

Influencing Factors of Contact Force Distribution in Pedestrian Upper Legform Impact with Vehicle Front-End

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ABSTRACT

Pedestrian upper leg impact protection is a challenging requirement in the Euro NCAP assessment. In upper legform to bonnet leading edge tests, the legform impact force, the legform intrusion and the injury parameters (impact force and bending moment measured on the upper legform) are highly related to design of vehicle front-end styling and structure, as well as clearance underneath bonnet leading edge. In the course of impact, the contact area variation has significant influence on the stress distribution and consequently the force and the bending moment on the upper legform. Using finite element simulations of upper legform impact with a typical sedan, the deformation of the legform and the vehicle structure, and the variation of the contact force distribution are characterized and analyzed. Based on the study, a method for calculating the contact force is put forward by assuming a shape of the contact zone on the upper legform and a stress distribution function within the contact zone. The calculation method is verified using a simplified model of vehicle front-end structure developed in a previous study. Then a parametric study is conducted using the simplified vehicle front-end model to study influence of key design variables. The results of the parametric study, to some extent, have revealed relationship among vehicle front-end design parameters such as styling, geometry and stiffness, contact characteristics such as the maximum stress on outer foam, and the injury parameters (mainly the impact force).

CITATION: Nie, B., Huang, J., Xia, Y. and Zhou, Q., "Influencing Factors of Contact Force Distribution in Pedestrian Upper Legform Impact with Vehicle Front-End," *SAE Int. J. Passeng. Cars - Mech. Syst.* 5(1):2012, doi: 10.4271/2012-01-0272.

INTRODUCTION

In the current pedestrian impact safety assessment test methods, the upper legform impactor is used to represent the human femur and pelvis. For vehicles with high front ends, e.g. SUVs, the bonnet and its leading edge are most frequent sources of injury [1]. The aim of the upper legform to bonnet leading edge test is to evaluate the aggressiveness of the bonnet leading edge in causing femur/pelvis fractures [2]. Responses of the human body FE model and upper legform when impacted with a vehicle have been compared since 2001 [3-4]. It is revealed that the upper legform to bonnet leading edge impact test method has low biofidelity. Nevertheless, widely accepted conclusion has not been obtained yet [5-6]. Compared to the pedestrian head impact protection and lower leg impact protection, there have been much fewer vehicle models that have received good scores in the Euro NCAP assessment test of the upper legform to bonnet leading edge [3]. Some research show that proper spatial arrangement and structure design of the parts underneath the bonnet lead may benefit the upper legform impact response [7]. Though some concept design could be

examined using simulations of upper legform impacting vehicle front-end [8], guidance for vehicle front-end design for upper legform protection is seldom proposed in recent years. Pedestrian upper leg impact protection is still a quite challenging requirement.

The upper legform impactor consists of rigid front and rear members and has a foam padding covering the contact side. Such an upper legform structure can represent the characteristics in the human femur and pelvis impact with real vehicles [9, 10, 11]. In upper legform tests, the initial kinetic energy, the initial velocity and impact angle are determined by the bonnet leading edge height (BLEH) and the bumper lead (BL) of the target vehicle. The sum of the impact forces and the peak bending moment measured in the main legform member are the injury indexes. The Euro NCAP test prescribes threshold values to the injury indexes for their assessment rating. Some research shows that the force to moment ratio on upper legform can be taken as a constant [12]. In general, when the summed force is below the threshold, the peak bending moment can always meet the requirement. For this reason, in this study, the impact forces

are taken as the study object while the peak bending moment is only monitored. A substantial portion of the initial legform kinetic energy will be absorbed by the deformation of the vehicle body components around the impact area. Proper vehicle front-end styling, structure design or spatial arrangement of the parts underneath the bonnet lead will benefit the upper legform impact response [13, 14, 15, 16].

In upper legform tests with bonnet leading edge, the impactor is launched with a specified velocity and its motion is constrained by a guiding system. Thus the upper legform can only move in the straight direction of the guiding when contacting with the target vehicle. The first contact point is around the mid-point on the upper legform, and, as the outer flesh foam of the legform and the affected vehicle structure are compressed, the contact area spreads out in the course of the impact. The contact area variation has significant influence on the stress distribution and consequently the force on the upper legform. And the size and shape of the contact zone and their variation in the impact are determined by the vehicle styling parameters and stiffness parameters around the bonnet leading edge.

To obtain a good understanding to this problem, finite element (FE) simulations of upper legform impact with a typical sedan are conducted. The impact pulse, characterized by the impact force vs. legform impactor intrusion measured on the upper legform, is studied. The shape and size of the contact zone on the upper legform is analyzed. A calculation method for the contact force estimation is put forward by assuming a shape of the contact zone on the upper legform and a stress distribution function within the contact zone. The calculation method is verified using a simplified model of vehicle front-end structure developed in a previous study. Using this simplified model, a parametric study is conducted to study influence of key design variables related to vehicle geometry and stiffness characteristics of the local area around the bonnet leading edge. The results of the parametric study have revealed relationship among vehicle front-end design parameters such as stiffness, styling and geometry, contact characteristics such as the maximum stress on the most outside layer in the outer foam, impact energy absorbed by the outer foam and the injury parameters.

TYPICAL RESPONSE OF UPPER LEGFORM IMPACT TESTS

UPPER LEGFORM IMPACT PULSE

Figure 1 shows typical simulation results of upper legform impact on a sedan model in the middle position. The impact force is the summation of the two individual forces measured at each end of the upper legform impactor front member, as specified in the test methods. In this simulation, the mass of the legform is 14.60 kg and the initial impact velocity is 8.75 m/s.

The upper legform impact force response is caused by the contact of vehicle front-end and usually exhibits multi-peak

characteristics. The first peak is in accordance with the first contact of the upper legform on the bonnet lead area with higher relative velocity. During this period the bonnet leading edge usually receives support from the upper cross-member behind it and is difficult to deform. For easier description, this group of parts related in the impact is marked as “Group 1”. It usually acts beneath the midpoint of the upper legform. The second force peak is in accordance with impact on the hard points underneath the bonnet lead. This group of related vehicle parts is marked as “Group 2”, including the bonnet latch structures, upper beam of the water tank, etc. It acts above the midpoint of the legform. Although at this time the upper legform is of lower velocity, structure stiffness of “Group 2” is usually higher, which leads to a higher second force peak value, as marked in Figure 1.

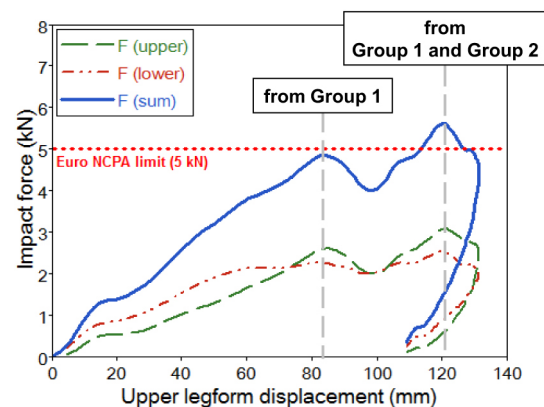


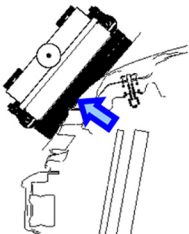
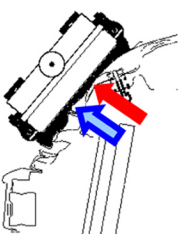
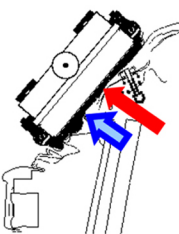
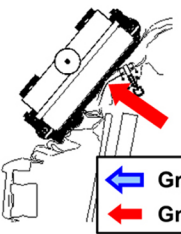
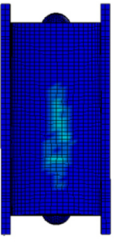
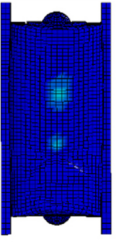
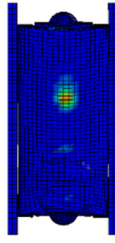
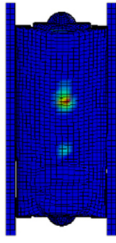
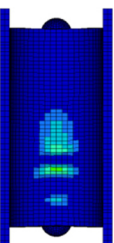
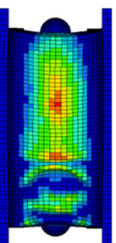
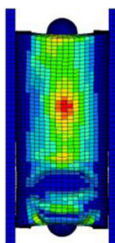
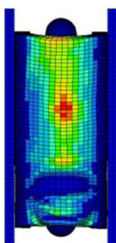
Figure 1. Typical upper legform impact pulse (14.60 kg, 8.75 m/s).

CONTACT FORCE DISTRIBUTION DURING IMPACT

Denote the impact force on upper legform as F_i , and the intrusion of the upper legform as D . Evolution of these variables as well as vehicle deformation and stress/strain distribution on legform outer foam during impact are shown in Table 1. It can be found that the stress concentrated in the center of the contact zone between the upper legform and the vehicle, although the strain distribution covers much larger area. From the initial contact to the occurrence of the first force peak, the stress is mainly generated at the “Group 1” position. After the first peak, part “Group 2” dominates the impact process till the legform rebounds. Stress on the outer foam reaches the maximum value at the center point and decreases to zero towards the boundaries of the contact zone.

As shown in Figure 2, the impact force F_i is exerted on the front members from the rear members of the upper legform. Denote the two individual forces measured at each end of the upper legform as F_{up} and F_{low} respectively, that is, $F_i = F_{up} + F_{low}$. Denote the contact force on upper legform from vehicle front-end as F_c , which is exerted on the most outside foam layer. Take the front member on upper legform

Table 1. Variable evolution during upper legform impact.

	Contact starts ($t = 3.0$ ms)	1 st force peak ($t = 12.0$ ms)	2 nd force peak (max.) ($t = 19.2$ ms)	Rebound ($t = 27.0$ ms)
Vehicle deformation				
Stress distribution (outer foam) (MPa)	Effective stress (MPa) 2.00 1.60 1.20 0.80 0.40 0.00 	Effective stress (MPa) 8.00 6.40 4.80 3.20 1.60 0.00 		
Strain distribution (outer foam)	Strain (vonMises) 1.13 0.85 0.57 0.28 0.00 			
F_i (kN)	1.36	4.84	5.60	4.26
D (mm)*	18.67	84.05	120.20	131.85

*Suppose the upper legform is 0 mm at the first contact with vehicle front.

as the subject investigated; it can be found that F_c is summation of the impact force F_i and the inertia force of the frontal parts (including the front members and the outer foam). That is, $F_{veh} = F_i + m_F \cdot a$. Approximately, we have

$$F_{veh} \approx k \cdot F_i, \quad k = 1 + \frac{m_F}{m_R} > 1$$

$F_{veh} = m_{UL} \cdot a$. Then there is

Therefore the contact force F_c can be taken as in linear relationship to the impact force F_i .

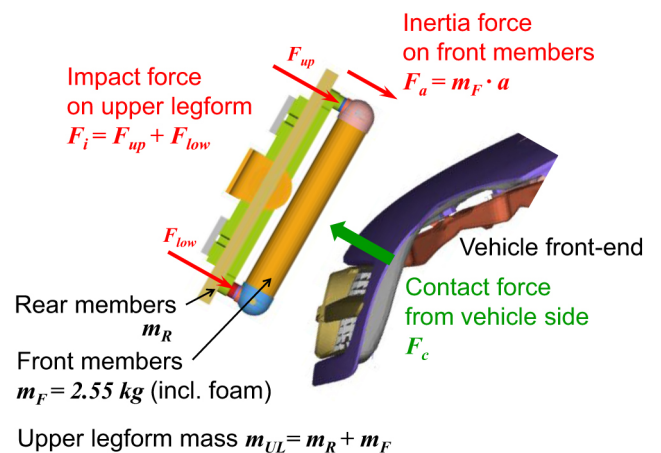


Figure 2. Relationship between impact force F_i and contact force F_c (outer foam on upper legform not displayed).

To identify the contact area variation in the course of impact, the outer foam elements on the legform are divided into three different sets according to their stress value as below. As shown in Figure 3, according to the foam material definition, Set-1, Set-2, and Set-3 approximately correspond to stress level of the plateau of deformation stage, transition between the plateau and densification, and the densification stage respectively.

- Set-1: elements with stress in the [0.1-0.2) MPa range
- Set-2: elements with stress in the [0.2-0.5) MPa range
- Set-3: elements with stress higher than 0.5 MPa

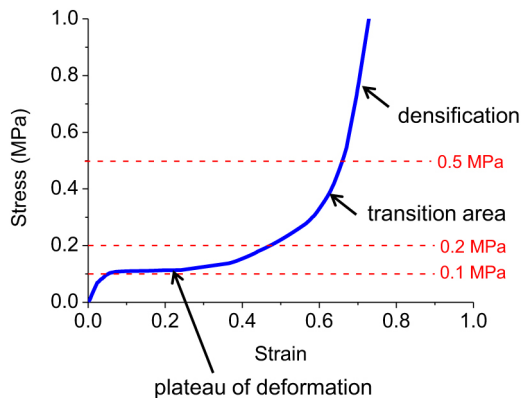
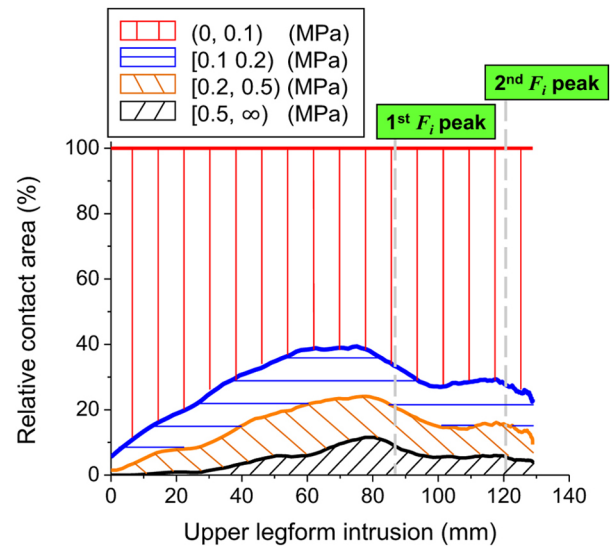


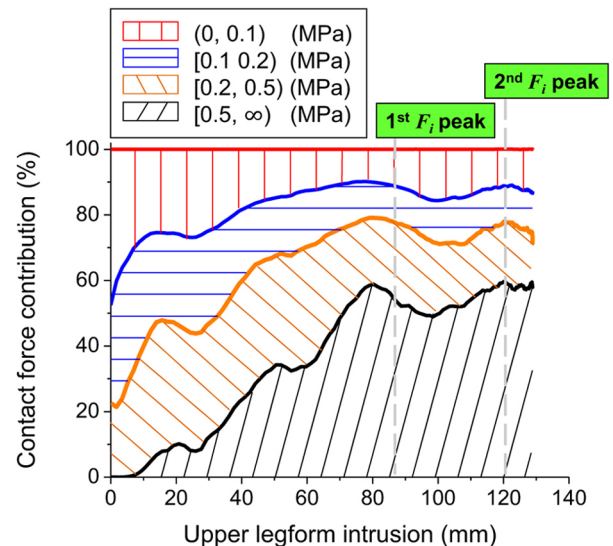
Figure 3. Material definition under typical strain rate of the outer foam.

The contact area variation considering different elements sets is given in Figure 4a. It can be found that, the elements with stress level lower than 0.5 MPa (Set-1 and Set-2) account for the majority in the whole contact zone, which is also in accordance with that in Table 1. The elements with higher stress level (Set-3) increase till the first impact force peak occurs and then decrease slightly. The contributions to the contact force from the different element sets are plotted in Figure 4b. The contact force on the outer foam is mainly undertaken by those high-stressed elements, which only account for a small percentage in the contact zone. That is to say, occurrence of the peak impact force is due to a quite small concentrated high-stressed area, which may be named as “effective contact area” on vehicle front-end.

It is also found that, with larger effective contact area, the energy absorbed by the impactor itself due to flesh foam compression is greater, which indicates that the energy to be considered in estimating the energy absorbing (EA) space underneath bonnet leading edge at the vehicle side could be even less.



(a). Relative contact area variation



(b). Contact force contribution variation

Figure 4. Contact area comparison of different sets of outer foam elements.

IMPACT PULSE WAVEFORM EFFICIENCY

To further evaluate the upper legform protection performance of the vehicle, a pulse waveform efficiency calculation method is introduced. It's originally used in performance evaluation of front-end structure in full vehicle crash [17]. An ideal situation for the impact pulse of the upper legform is that it is close to a square wave and the plateau force is close to the injury threshold. Considering that the foam compression in the early impact stage is only subject to a much lower force level than the deformation of the vehicle body components in the later impact stage, in reality, it is impossible to achieve a square wave for the entire impact process. However, the square wave could be used for