Full body simulations of motorcyclist accidents

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SUMMARY. Motorcyclists are among the most vulnerable road users and often suffer fatal head injuries. Therefore the safety helmet is one of the most important elements of personal protective equipment for riders. The present paper discusses several issues related to the standards to be used in order to certify the helmets as road-worthy.

1 INTRODUCTION

According to statistical investigations [1] in the EU-15 countries there are approximately 8.6 million motorcycles (not counting mopeds) which are responsible for about 5 thousand fatalities annually, accounting for a substantial proportion (16%) of total road fatalities. Since the number of fatalities in motorcyclists' accidents is high in comparison with the number of motorcycle users, and a high percentage of them is due to head injuries, the most important element of personal protective equipment for motorcyclists is the safety helmet. Results of statistical investigations about motorcycle accidents in the US revealed that about 51% of the un-helmeted riders suffered head injuries compared to 35% of the riders wearing a helmet [2, 3].

In order to certify the performance of safety helmets, they are tested according to one of the accepted helmet testing standards [4]. Almost all the standards follow the same concepts in evaluating the effectiveness of the helmets during accidents, which are:

- the helmet has to be able to absorb enough impact energy;
- it has to remain on the head during the accident;
- it has to resist penetration.

However, details of procedures in force in various countries are different. Hence, it is probable that a helmet satisfying the requirements of a standard will not comply with all requirements of another standard. The first requirement of the previous three is the most important and the present paper will investigate some aspects of the EU standards relevant to it.

In the next section a short description of the main impact tests required by the testing standard ECE 22.05 [5], currently in use in the EU, will be provided. In section 3 an important difference between the standard configuration and real world accidents will be highlighted. In section 4 a simple model will be described and will be used to suggest possible improvement of the test configurations. A few concluding remarks will bring the paper to its end.

2 THE HELMET ENERGY ABSORPTION TESTS

Usually a motorcycle helmet is made of four main parts as shown in figure 1:

- The shell of the helmet is the external component which directly experiences the impacts. Its duties are: distribution of the external load on a larger area of the underlying component which is the liner, contribution to the impact energy absorption and prevention from penetration of sharp objects. Shells are usually made of thermoplastic materials or composites.
- The energy absorbing liner is composed of crushable foam, often made of expanded polystyrene (EPS), which provides the main contribution to absorb impact energy.
- The comfort liner is made of easily deformable foam, and provides the best fit to the wearer's head.
- The retention system, or chin strap, should retain the helmet on the head during an impact or a series of impacts.

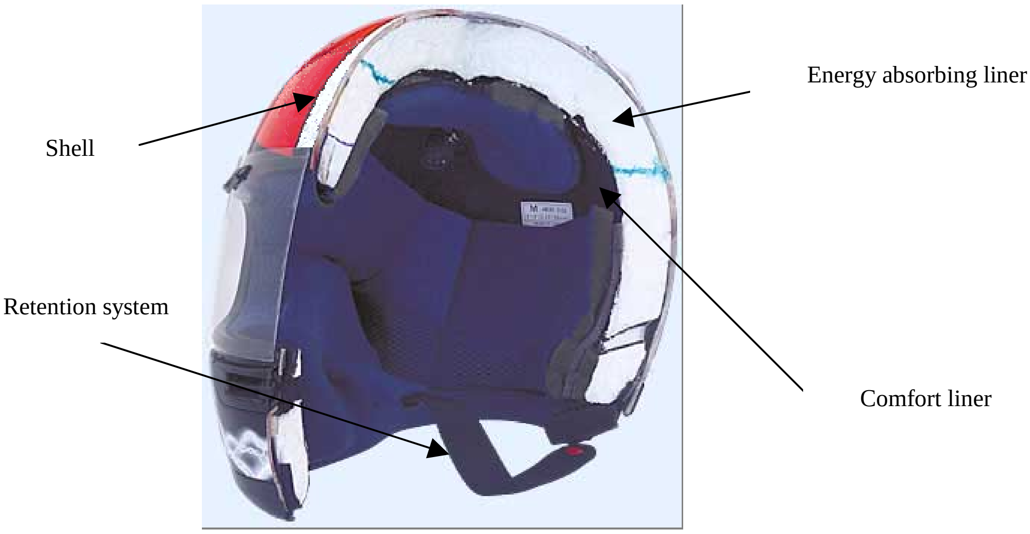

Figure 1: Structural components of a conventional helmet.

In ECE 22.05, the impact absorption capacity of the helmet is determined by recording against time the acceleration imparted to a headform fitted with the helmet, when dropped in guided free fall at a specific impact velocity upon a fixed steel anvil. Every helmet has to undergo four impacts on four different points: the front, the side, the top and the back. Two anvils are used, one is flat and the second has the shape of a kerbstone. The standards fully define the positions where the impacts have to take place and the shape of the anvils. The impact speed is 7.5 m/s. During impact the linear acceleration of the headform at its centre of gravity is recorded against time. From the resultant linear acceleration-time data, the head injury criterion (*HIC*) is calculated with the following equation:

$$HIC = (t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2.5} \tag{1}$$

where $a(t)$ is the resultant acceleration, expressed in multiples of g, versus time, in seconds, and t_2 and t_1 are respectively any two time instants during the impact pulse duration. Both the maximum value of the resultant acceleration and the *HIC* value have to be below given thresholds at all impact tests for the helmet to pass the tests. Figure 2, taken from [4] shows a sketch of the equipment used for impact tests.

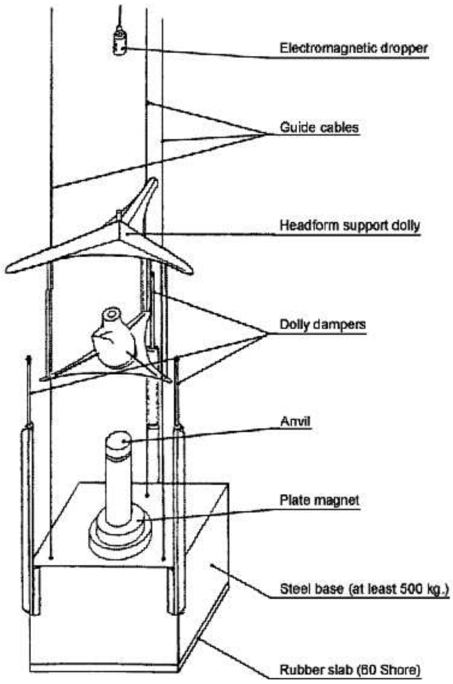

Figure 2: Impact absorption test machine.

3 THE EFFECT OF THE BODY

It is apparent that the main difference between a real world accident and the test conditions is provided by the absence of the body in the standardized tests. To the best of our knowledge the effect of ignoring the rest of the body, by using a detached headform, on head injury indicators has received little attention. It is not clear if the impact conditions implicitly take into account the effect of the body, but it does not seem so. The masses of the various headforms are realistic human head masses, moreover the impact speed of 7.5 m/s and the threshold value of 275g compare well respectively with impact speeds in real accidents and with the value of acceleration believed to cause serious injuries to the head (AIS3) [1]. The authors therefore believe that when the regulatory bodies decided about the impact configurations and thresholds they were aiming at reproducing realistic impact conditions in a way which was simple enough to be adopted in industrial labs. The authors believe the ‘level of realism’, i.e. the similarity between tests and real accident impacts, can be improved and therefore as a consequence the protective capability of motorcycle helmets increased.

One way to consider the effect of the body is to use anthropometric dummies in drop tests. For example, Aldman et al. [6-8] dropped an Ogle-Opat dummy wearing a helmet onto a surface made of asphalt concrete at two impact speeds: 4.4 and 5.2 m/s and measured linear and rotational accelerations of the headforms. In a similar research [1], a Hybrid III dummy and the detached headform of a Hybrid III dummy were fitted with helmets and dropped onto flat anvils at 4.4, 5.2 and 6 m/s, and linear and rotational accelerations of the head were recorded. These impact velocities were chosen "to simulate realistic impact conditions and to limit the risk of severe damage to the dummy". The conclusions derived in [1] were that "the effect of the body and the neck is thus a decrease of the measured linear acceleration values when compared with headform measurements". In spite of using helmets certified according to the European standard (ECE22.05, 2002), the dummy and headform drop tests were compared at impact speeds less than that set in ECE22.05, i.e. 7.5 m/s; consequently, the conclusions were confined to the maximum impact speed of 6 m/s.

It is important to notice that, even for a fixed impact configuration, the force transmitted to the head during an impact is not a linear function of the impact speed or other simple impact parameters because the constitutive law of the expanded polystyrene foam liner is highly non-linear, as shown in figure 3. After a brief initial linear elastic branch (I) the stress-strain relationship of the foam is characterised by a long plateau in which σ is almost independent on ε (II). Once the foam is compacted its behaviour becomes much stiffer following the third branch of figure 3 and therefore if a large strain is reached much higher contact forces can develop.

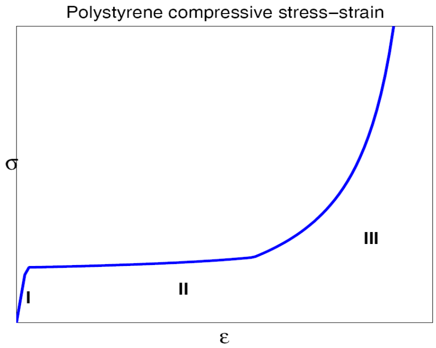

Figure 3: Stress-Strain curve of a typical EPS [10].

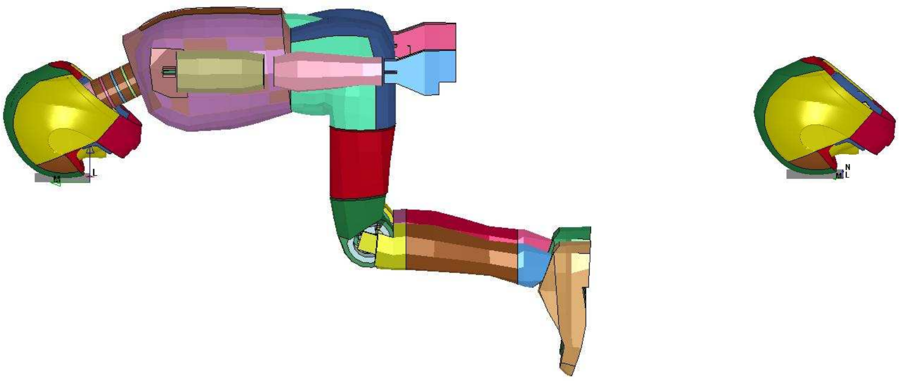

Figure 4: Virtual drop tests using Hybrid III dummy and its detached head.

Therefore it is not easy to extrapolate at higher values of the impact speed the experimental results obtained with lower impact velocities.

Virtual testing provides another way to evaluate the effect of the presence of the body in safety helmet impact tests. The two models shown in figure 4 were generated and used to carry out virtual tests with the software LS-Dyna [10]. Both models were virtually impacted against a flat anvil and the acceleration at the centre of mass of the head of the dummy Hybrid III is compared to that recorded at the centre of mass of the detached head at two impact speeds: 6 and 7.5 m/s.

Figure 5 shows the results of the simulations and reveals that at 6 m/s the peak value of the acceleration is higher in the detached head whereas at 7.5 m/s it is higher in the case with the whole body.

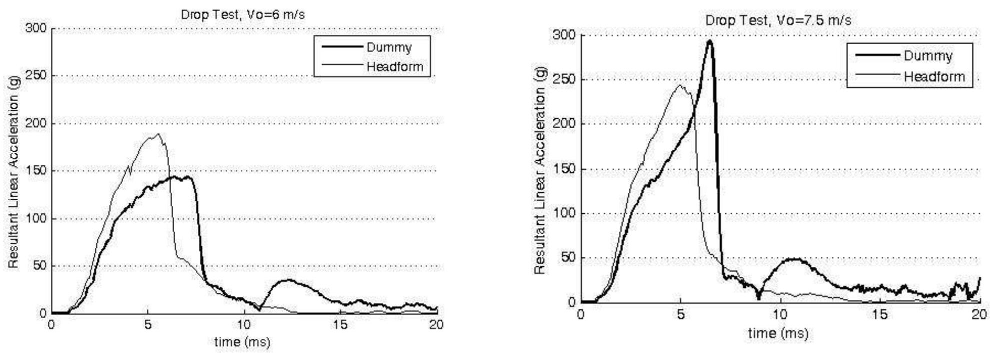

Figure 5: acceleration histories at 6 and 7.5 m/s for dummy's head and detached headform.

A closer examination of the computational results shows that the maximum value of the contact force between helmet and anvil is higher when the body is included at both impact velocities. The higher force increases the compression of the foam, which reaches the compaction branch of the constitutive curve in the case with the whole body at the impact speed of 7.5 m/s. It seems that the conclusions of previous experimental studies were correct for an impact speed up to 6 m/s, but they are not necessarily true for higher speeds. The thickness of the liner is another important parameter, since thicker foams would remain in the plateau regime for longer compression lengths. The thickness of the liner is however controlled by considerations of practicality, esthetic … The authors believe that it cannot be varied in any significant way.

This simulation (and others not shown here) suggests that body inertia is an important parameter and perhaps, it should be considered when evaluating the protective capability of safety helmets. Since using a dummy in standard tests would have huge impacts on the costs of the tests and therefore on the price of helmets, other measures should be found that are simpler and more economical.

4 SIMPLE ANALYTICAL MODEL TO UNDERSTAND HOW TO MODIFY THE TESTS

The effect of the body, for the impact configuration shown in figure 4, is to reduce the acceleration at the headform mass centre and increase the contact force, for an impact velocity which does not cause the compaction of the EPS liner. An analytical model will be presented in order to have a deeper understanding of how the various ‘input’ parameters, such as impact velocity and the weight of the falling mass, can affect the ‘output’ parameters, such as resultant acceleration and contact force.

In an impact, two parts of a helmet absorb energy: liner and shell. The liner of the commercial helmets is often made of EPS whose typical stress-strain curve is shown in Figure 3. Gilchrist and Mills [11] assumed a constant yield stress for the liner foam (S_Y) the plateau value in the crushing zone (zone II) and derived the following relation between the normal force on the helmet (F) impacting a flat anvil, and the deflection of the foam at the impact location (y):

$$F=2\pi R S_Y y \tag{2}$$

For the derivation of equation (2), the helmet was simplified as being locally spherical with radius R. This equation was found to give a good approximation of the impact behaviour of thin-shelled helmets such as bicycle helmets. However, the shell of motorcycle helmets increases the contact area on the foam, especially for impacts onto kerbstone or spherical anvil, and absorbs part of the impact energy. Simulations show the internal energy history of the liner and shell of the helmet fitted on the dummy head and dropped onto a flat anvil at 7.5 *m/s* impact velocity [12]. After 15 ms, the internal energies of the two components become constant, which indicates the absorbed energy. In the example presented in [12] the energies absorbed by the liner and shell are about 83 *J* and 12 *J*, respectively. The composite shell gives a contribution to energy dissipation of 12-15%, which is a considerable portion. This result is in agreement with what reported in the literature [13].

For impacts onto flat anvils, we neglect the effect of the shell on increasing the contact surface of the foam. In addition, we assume that the shell and the liner absorb the impact sequentially. Consequently, an impact of a helmet onto a flat anvil is equivalent to the same impact at reduced velocity when the shell is removed. To calculate the reduced velocity, the energy conservation principle is employed by imposing the condition that the initial kinetic energy is equal to the energy dissipated by shell and liner:

$$\frac{1}{2}mV_0^2 = DE_{shell} + DE_{liner} \tag{3}$$

where m is the combined mass of helmet and headform, V_0 the impact velocity and DE the dissipated energy. Using the ratio of the total dissipated energy to that dissipated by the liner (α), we have:

$$\frac{1}{2}mV_0^2 = \alpha DE_{liner} \tag{4}$$

or

$$DE_{liner} = \frac{1}{2}m\left(\frac{V_0}{\sqrt{\alpha}}\right)^2 \tag{5}$$

Thus, the reduced velocity is:

$$V_{0,r} = \frac{V_0}{\sqrt{\alpha}} \tag{6}$$

In order to calculate the acceleration of the centre of gravity of the headform, we assume that the helmet and headform are one rigid body with the centre of gravity located at the centre of gravity of the headform. Using Newton's second law and substituting the force expression of equation 2, give:

$$md^2y/dt^2=2\pi RS_Y y \tag{7}$$

The earth's gravity is negligible compared to the accelerations expected in helmet drop tests; hence, it does not appear in this equation. Assuming $y(0)=0$, the solution of the differential equation (7) is:

$$y(t) = \frac{V_{0,r}}{\omega}\sin\omega t, \qquad \omega = \sqrt{\frac{2\pi RS_Y}{m}} \tag{8}$$

The derivation of the peak linear acceleration (*PLA*), the maximum force on the anvil (*MFA*) and the maximum compression of the foam (δ_{max}) is straightforward by using equations (2), (7) and (8):

$$PLA = \frac{V_{0,r}}{\sqrt{m}}\sqrt{2\pi RS_Y} \tag{9}$$

$$MFA = \sqrt{m}V_{0,r}\sqrt{2\pi RS_Y} \tag{10}$$

$$\delta_{\max} = \frac{\sqrt{m}V_{0,r}}{\sqrt{2\pi RS_Y}} \tag{11}$$

These equations are written in a way to clarify the effect of the input parameters on the impact outputs. The comparison between the helmeted headform and helmeted dummy drop tests revealed that while the helmet liner is loaded below its energy absorption capacity, the peak linear acceleration of the head is lower using the dummy, but the maximum force on the anvil and the maximum compression of the liner are greater compared to the headform drop test. Referring to equations (9), (10) and (11), the only parameter that influences the impact outputs of a helmeted headform drop test in a similar way is the mass of the falling object. In other words, these equations show that by increasing the mass of the headform, the peak linear acceleration decreases, but the maximum force on the anvil and the maximum compression of the foam increase. Since simulations show that the peak value of force and acceleration happen at the same time, an equivalent mass of the helmeted detached headform may be obtained from the following relation:

$$m_e = \frac{MFA_{dummy}}{PLA_{dummy}} \tag{12}$$

which is the ratio of the maximum force on the anvil to the peak linear acceleration of the head measured in the dummy drop test. m_e is the mass of the detached head-helmet system which should reproduce the impact conditions corresponding to the presence of the whole body. For instance, this ratio for the aforementioned dummy impact at 6 m/s is (10.7kN/144g) 7.597kg. After subtracting the helmet mass from this value, the equivalent mass of the headform will be 7.051kg which is 50% more than the dummy detached head mass.

Numerical simulations [12] reveal that whereas the difference in PLA between the case of dummy drop test and that of detached headform drop test is of the order of 30-35% for both impact speeds, the use of the equivalent mass headform in the detached headform drop test reduces such a difference to less than 10%.

5 DISCUSSION AND CONCLUSIONS

It has been shown that the presence of the whole body in helmet drop tests reduces the *PLA* but increases the *MFA* and δ_{max} when the liner does not enter the compaction zone of its characteristic stress-strain curve (zone III in figure 3); these results are similar to the experimental results reported in COST327 for the maximum impact speed of 6 m/s. However, an increase in the impact velocity from 6 m/s to 7.5 m/s revealed the catastrophic effect of the liner reaching the compaction zone on the *PLA* and *MFA* that is a phenomenon that happens when the whole body is attached to the head. These results raise doubts about standard helmet testing procedures because they employ a detached headform in drop tests.

The 1D analytical formulation showed that, if the standards have to be modified in order to make impact testing more significant for real world accidents, the mass of the headform is probably the best impact parameter to be changed. The comparison, presented in [12], between the results of virtual drop tests using a dummy and those obtained using a modified headform confirmed this assumption, as long as the *PLA*, *MFA* and δ_{max} values are concerned. The dummy, applied in this study, was a 50^{th} percentile adult male whose head is 4.8 *kg* that is similar to the 4.7 *kg* mass of the middle size ISO headform.

The value of the equivalent mass is dependent on the dummy impact configuration, i.e. the impact site and the body impact angle. Reference [12] shows the values of *PLA* and *MFA* obtained in [1] by dropping a helmeted Hybrid III pedestrian dummy at different impact configurations and velocities. Although a helmet different from that of our simulations was used in the experimental study of [1] and the dummy was in the standing posture, the calculated mass of the modified headform is close to that obtained by the FEA of the frontal impact of the present study; the mean value of the experimental results is 6.55 kg that is comparable to 7.0 kg of the present FEA work. By changing the impact configuration and body impact angle, a different value is obtained for the equivalent mass of the modified headform; nonetheless, it seems to be largely independent of the impact speed.

The effect of adopting the equivalent head mass on the *HIC* factor has not been investigated yet.

The proposal on which the authors are working is to introduce new headforms, with increased mass with respect to the existing ones, to make the standard tests more linked to real accidents and therefore increase the protective capability of safety helmets. Different equivalent mass values have to be defined to take into account different impact configurations. Statistical considerations have to indicate which accident configurations are the most common and they have to be used to define the various values of headform masses.

Having more than one headform to represent the same body mass in impact tests appears as an additional complexity which should be acceptable to helmet manufacturers in order to increase the quality of their products.

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