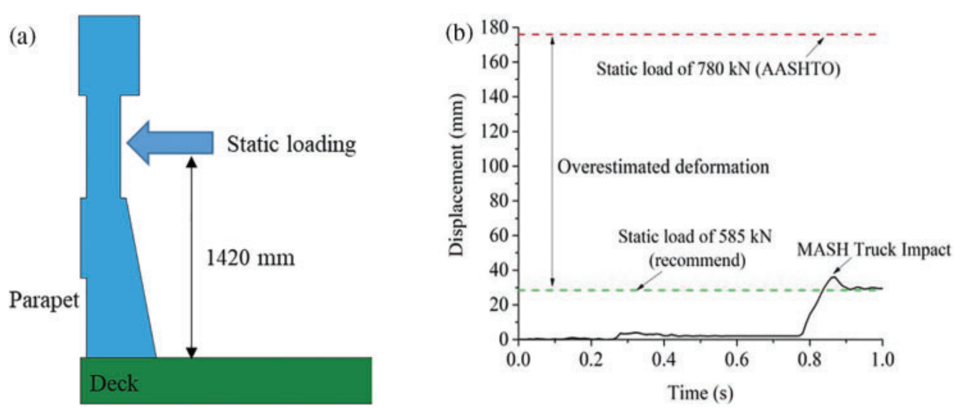

Figure 13. Comparison of the barrier deformation by truck impact and static loading: (a) application of the static loading per AASHTO-LRFD; (b) lateral displacement of the barrier

Table 1. Comparison of loading effects from truck impact and static loading

	Loading (kN)	Lateral deformation (mm)
MASH truck impact	930 (impulse, duration < 0.2 sec)	30
AASHTO	780 (static)	176
Proposed demand	585 (static)	30

Conclusions

A representative MASH TL-6 tractor-tanker trailer was developed and validated against an instrumented wall test. Using the validated TL-6 truck model, the characteristics of the truck impact loading on TL-6 barriers were investigated. Unlike previous studies that modeled the barrier as rigid, the nonlinear responses of the impacting truck and concrete barriers were both considered in the finite element simulations. It was found that the current MASH TL-6 barrier design could successfully redirect a 360-kN truck traveling at 112 kph with only mild damage to the barrier. This observation, coupled with the fact that the impact speed is 40% faster than the speed prescribed in the design guidelines, suggests that the barrier design in current use is overly conservative.

The effects of the barrier height on the MASH TL-6 truck demand were also discussed. The simulation showed that a 15% reduction in the barrier height would cause negligible effects on the impact force and truck behavior. Therefore, the applicability of TL-6 barriers with a lower height could be further investigated through field crash tests.

The design load for the TL-6 barrier prescribed in the current AASHTO-LRFD was further critiqued by comparing the barrier deformations caused by truck impact and the applied static design load. It was confirmed that the current design load could provide significantly higher deformation than that from the truck impact, which may lead to an uneconomical design of the barrier and the supporting bridge deck overhang. Based on the simulation results, a reduced static demand at 585 kN was proposed for a future TL-6 barrier design that delivers a similar loading effect as the truck impact. Further studies can be carried out to incorporate the demand model and calculations of barrier capacities in a performance-based design framework.

Acknowledegments

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Data Availability Statement

All data shown in the paper are available from the corresponding author by request.

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Appendix

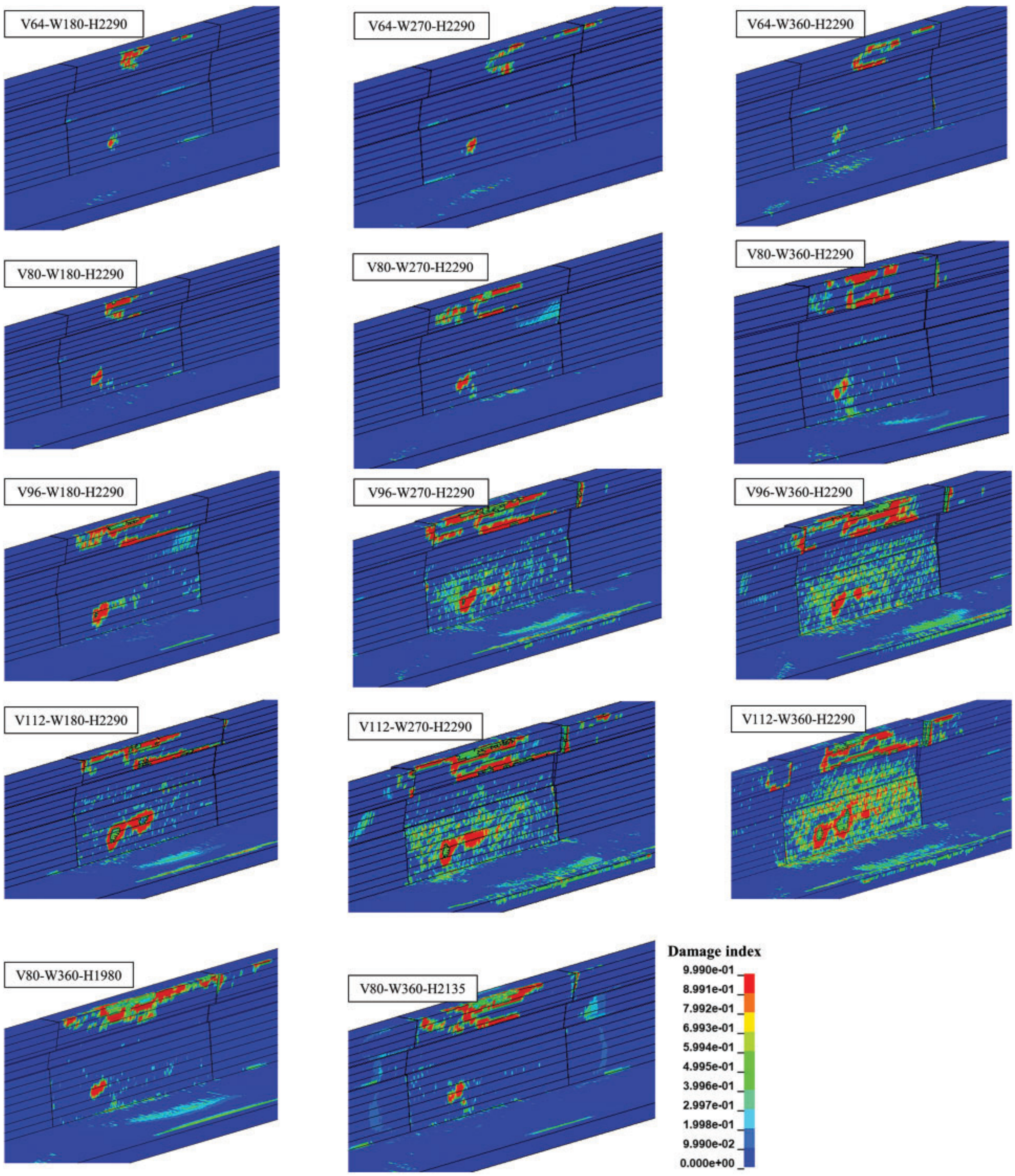

Figure A1. Damage mode of the concrete barrier from the parametric simulations. (V is the speed in kph, W is the weight in kN, and H is the barrier height in mm.)