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Product Performance

Understanding the impact properties of polymeric sandwich structures used for motorcyclists' back protectors

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ABSTRACT

Conventional back protectors are comprised of two main parts: elastomeric foams to absorb the impact energy; and thermoplastic polymers to distribute the impact force on a wider area before the absorption process. Thermal comfort is usually maintained by vent holes within the structure. In the present work, the impact behavior of a number of samples made of materials commonly used for manufacturing such protectors was studied. Nitrile butadiene rubber as the soft layer and polyethylene thermoplastic as the hard layer were considered. The variables for the analyses were the thickness of the layers, the sample temperature and the distribution of the vent holes in the sample. The key findings are: the force distribution capability of the hard part and the stability of the impact properties with respect to temperature variations are fairly dependent on the thickness of the soft part; and a reasonable distance between two consecutive vent holes is required for achieving optimal impact protection.

1. Introduction

Motorcyclists (including moped riders) are the most vulnerable road users in terms of injury protection. ACEM, the European Association of Motorcycle Manufacturers reported the injury statistics of accidents involving 921 PTW (Powered Two Wheeler) riders and 79 PTW passengers in five European countries: France, Germany, Netherlands, Spain and Italy [1]. The statistics indicated the total number of injuries (=3417) to the PTW riders involved in the accidents as 100%. Lower extremity injuries were the most frequent (31.8%), followed by upper extremity (23.9%), head (18.4%), thorax (7.4%), spine (5%), abdomen (4.1%), pelvis (2.2%), neck (1.1%) and whole body (5.5%). It should be noted that the ‘upper’ and ‘lower’ extremities accumulate the results for multiple body parts such as shoulder, arm, forearm, wrist, hand, hip, thigh, leg, knee, ankle, and foot. Therefore, as a singular part, the spine can be considered as one of the body parts most frequently injured in motorcycle crashes. ACEM also reported the severity of the injuries in AIS (Abbreviated Injury Scale) coding system ranging from minor injuries (AIS1) to maximum injuries (AIS6). The associated graph showed that, among the 124 spinal injuries, 50% were minor (AIS1), 28% were moderate (AIS2), 5% were serious (AIS3) and 17% were severe and life-threatening (AIS3+). Hence, the protection of the spine as well as the construction of effective back protectors is of great importance.

The back protectors for motorcyclists are defined as a form of personal protective equipment (PPE). Three types of back protector are available: full, central and lower back protectors; which are designed considering the main requirements of injury biomechanics: energy absorption and distribution of the impact stress over a larger area protecting the thoracic and lumbar spine. Material selection considering the weight, ergonomics and breathability for the riders' comfort is also important in designing a protector. Based on these features, the manufacturers select energy absorbing materials for back protectors considering the requirements for more energy absorption, less weight and more ventilation in order to increase safety and also thermo-physiological comfort of the riders.

Usually, the structure of a back protector can be divided into a hard part and a soft part [2], although some back protectors have been designed with no hard part. The soft part consists of elastomers providing the viscoelastic characteristics and the hard part consists of thermosets or thermoplastics that will distribute the force to an area wider than that of the impact [3]. There are also

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some back protectors developed with special viscoelastic materials providing pseudo dilatant nature, which exhibit a hard behavior at fast response and soft behavior at slow response [4].

It is of great importance for a back protector to meet the temperature and humidity requirements. Poor heat and moisture balancing greatly reduce the probability of a back protector being used by riders [5]. In a volunteer test, the back protector with the highest level of ventilation was preferred the most [6] as the overall comfort depends more on skin moisture than on skin temperature [7]. The body temperature and moisture removal should be balanced to meet human thermal comfort [8]. Normally, vent holes are included in the protectors to satisfy the thermal comfort of the users, which result in a reduction of the material volume, and hence in an increase in thickness to avoid a reduction in the amount of absorbed energy.

Temperature dependency of mechanical properties of the materials used for the back protector is also significant. The motorcycle use is not limited to a specific time of the year. As a consequence, the protector is used at different temperatures, lower and higher, than the ambient temperature at which it has been assembled. A good protector should be thermally stable. However, temperature usually influences the deformation and energy absorption properties of polymeric materials [9].

The experimental analyses presented in this work had been conducted based on the standard for motorcyclists' back protectors EN 1621-2:2013 [10]. This study involves a considerable number of experiments and has been complemented with numerical analyses to understand the stress distribution in the samples during an impact.

The motivation of the study is to understand the impact behavior of the energy absorbing soft materials, with and without a hard part, the effects of the insertion of vent holes and those of temperature variations from the point of view of industrial manufacturers. The most important findings according to our results are:

- The temperature dependency of the soft materials used to manufacture the back protectors can reduce the protective capability in terms of impact properties. The thickness of the soft layer and the ambient conditions at which it is employed can make the performance worse than that recorded in standard tests. Therefore, it is recommendable to modify the test conditions of the ambient impact test of the standard (details in Section 4.3).
- The distribution of the vent holes has a significant impact on the performance of the protectors. Within reasonable limits, increasing the size of the holes seems preferable to increasing their number with reduced size (details in Section 4.2).

The approach of using numerical simulations in comparison with experimental results will provide an initial understanding to develop improved back protectors. Moreover, these methods and findings are also applicable to other types of impact protectors (e.g. chest, shoulder, elbow, hip and knee) for motorcycle use and for other uses such as winter sports, cycling, horse riding etc.

2. Experimental approach

2.1. Materials

Two types of sample in relation to sandwich design were used for the impact tests: the first made of nitrile butadiene rubber (NBR) only; and the second made of two layers, NBR as the soft part and polyethylene (PE) thermoplastic as the hard part. The thickness for NBR varied between 12 mm and 24 mm; and the thicknesses of PE were taken as 1 mm, 1.5 mm and 2 mm. Fig. 1 shows four pairs of different configurations of the samples used in the experiments varying the size and density of the vent holes. Firstly, the solid samples (11 × 11 cm) of NBR and PE were prepared (type 1 and type 5). Then, holes of 8 mm diameter were drilled in an 8 × 8 array in the solid samples to prepare the sample types 2 and 6. Holes of 5 mm diameter were also drilled in the solid samples in an 8 × 8 array (type 3 and type 7) in order to compare the consequence of having an equal number of holes but with different diameter. Lastly, 5 mm diameter holes were drilled in the solid samples but in a 13 × 13 array (type 4 and type 8). This had been done to understand the effect of having the same volume of void but with different distribution of the holes. The volumes of void could not be kept exactly the same in the two samples, but the approximation was considered as acceptable with ±1.5% tolerance.

The samples were conditioned for 24 h in an atmosphere with a temperature of $23 \pm 2\ ^\circ\mathrm{C}$ and a relative humidity of $50 \pm 5\%$ in order to carry out the ambient impact tests. All the samples used for the analyses of temperature effects in Section 4.3 were conditioned inside temperature and climatic chambers for 12 h.

2.2. Drop weight impact test

The impact test makes use of a dropping apparatus as shown in Fig. 2(a) according to the standard for motorcyclists' back protectors EN 1621-2:2013 [10]. The samples were placed on the test anvil (Fig. 2(b)) and hit by a kerbstone bar impactor (Fig. 2(c)). The anvil and the kerbstone are made of polished steel. The mass of the impactor and guided mass was 5000 ± 5 g and its kinetic energy on impact was 50 ± 1.5 J.

The force transmitted through the sample is the resultant force recorded by a load cell placed inside the anvil. The performance levels (Average $F_{\mathrm{transmitted}} \leq 18$ kN for level 1 and average $F_{\mathrm{transmitted}} \leq 9$ kN for level 2 [10]) of a back protector are defined based on this resultant force. Three impacts on each sample configuration were conducted to indicate consistency of the results. Each peak-transmitted force presented in this paper was estimated as the average of the three impacts. The impacts, producing level 1 and 2 performance (≤ 18 kN), were more consistent than those providing impact forces above 18 kN. The standard deviation of ±0.5 kN for the resultant forces below or equal to 18 kN and standard deviation of ±1 kN for those above 18 kN were considered as acceptable. The error was calculated as [(|value of individual impact − average value|/average value) × 100]. An average of all the errors (a total number of 207 impacts), calculated for all the data presented in this paper, is 2.2%, where the maximum errors are 7.8% for the results below or equal to 18 kN and 4.5% for the results above 18 kN.

3. Numerical method

A number of simulations of the drop weight impact test were carried out using the finite element solver LS-DYNA® to better understand the stress distribution in the different samples. Fig. 3 illustrates the numerical model of the drop weight impact test, which includes four different parts: kerbstone impactor, hard and soft parts of the sample, and anvil.

Eight-node brick elements were used to model the kerbstone impactor and four-node quadrilateral shell elements were used to model the anvil. The apparatus (both impactor and anvil) was modeled using the material model MAT020_rigid available in LS-DYNA material library [11], where the deformation has been neglected as the Young's modulus of steel is much larger than that of the sample materials.

The hard PE was modeled with four-node quadrilateral shell