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Comparative Studies of Finite Element Model of Frontal Impact Dummy

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Abstract: In order to make valid tests of protective systems, the human body is needed to test the system concepts and evaluate the protective efforts in crash testing. Practical and ethical concerns also restrict the use of actual occupants for risk assessment. The anthropomorphic test dummies have been demonstrated to be highly repeatable, reproducible, durable and serviceable test devices. These test dummies thus have been widely used in numerous applications related to human dynamic simulations. In order to understand the dummy model components and offer validated finite element models for these crash simulations, this study investigates four types of finite element models of the frontal impact dummy. All dummies are calibrated based on FMVSS 49 part 572 regulations test procedures. For comparing the difference between these dummy models, sled test simulations are performed using the LS-DYNA finite element code. The dynamic responses of dummy models are measured and compared. The finite element dummy models obtained here have potential for evaluating vehicle crash safety and guiding the future development of safety technologies.

Key words: Frontal impact dummy, finite element model, LS-DYNA, dummy model calibration, sled test simulation

INTRODUCTION

The automobile has become a part of daily life. The number of cars is increasing, leading to more congested traffic and accidents. Since impact forces are transmitted directly to vehicle occupants during an accident, traffic accidents have become one of the leading causes of death in modern times. Car safety has become the most important issue in automobile development. Hence, car manufacturers now incorporate a wide range of safety devices and features into their vehicles, including airbags, energy-absorbing steering columns, side door beams, etc. In spite of the huge effort devoted to the development and improvement of protective systems, it is necessary to develop an efficient evaluation and analysis methodology with which to examine the safety aspects of a vehicle. Crash testing is a commonly employed technique for evaluating the occupant protection capability of a particular vehicle. Evaluating the effectiveness of these protective devices involves investigating the dynamic response of the human body in a traffic accident situation. In order to make valid tests of protective systems, the human body is needed to test the system concepts and evaluate the protective efforts in crash testing.

For measuring the response of vehicle occupants, human cadavers or volunteers were employed in the crash test. They were used to obtain fundamental information about the human bodys ability to withstand the crushing and tearing forces in an accident (Davis, 1998; Kallieris *et al.*, 1989; Anderson *et al.*, 1998; Braun *et al.*, 2001). Practical and ethical concerns also restrict the use of actual occupants for risk assessment. In the years between 1950 to 1970, automotive crash test dummies were developed based on aerospace models. The hybrid and ATD (Anthropomorphic Test Dummy) series of test dummies developed by General Motors are industry standards in car collision testing. These test dummies have been demonstrated to be highly repeatable, reproducible, durable and serviceable test devices. They are considered to have excellent bio-fidelity and instrumentation capability. Research and development tests using dummies now can simulate human responses in a car collision (Sances, 2000; Siegmunt *et al.*, 2005; DeRosia *et al.*, 2004; Stefan *et al.*, 2003). Test dummies thus have been widely used in numerous applications related to human dynamic simulations. Rapid advances in computer technology in recent years have enabled applied mathematicians, engineers and scientists to make significant progress in solving previously intractable problems. Numerical simulations of vehicle crashes provide valuable data for automotive engineers. Typical software packages capable of performing these types of analyses include MSC-DYTRAN, LS-DYNA/3D, Pam Crash, etc. In vehicle collision analysis, finite element

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modeling provides an essential tool for investigating the occupant's dynamic behavior and analyzing the sustained injuries. Various dummy models which accurately simulate human response in crash simulations have been developed for research and development purposes. For example, Pal and Hagiwara (1998) developed a finite element dummy model based on the initial NHTSA model. A number of modifications are performed based on the combined simulation and experimental verifications of the dynamic characteristics of different materials. Furthermore, Abe *et al.* (1999) investigated various vehicle-to-vehicle collision phenomena in three dimensions by applying a simple method which makes it possible to perform calculations on a personal computer, with a satisfactory result. Moreover, Londsdale and Patitet (2000) introduced parallel programming paradigms for nonlinear, explicit finite element simulations, mainly employed for crashworthiness and occupant safety simulation in the automotive industry. Watanabe *et al.* (2001) developed a practical and simplified human body FEM model. This model is specialized for automotive crash injury analysis used mainly to calculate injury data. Finally, Noureddine *et al.* (2002) developed a finite element model for computer crash simulation with the Hybrid III crash test dummy. The reasonable accuracy of the model makes it useful for crashworthiness simulation. Kirkpatrick (2000) performed a program to develop and validate a high fidelity finite element model of a full size car for crashworthiness analysis. The resulting set of vehicle models can then be used to study the overall crash safety effect of future lightweight vehicles or other changes in the current highway vehicle fleet composition. Kirkpatrick *et al.* (2003) presented the development and validation of an LS-DYNA finite element occupant model suitable for use in crash analyses of roadside safety features. Using the correct combination of deformable and rigid components, results in an occupant model that is computationally efficient and capable of simulating occupant kinematics in a collision.

Numerical crash simulations provide a valuable tool for investigating crash safety. The finite element dummy model in crash simulations can directly predict the injury outcome from the crash analysis. However, the model has a serious problem with the complex geometry and multiple material compositions of the dummy. As a consequence, the dummy model must be rigorously calibrated before it can be applied to a crash testing. In order to understand the dummy model components and offer validated finite element models for these crash simulations, this study investigates four types of finite element models of the frontal impact dummy. All dummies are calibrated based on FMVSS 49 part 572 regulations test procedures. For comparing the difference between these dummy models, sled test simulations are performed using the LS-DYNA finite element code. The dynamic responses of dummy models are measured and compared. The finite element dummy models obtained here have potential for evaluating vehicle crash safety and guiding the future development of safety technologies.

DUMMY CALIBRATION REGULATION

FMVSS 49 Part 572 describes the anthropomorphic test devices to be used for safety standard compliance testing of motor vehicles and motor vehicle equipment. The design and performance criteria specified in this regulation are intended to describe measuring tools with sufficient precision to give repetitive and correlative results under similar test conditions. The criteria must also adequately reflect the protective performance of a vehicle or item of motor vehicle equipment with respect to human occupants. Part 572 provides standard test procedures for performing receiving-inspection and performance calibration tests on the dummy so that repetitive and correlative test results can be obtained. The test items of dummy calibration regulation include head drop test, neck flexion and extension test, thorax impact test and femur impact test.

Head drop test: The head is suspended and the lowest point on the forehead is 12.7 mm below the lowest point on the dummy's nose when the midsagittal plane is vertical. Drop the head from a height of 376 mm by means that ensures instant release onto a rigidly supported flat horizontal steel plate, 50.8 mm thick and 610 mm square. The peak resultant accelerations at the location of the accelerometers mounted in the head shall not be less than 225 g and not more than 275 g. The acceleration/time curve for the test shall be unimodal to the extent that oscillations occurring after the main acceleration pulse are less than ten percent (zero to peak) of the main pulse. The lateral acceleration vector shall not exceed 15 g (zero to peak).

Neck flexion and extension test: The head-neck assembly is mounted on a rigid pendulum, so that the head's midsagittal plane is vertical and coincides with the plane of motion of the pendulum's longitudinal axis. Release the pendulum and allow it to fall freely from a height such that the tangential velocity at the pendulum accelerometer centerline at the instance of contact with the honeycomb is 23.0±0.4 and 19.9±0.4 ft $\sec^{-1}$ for flexion testing and extension testing, respectively. The characteristics of pendulum deceleration pulse for flexion testing shall confirm to 22.5~27.5 g between 0 and 10 msec, 17.6~22.6 g between 10 and 20 msec, 12.5~18.5 g between 20 and 30 msec and less than 29 g on other time above 30 msec. The characteristics of pendulum deceleration curve for extension testing shall confirm to 17.2~1.2 g between 0 and 10 msec, 14~19 g between 10 and 20 msec, 11~16 g between 20 and 30 msec and less than 22 g on other time above 30 msec. Plane D shall rotate between 64 and 78 degrees, which shall occur between 57 and 64 msec from time zero for flexion testing. Also, plane D shall rotate between 81 and 106 degrees, occurring between 72 and 82 msec from time zero for extension testing.

Thorax impact test: The dummy is seated on a surface without back and arm supports. A test probe with a mass of 23.4 kg and diameter equal to 150 mm impact the thoracic mid-region at a velocity of 6.59~6.83 m $\sec^{-1}$. Measurement of the horizontal deflection of the sternum relative to the thoracic spine along the line established by the longitudinal centerline of the probe at the moment of impact should equal between 64 and 73 mm.

Knee impact test: The test probe used for the knee impact tests is a 76 mm diameter cylinder that weights 5 kg. Impact the knee with the test probe at a velocity of 2.07~2.13 m $\sec^{-1}$. The peak knee impact force, which is a product of pendulum mass and acceleration, shall have a minimum value of not less than 4.7 kN and a maximum value of not more than 5.8 kN.

NUMERICAL DUMMY MODELS DESCRIPTION

In this study, four types of numerical models of the Hybrid III 50% dummy were considered and the physical characteristics of model building were compared. The LSTC Hybrid III 50% rigid dummy model was developed by LSTC (Livermore Software Technology Corporation). The model is composed of 113 parts, 6437 nodes and 3963 elements. Parts are connected together using joint definitions to constrain the relative motion of two parts. The majority of the parts (about 40%) constituting the dummy skeleton are defined as rigid materials. Other materials include low-density foam material, visco-elastic materials and null materials. The LSTC Hybrid III 50% deformable dummy model was also developed by LSTC. The model is composed of 109 parts, 5731 nodes and 5825 elements. Only 20% of the parts constituting the dummy skeleton are defined as rigid materials. Elastic materials, elastic-plastic materials, visco-elastic materials and null materials were used to simulate human skin. Low-density foam materials were used to simulate human soft tissue. The VPG Hybrid III 50% deformable dummy model was also developed by LSTC. This model can be used in the built-in feature of the VPG (Virtual Proving Ground) package. The model is composed of 101 parts, 8512 nodes and 5694 elements. Only 10% of the parts constituting the dummy skeleton are defined as rigid materials. Other materials include elastic materials, visco-elastic materials, null materials and low density foam materials. A FT-ARUP Hybrid III 50% deformable dummy model was developed by FTSS (First Technology Safety Systems) and ARUP (Ove Arup®Partners International Limited). The model is composed of 267 parts, 24230 nodes and 24243 elements. Thirty four percent of the parts constituting the dummy skeleton are defined as rigid materials. Other materials include elastic materials, elastic-plastic materials, visco-elastic materials, null materials and low-density foam materials. Table 1 provides a comparison of dummy models. The considerably small difference in the LSTC rigid dummy model, LSTC deformable dummy model and VPG deformable dummy model are described as Table 1. However, the FT-ARUP deformable dummy model is more complicated than other models. An obvious difference is the mesh of the numerical model. In addition, the joints and weight of the dummy model is significantly different.

Table 1: No. of part, material, element and node of dummy models

	Dummy model			
Properties	LSTC Hybrid III 50% rigid dummy model	LSTC Hybrid III 50% deformable dummy model	VPG Hybrid III 50% deformable dummy model	FT-ARUP Hybrid III 50% deformable dummy model
No. of part	113	109	101	267
No. of material	109	99	94	159
No. of element	3963	5825	5694	24243
No. of node	6437	5731	8512	24230

CALIBRATION OF NUMERICAL DUMMY MODELS

In order to ensure the dummy models are responding correctly, the numerical models need to perform calibration tests based on FMVSS 49 part 572 regulations test procedures. The calibration results of the numerical model were also compared with the physical dummy. The calibration tests of the physical model are performed at the Automotive Research and Testing Center (ARTC). The calibrations of four types of dummy model are described as follows.

Calibration of head model: Drop the head model from a height of 376 mm onto a platethat is simulated based on the regulation of the head drop test. Figure 1 shows the head acceleration at the center of gravity. For the LSTC rigid dummy model, the peak value of acceleration is 257 g at 2.7 msec. For the LSTC deformable dummy model, the peak value of acceleration is 255 g at 2.4 msec.

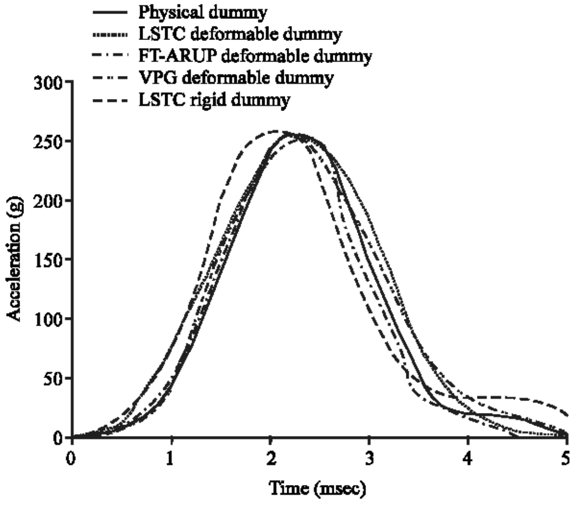

Fig. 1: Head acceleration at the center of gravity

For the VPG deformable dummy model, the peak value of acceleration is 253 g at 2.3 msec. For the FT-ARUP deformable dummy model, the peak value of acceleration is 252 g at 2.3 msec. According to the FMVSS 49 specification, the peak resultant head accelerations shall not be less than 225 g and not more than 275 g. The calibration results show that all of the head models fall within the limit range of specification. As Fig. 1 indicates, the head acceleration of the FT-ARUP dummy model achieved the best agreement with the physical dummy data.

Calibration of neck model: For simulation of the neck model calibration, the head-neck assembly is not mounted on a rigid pendulum as in the FMVSS 49 specification. A pendulum deceleration curve measuring the calibration of the physical model is performed on the head-neck assembly. Figure 2 shows the rotation angle of plane D for neck extension testing. For the LSTC deformable dummy model, the peak value of rotation angle is 86 degrees at 80 msec. For the VPG deformable dummy model, the peak value of rotation angle is 86 degrees at 78 msec. For the FT-ARUP deformable dummy model, the peak value of rotation angle is 92 degrees at 72 msec. According to the FMVSS 49 specification, plane D shall rotate between 81 and 106 degrees which shall occur between 72 and 82 msec from time zero for extension testing. The calibration results show that all of the deformable model neck parts fall within the limit range of specification. The head-neck assembly of the LSTC rigid dummy model is simulated by a rigid part, however and cannot perform neck calibration tests. As Fig. 2 indicates, the neck calibration of the FT-ARUP dummy model achieved the best agreement with the physical dummy data.

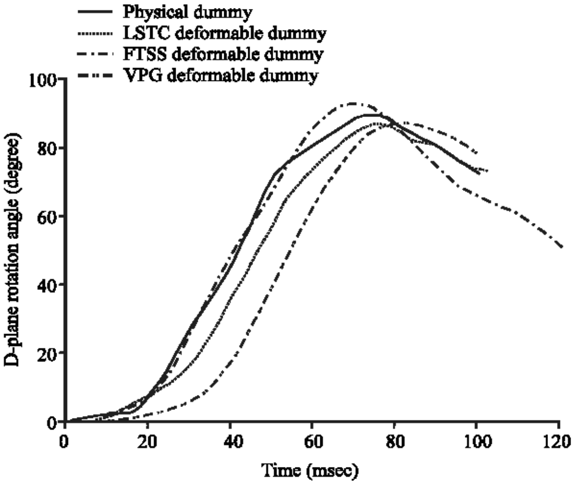

Fig. 2: Rotation angle of plane D for neck extension testing

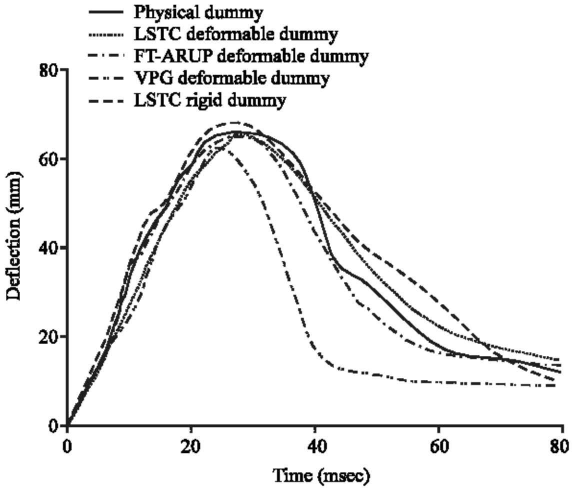

Fig. 3: Horizontal deflection of the sternum

Calibration of thorax model: A test probe impacts the thoracic mid-region of the dummy model at a velocity of 6.71 m sec^{-1} based on the regulation of the thorax impact test. Figure 3 shows the horizontal deflection of the sternum. For the LSTC rigid dummy model, the peak value of deflection is 70 mm at 30 msec. For the LSTC deformable dummy model, the peak value of acceleration is 65 mm at 31 msec. For the VPG deformable dummy model, the peak value of acceleration is 64 mm at 23 msec. For the FT-ARUP deformable dummy model, the peak value of acceleration is 66 mm at 25 msec. According to the FMVSS 49 specification, the peak horizontal deflection of the sternum should equal between 64 and 73 mm. The calibration results show that all of the thorax of models fall within the limit range of specification.

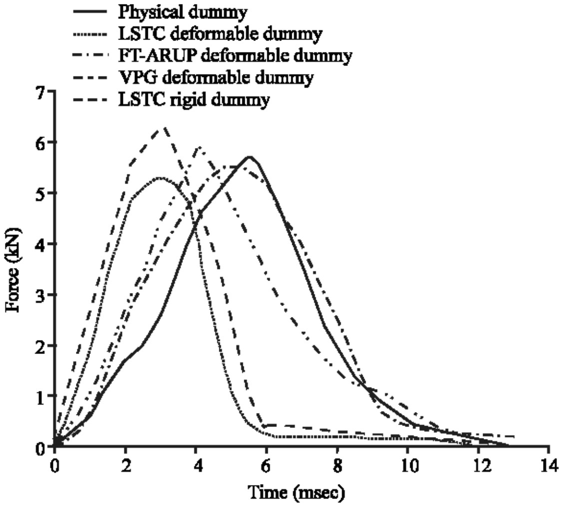

Fig. 4: Impact force of the knee

As Fig. 3 indicates, the thorax deflection of the FT-ARUP dummy model achieved the best agreement with the experimental data.

Calibration of knee model: A test probe impacts the knee of the dummy model at a velocity of 2.1 msec based on the regulation of the thorax impact test. Figure 4 shows the impact force of the knee. For the LSTC rigid dummy model, the peak knee impact force is 5.8 kN at 3 msec. For the LSTC deformable dummy model, the peak knee impact force is 5.2 kN at 2.8 msec. For the VPG deformable dummy model, the peak knee impact force is 5.6 kN at 4.5 msec. For the FT-ARUP deformable dummy model, the peak knee impact force is 5.3 kN at 5.7 msec. According to the FMVSS 49 specification, the peak knee impact force shall have a minimum value of not less than 4.7 kN and a maximum value of not more than 5.8 kN. The calibration results show that all of the knee of models fall within the limit range of specification. As Fig. 4 indicates, the knee impact force of the FT-ARUP dummy model also achieved the best agreement with the experimental data.

FRONTAL CRASH SIMULATION

In order to understand the application and comparison of dummy models on crash testing, sled test simulations are performed using the LS-DYNA finite element code. For the sled simulations, numerical dummies are placed in the front seats of the sled and secured with safety belt. Sled tests were conducted at a velocity of 48 km h^{-1} and performed with four types of dummies. The human model responses are analyzed by investigating the accelerations of the head, chest and pelvic regions.

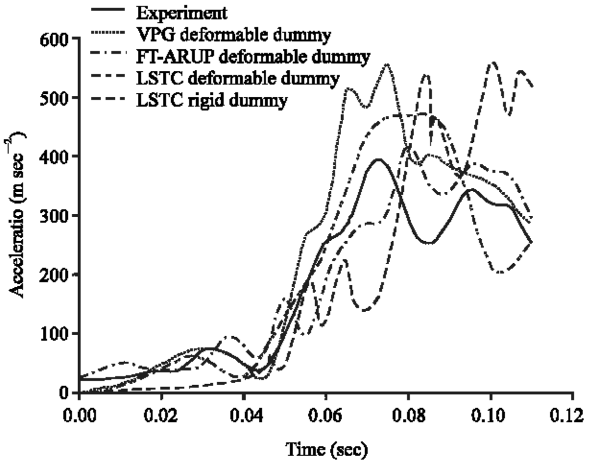

Fig. 5: Acceleration of head in frontal collision

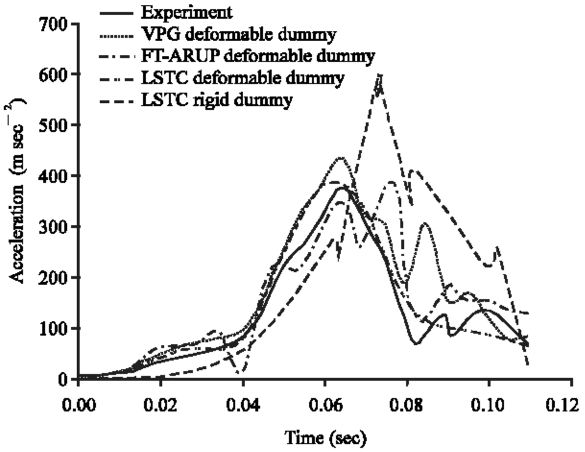

Fig. 6: Acceleration of chest in frontal collision

These data indicate the severity of injuries sustained by the vehicle occupant in a frontal impact. The analysis results were also compared with the experimental results provided by Prasad (1990).

Figure 5-7 show the acceleration of the head, chest and pelvis of dummy models in frontal collisions, respectively. Responses from four types of dummies indicate similarities and variations among simulation and experiment. In general, the accelerations of the FT-ARUP model are closer to the experiment results than other dummies in the head, chest and pelvis. It is clear that the dummy models constructed in the current study are capable of accurately calculating the acceleration of each part of the human body and analyzing the resulting injuries to the occupant. Therefore, the finite element dummy model can be used in numerical crash simulations for evaluating the crashworthiness of a vehicle. Although the crash simulation of the FT-ARUP model is closer to

Table 2: CPU times of sled test simulation

	LSTC Hybrid III 50% rigid dummy model	LSTC Hybrid III 50% deformable dummy model	VPG Hybrid III 50% deformable dummy model	FT-ARUP Hybrid III 50% deformable dummy model
CPU time	25 min	1 h 11 min	1 h 27 min	4 h 21 min

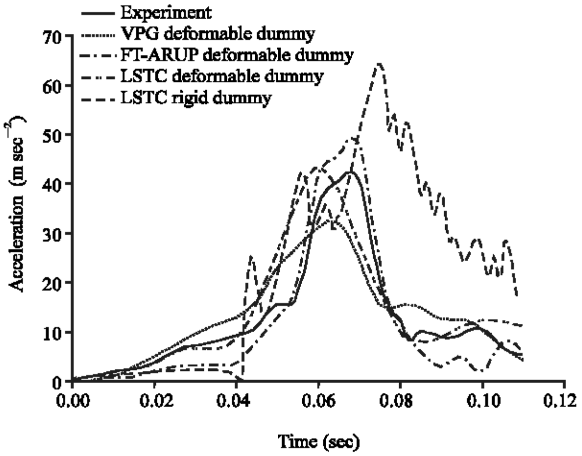

Fig. 7: Acceleration of pelvis in frontal collision

the experiment results than other dummy models, the CPU time is also an important evaluation index of the numerical analysis method. For a 150 msec simulation sled test with four types of dummy models, the CPU time on the parallel processor and the LS-DYNA 960 SMP version is shown in Table 2. As indicated in Table 2, the CPU time associated with the FT-ARUP model is much more than those of other dummy models. The CPU time of the VPG deformable dummy model is very low and also achieves more agreement with the experimental data than the LSTC deformable dummy model.

CONCLUSION

In this study, four types of finite element frontal impact dummy models were developed for crashworthiness analysis. Owing to the rigid head-neck assembly, the LSTC rigid dummy model is not suitable for simulating the occupant in the numerical crash analysis. The other three dummy models were validated by comparing the results of simulations to those of the experimental tests performed on the physical dummy. For the consideration of CPU time, the accuracy of the VPG deformable dummy model renders it a valuable tool for crashworthiness simulations. The proposed dummy models can be used to study the dynamic behavior of occupants and analyze injuries in frontal impact accidents. Moreover, this study proposes a sled test finite element model and its application, which allows the establishment and satisfaction of vehicle impact design requirements. Numerically measuring human responses in accident impact is useful. The simulated sled test models obtained herein give design guidelines for the vehicular structure and safety equipment needed to protect occupants.

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