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Design of pedestrian friendly vehicle bumper[†]

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Abstract

Car-pedestrian accidents take thousands of lives worldwide annually. Therefore, pedestrian protection is an important issue in traffic safety. How to consider a pedestrian friendliness vehicle and then propose pedestrian protection methods are urgent works for minimizing pedestrian injury. For designing a pedestrian friendly vehicle bumper, this study adopts the European Enhanced Vehicle-safety Committee/ Working Group 17 (EEVC/WG17) regulations of legform impactor to bumper tests. Analyzing the pedestrian friendliness of a vehicle bumper by using LS-DYNA is described in detail. Simulation results were analyzed to identify the reasons for the unfriendliness. Furthermore, the analysis of the influence of bumper structure on pedestrian leg was performed and then some guideline was suggested. The analyzed models and results obtained could help evaluate pedestrian friendliness of a vehicle and guide the future development of pedestrian friendly vehicle technologies.

Keywords: Bumper; Subsystem impact tests; Working Group 17; Pedestrian safety

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1. Introduction

Traffic accident is one of leading causes of death in modern times. Car manufacturers incorporate numerous safety devices and features into their vehicles to reduce the injury to vehicle occupants. However, the pedestrian safety is not considered enough in design, even though the car-pedestrian accidents take thousands of lives worldwide annually. In each country, pedestrian accidents occupy large number of fatality and injury. In the European Union more than 7000 pedestrians are killed each year in accidents with vehicles while hundreds of thousands are injured [1]. Therefore, how to consider a pedestrian friendliness vehicle and then propose a pedestrian protection method are urgent works for minimizing pedestrian injury.

EEVC managed its members and cooperated with other scientists to conduct many car-pedestrian safety relating studies for many years. EEVC members recapitulated their findings, recommendations and published "EEVC/WG17 Report - Improved Test Methods to Evaluate Pedestrian Protection Afforded by Passenger Cars" in 1998. In 2002 this document was updated based on further work of WG17. The document of EEVC/WG17 [1], published in 1998, describes the descriptions of pedestrian impactor models including headform, upper legform, and legform impactors. The EEVC/WG17 testing subsystems are shown in Fig. 1. They also describe the procedures to do the certification tests of these models. The subsystem tests are also depicted very carefully. Some automobile organizations have already considered the subsystem tests. General Motors Corp. and Suzuki Motor Corp. built the finite element models of pedestrian impactors [2]. Although the headform follows the descriptions of WG10, but the upper legform and legform follow WG17. The Transport Research Laboratory (TRL) has played a major part in WG17, including the study of accidents and injuries, and development of the test procedures. It has developed the upper legform and the legform impactors. With different structures of vehicle, its energy absorbing ability will change.

The European Commission is working on new regulations to improve passive pedestrian protection on passenger cars significantly. Recently, European Parliament has made the decision to support the commitment on pedestrian safety proposed by the European Automobile Manufacture Association. Therefore, pedestrian protection measures will be required on all passenger cars sold in Europe from 2005. In order to speed up the development of pedestrian friendliness cars, the European Commission intends to introduce a directive dealing with pedestrian safety minimum requirements. There are two proposals, one by ACEA *(European Automobile Manufacture Association)* and one by EEVC/WG17. Euro-NCAP *(European New Car Assessment Programme)* adopts EEVC/WG17 test methods and limits with some modifications of its own [3].

Pedestrian protection is an important issue in traffic safety.

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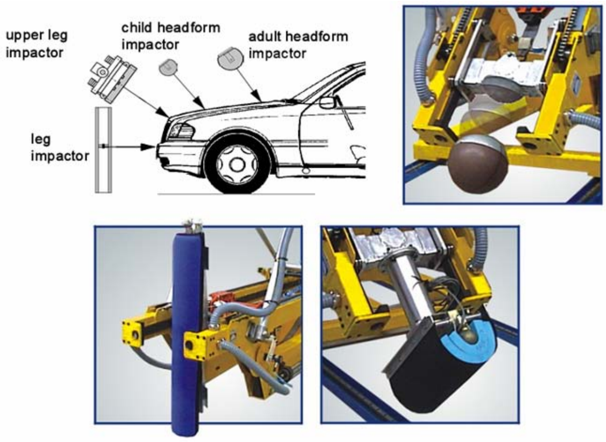


Fig. 1. EEVC/WG17 testing subsystems [4], [8].

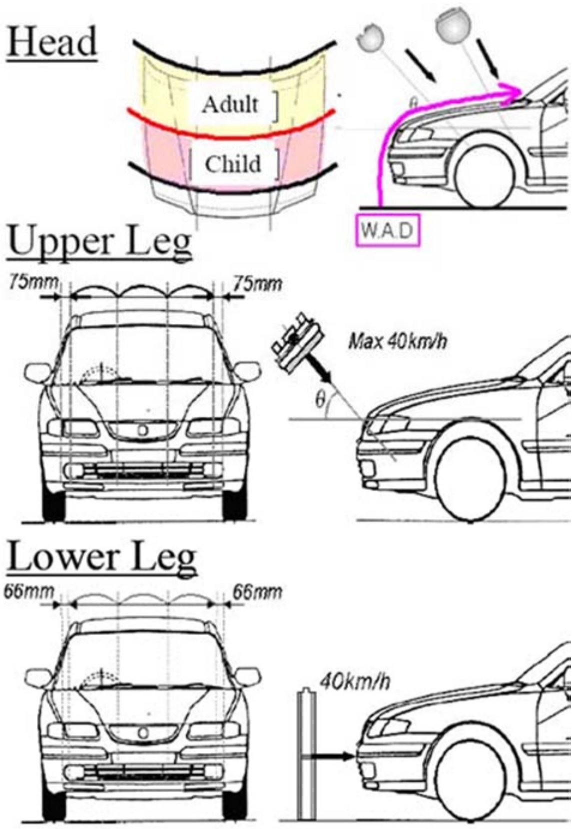


Fig. 2. Definition of EEVC/WG17 subsystem tests [9].

There are two pedestrian safety research directions. In the first way, the front structure must be redesigned. The structure should be smoother and reasonable shape to reduce injury for pedestrian when impacting. The engine room should be rearranged for the non-impact between bonnet structures and some parts of the engine. The material for the bonnet also needs to be changed. New materials will absorb impact energy better and increase deceleration time. The FKA did the optimization of bonnet and bonnet reinforcement structure [4]. In the second direction, car manufacturers develop some new device to detect accidents and reduce injure for pedestrian like some kinds of sensor, then activate safety equipment to protect pedestrian such as external airbags or lifting of the whole bonnet. Zanella et al. [5], FIAT, Italy developed smart bumper for pedestrian protection. This bumper can detect coming pedestrian and give solutions to avoid potential accidents.

Assessing the pedestrian friendliness of a vehicle and then proposing the design guideline are necessary for developing an effective pedestrian protection system. Besides, numerical simulations are valuable design tools for automotive engineering. The versatility and low repeating cost of the finite element method help designers to perform many more tests for pedestrian safety [6, 7]. For designing a pedestrian friendly vehicle bumper, this study adopts the WG17 regulations of legform impactor to bumper tests. Analyzing the pedestrian friendliness of a vehicle bumper with LS-DYNA is described in detail. Simulation results were analyzed to identify the reasons for the unfriendliness. Furthermore, the analysis of the influence of bumper structure on pedestrian leg was performed and then some guideline was suggested. The design guideline obtained in this study may serve as a useful reference for designers with pedestrian safety application.

2. Legform impactor to bumper test

In EEVC/WG17 subsystem tests, three impactor models represent three parts of human body that often have most serious injury in car-pedestrian accidents. These models are headform, upper legform, and legform impactors, representing head, upper leg or pelvis, and leg of pedestrian. The method is to check transient responses of these three models to evaluate the danger from vehicle that would happen to pedestrian during impact. In the subsystem tests, each impactor impacts with corresponding areas on vehicle to assess the pedestrian friendliness at these areas. The headform, upper legform and legform impactors are utilized to assess the forward section of the bonnet top, leading edge and bumper, respectively. Fig. 2 presents the definitions of EEVC/WG17 subsystem tests. The purpose of legform impactor to bumper test is to evaluate the pedestrian friendliness of the bumper. The first parameter, dynamic bending angle, is used to evaluate the structure of bumper that would bend the pedestrian leg to cause heavy injury. The second parameter, dynamic knee shearing displacement, is used to evaluate the bumper structure that would cause injury for pedestrian knee, because the relative displacement in the knee is often caused by the smoothness of the bumper. The third parameter, the acceleration, is used to evaluate the energy absorbing ability of the bumper. The requirements of tests are the maximum dynamic bending angle must not exceed 15^0, the maximum dynamic knee shearing displacement must not exceed 6.0 mm, and the acceleration measured at the upper end of the tibia must not exceed 150 g. The test will be performed at a minimum of three different positions in thirds at most likely to cause injury locations. The distances between impact points and corners are not as small

Table 1. Impact locations of the legform impactor in tests with original bumper.

Impact location	Description	Accel. (g)	Bending angle (deg)	Shearing disp. (mm)
The original (8.2 Kg)				
U1	Center of bumper	295	60.5	4.07
U2	RHS longitudinal	359	53.6	4.55
U3	370 mm on the left of vertical longitudinal plane	364	56.2	4.25

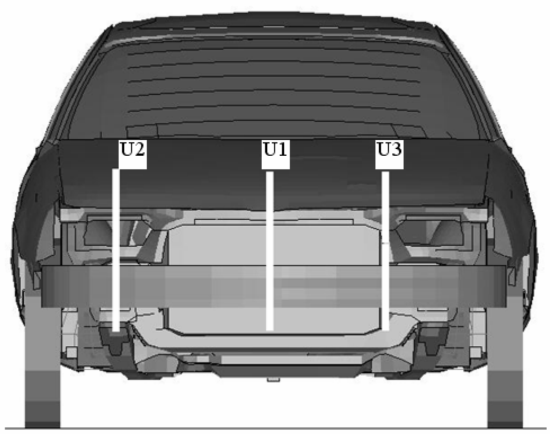


Fig. 3. Impact locations of the legform impactor.

as mentioned in the report. The impact direction must be in the horizontal plane and parallel to the longitudinal vertical plane of vehicle. The impact velocity is 40 km/h or 11.11m/s. Table 1 and Fig. 3 present the bumper-legform impact locations.

3. Finite element model of legform impactor

The finite element model of legform impactor, described in detail in [10], is shown in Fig. 4. This model consists of 4820 nodes, 10 beams, 1210 shell elements, 3324 solid elements, and 16 dampers and springs. The tibia and femur are modeled using shell elements and rigid material to describe the cylinders and steel material. The flesh is modeled by using solid elements and low-density foam to present Confor™ CF-45 material. The skin is modeled by using solid elements and elastic material model to present neoprene material. The total mass of the femur and tibia are 8.65 kg (8.6 ± 0.1 kg) and 4.76 kg (4.8 ± 0.1 kg) respectively. Thus, the total mass of the legform impactor is 13.41 kg (13.4 ± 0.2 kg).

The knee is represented by 16 dampers and springs that make the knee flexible in translation and rotation (Fig. 4). One and four beams are connected rigidly to the lower knee and upper knee, respectively. Then each damper or spring connects one beam on the upper knee and one beam on the lower knee together. Thus, the knee has three degrees of freedom. It can be bent, shorn and slightly lengthened. To make the force versus bending angle and force versus shearing displacement fall within the limits, non-linear elastic spring models were used. First, the static certification tests were done to find the behavior of the springs. Then, the dynamic certification tests were used to adjust the damping factors. To avoid the relative displacement between the knee and the tibia, the knee and the femur, the lower and upper knees are fixed to the tibia and femur, respectively, by rigid connections. This legform impactor model has passed all the EEVC/WG17 certification tests [10], demonstrating the feasibility of its use in simulating legform impactor tests.

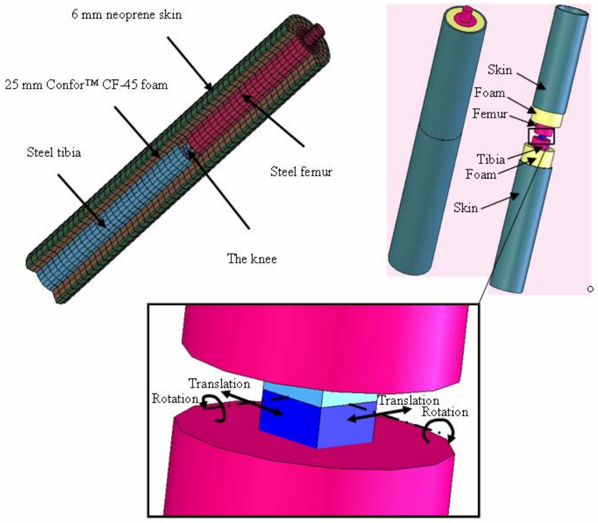


Fig. 4. Finite element model of the legform impactor.

4. Analysis of bumper-pedestrian friendliness

In the legform impactor to bumper test simulations, the legform impactor is used to impact to the bumper. The legform impactor was positioned vertically and impact with velocity of 40 Km/h or 11.11 m/s. The simulation of legform impactor to bumper test is shown in Fig. 5. Table 1 and Figs. 6 to 8 present the simulation results of the legform impactor to original bumper simulations. No position on the bumper satisfies the EEVC/WG17 requirements. Data for the three impact locations are significantly similar. This similarity is due to the equal distribution of material and geometry throughout the bumper. All knee shearing displacements satisfy the EEVC/WG17 requirements due to the flatness of the bumper. The flatness and height of the bumper affects the shearing displacement. All knee bending angles exceeds the limits due to the sharpness of the bumper. The lower and upper bumper reference lines, as determined in the EEVC/WG17 regulations of three component subsystem tests [1], are located far from the parts behind the bumper.

In summary, the structure of the vehicle bumper is not friendly to pedestrian because of its structure. To improve its friendliness, its profile must be altered. The bumper should be wider in vertical direction to support the knee better to reduce the shearing displacement. Moreover, it would make the

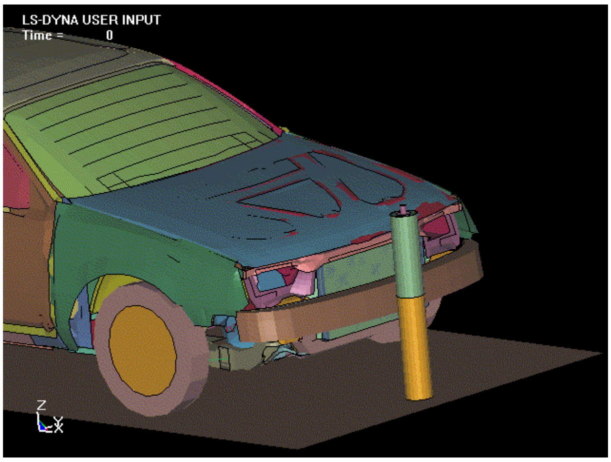


Fig. 5. Finite element model of the legform impactor to bumper tests.

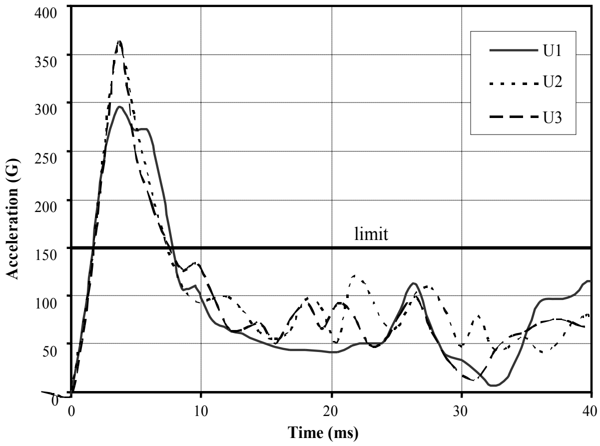


Fig. 6. The accelerations of the legform impactor in tests with original bumper.

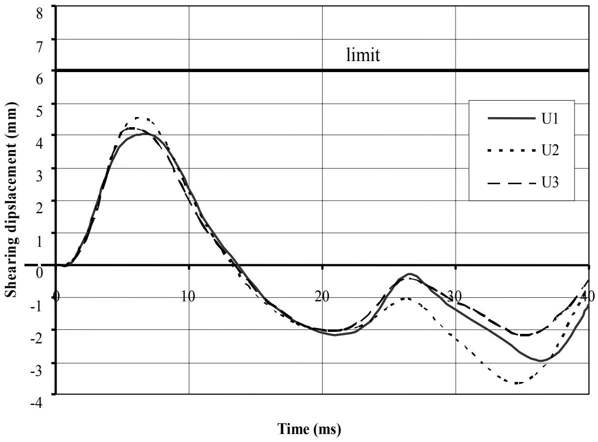


Fig. 7. The shearing displacement of the knee in tests with original bumper.

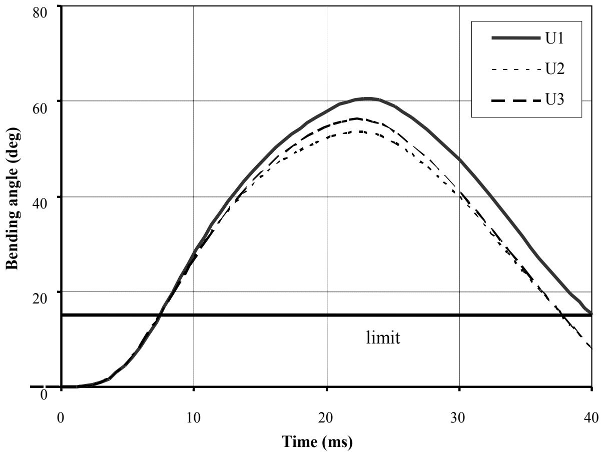


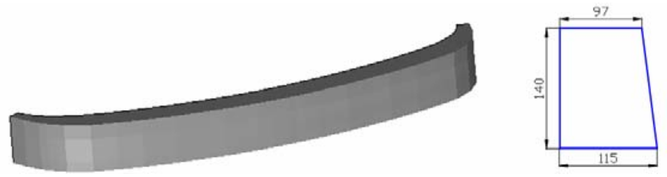
Fig. 8. The bending angle of the knee in tests with original bumper.

bumper softer. Therefore, the deceleration time of legform impactor will increase. The bumper also needs to be closer to behind parts because the behind parts can support the higher and lower areas of legform impactor better. That will decrease the bending angle of the knee.

5. Design of pedestrian friendly bumper

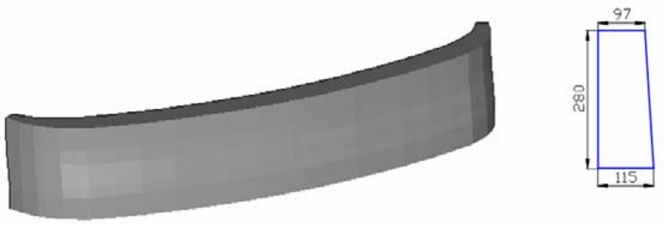
The bumper was changed according to the suggestions mentioned above. The bumper was first reduced in width to make the front side of the bumper close to the behind parts. Then, it was increased in height. So, the front side became softer. Therefore, to avoid impacting of the leg with the rear side through the front side, the width was increased. However, the edge of the bumper was still sharp. For type C, a filleted corner was created and the height was reduced to make a smooth rollover of the leg around bumper edge and behind parts. The design is focused on the middle position (U1) of the bumper where the radiator and bonnet top edge are close to the bumper. At the other two positions (U2, U3) the lights are slightly far from bumper and the structure is complicated. It is necessary to redesign the frontal structure of the vehicle to match with the design of the bumper. However, the design of the vehicle is not mentioned in this study. Therefore, the results of impact simulations at U2 and U3 are simply for reference. The dimensions of the new designs were estimated through relative relationship with surrounding structure and authors' designing experience. The purpose of this study is improving the structure design of bumper. Therefore, it is not necessary for final results to satisfy all requirements.

The dimension of the original bumper has shown in Fig. 9(a) is measure at maximum of right cross-section, but the average values are: 140 mm × (87 mm + 105 mm). The type of A (Fig. 9(b)) is gotten when the width of original bumper is reduced three times. The values of 29 mm (= 87 mm : 3) and 35 mm (= 105 mm : 3) equal to one-thirds of average width dimension. Type B (Fig. 9(c)) is gotten when the height of original bumper is increased two times (280 mm = 2×140 mm), whereas the width is kept intact. Type C (Fig. 9(d)) is gotten by modified Type A but kept the weight of cover part is con-

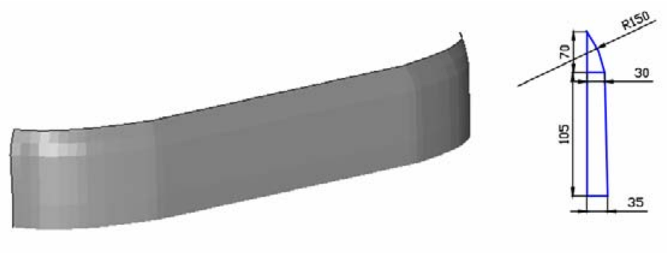


(a) Original (Unit: mm)

(b) Type A (Unit: mm)



(c) Type B (Unit: mm)



(d) Type C (Unit: mm)

Fig. 9. Four types of bumper and profiles.

stant. It mean that the cover area of type C is equal to type A.

The legform impactor also impacted with the bumper at the same positions as in the original bumper. These positions are at the center of bumper, at the center of right head light, and at 370 mm far from bumper center on the left. All other conditions were kept the same. The results are shown in Table 2 and Figs. 10 to 18.

Table 2 and Figs. 10 to 18 show the acceleration of the legform impactor, the bending angle and shearing displacement of the knee. In general, all the values are reduced by type A, B, and C. But there are some increased values. In the case of type A, all the measured values are reduced at positions U1 and U2 in comparison with the original case. But at position U2, the acceleration and bending angle still increase. That is because the connection between the bumper and the chassis. That makes the bumper very hard at that position. To avoid this phenomenon, the bumper needs to be wider in vertical direction as type B. In the case of type B, all the measured values are decreased at three all impact positions. That means the broader bumper is safer to pedestrian. In the case of type C, the measured values *(acceleration, bending angle, and shearing displacement)* at the center of bumper show that it is the best structure for bumper among four types. The bending angle and shearing displacement of the knee are lower than limits. Only the acceleration is slightly greater than limit. But at positions U2 and U3, almost the measured values are greater in comparison with type B. That is due to the connection between the bumper and the chassis. The ends of chassis support these areas of bumper. Therefore, when impacting with the bumper the legform impactor also impacts with inner side of bumper connected with the chassis.

6. Conclusion

The finite element model of legform impactor has passed all the regulations of EEVC/WG17 and can be used in EEVC/GW17 subsystem test simulation to evaluate the friendliness of vehicle bumper to pedestrian. Based on the results herein, the following conclusions are drawn:

(1) The bumper structure should be broader to support large

Table 2. Impact locations of the legform impactor in tests with types A, B and C.

Impact location	Description	Accel. (g)	Bending angle (deg)	Shearing disp. (mm)
Type A (5.5 Kg)				
U1	Center of bumper	284	33.9	2.11
U2	RHS longitudinal	523	55.9	3.36
U3	370 mm on the left of vertical longitudinal plane	273	44.8	3.28
Type B (12.6 Kg)				
U1	Center of bumper	232	21.5	2.31
U2	RHS longitudinal	225	18.4	2.43
U3	370 mm on the left of vertical longitudinal plane	242	23.5	2.27
Type C (6.3 Kg)				
U1	Center of bumper	177	10.9	2.97
U2	RHS longitudinal	303	35.8	2.52
U3	370 mm on the left of vertical longitudinal plane	305	21.9	3.05

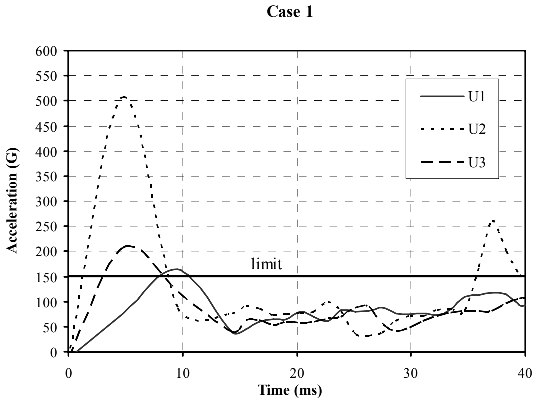

Case 1

Fig. 10. The accelerations of the legform impactor in tests with type A.

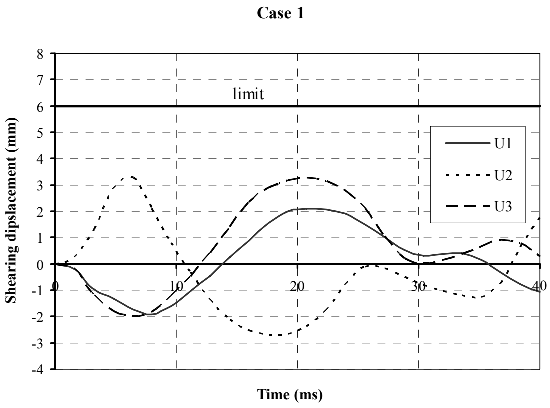

Case 1

Fig. 11. The shearing displacements of the knee in tests with type A.

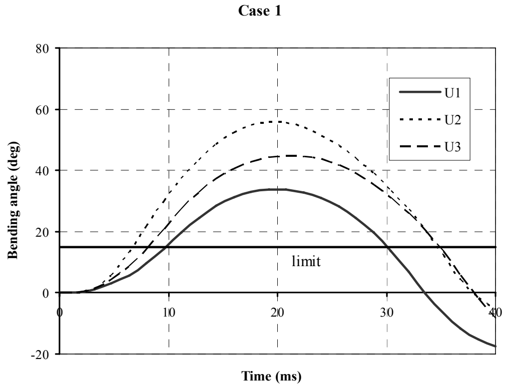

Case 1

Fig. 12. The bending angles of the knee in tests with type A.

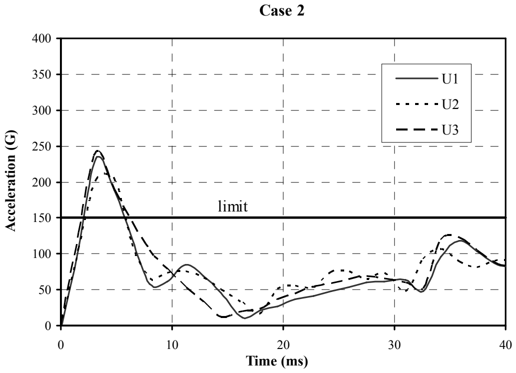

Case 2

Fig. 13. The accelerations of the legform impactor in tests with type B.

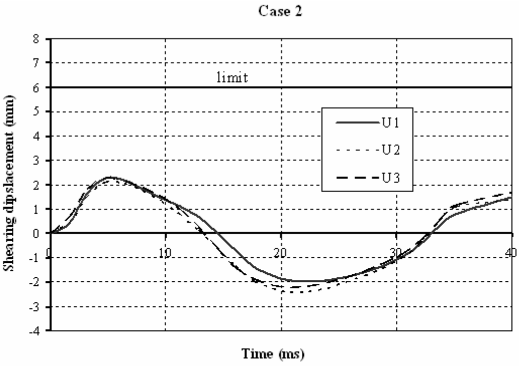

Case 2

Fig. 14. The shearing displacements of the knee in tests with type B.

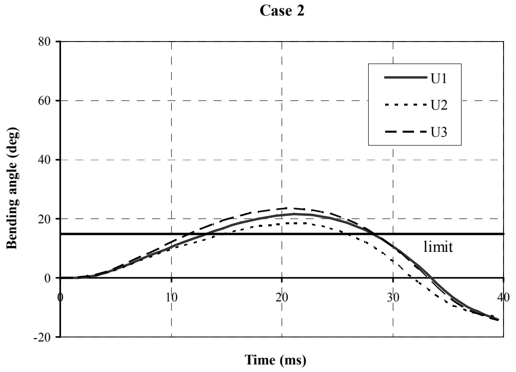

Case 2

Fig. 15. The bending angles of the knee in tests with type B.

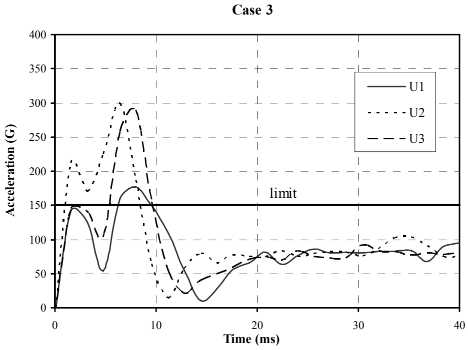


Fig. 16. The accelerations of the legform impactor in tests with type C.

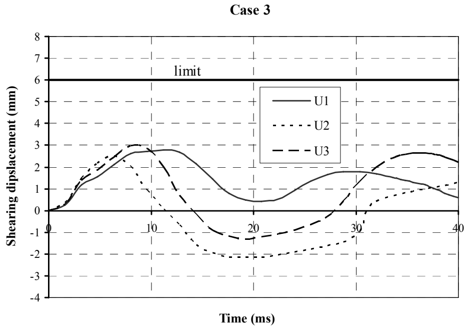


Fig. 17. The shearing displacements of the knee in tests with type C.

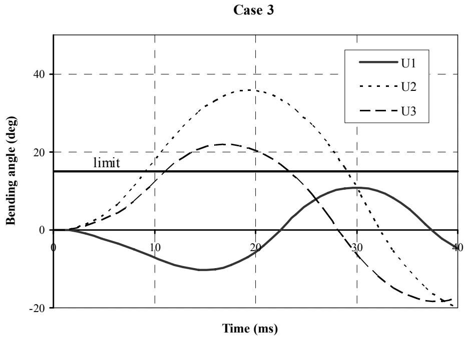


Fig. 18. The bending angles of the knee in tests with type C.

area of the knee and reduce the knee displacement.

(2) The bumper should be closer to the behind parts to support high and low parts of the legform impactor. That will reduce the bending angle.

(3) The upper edge of bumper should be filleted to make the combination of bumper and bonnet leading edge profiles smoother.

(4) The thickness of bumper should have lower limit to avoid the impact of the knee to the structures behind through the front side of bumper.

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