Impact Loading Performance Investigation of An Open-face Motorcycle Helmet with Hole in Inner Liner

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Abstract. Modification of a motorcycle helmet has been performed by inserting an electronic device in the helmet's inner liner. Therefore, a hole requires to be made to place the device. This study aims to analyze the impact loading performance of a motorcycle helmet due to an impact from the top, rear, and side. The investigation of stress distribution and acceleration experienced by the helmet is analyzed by utilizing finite element method simulation. The results indicate that the hole position is not in the impact area. The outer shell experiences higher stress than the inner liner in all testing conditions. The rear impact causes the highest value of the outer shell stress, where for the inner liner, the side impact contributes to the maximum value of the stress. Headform linear acceleration reaches the peak than is higher than the basic requirements of the helmet testing standard.

1. Introduction

Development, optimization, and improvement are continuously performed as the evolving trend of technology in transportation. A number of helmet innovations, such as a smart helmet for the readiness of motorcyclist [1], future helmet concept [2], additional helmet function for mobile phone power source [3], and internet integration concept in helmet [4] have been already developed. This research was conducted to develop an integrated electronic device in a helmet for riding assistance for the motorcyclist that is integrated into the helmet. Due to the need for an electronic device placed inside the helmet, a decision to mount an additional electronic device has been opted to be put inside the inner liner. As such, it is necessary to remove some material in the inner liner to integrate the equipment. It is also compulsory to have a helmet that is still safe for the motorcyclist and pass the helmet testing regulation standard. Therefore, a simulation to predict the helmet response against an impact requires to be conducted.

The dynamic response of a helmet varies depending on the impact velocity, material properties of the outer shell, and energy-absorbing liner [5]. Therefore, accurate modeling and testing of a helmet as both a protective system and the head is required [6]. In fact, the main cause of mortality due to head injuries causes by road accidents. The function of a helmet as a protective system for a motorcyclist is then highly essential. The effectiveness of helmet utilization [7] and new methodology to improve helmet performance against an impact [8] have been deeply investigated. Some other research reports are performing a simulation regarding an impact condition on the motorcycle helmet. Since motorcycle
helmets, almost all of the time, impacts the road surface in an oblique position [9], the finite element analysis tests on motorcycle helmet has been performed to analyze the impact behavior on a full-face helmet obliquely [10]. The conclusion has been made that the most appropriate way to reduce the head rotational acceleration is by decreasing the linear acceleration threshold experienced by the head. The impact energy of a helmet is also affected by the temperature of helmet use [11]. The variation of the working temperature of the helmet affects the impact energy absorbing. Moreover, the influence of environmental factors can also cause a different result of helmet impact absorption [12]. The mentioned environmental factors are hot-wet and pre-compression of the material of the helmet. The helmet motorcycle is subjected to the impact when the motorcyclist has undergone an accident and gets impacted on the road. The phenomenon could also be different if there is an impact of an object to the head [13]. The finite element method is widely used to estimate the impact energy absorbing of a helmet [13], [10], [14], [15]. The study on modification of the inner liner of the helmet has also been investigated by other researchers. The study includes the additional ventilation on helmet [16], [17]. Protecting the motorcyclist is then the first priority for the helmet to function. The helmet testing standard becomes the only method to determine whether the helmet is already standardized for a motorcyclist to use or not after performing the innovation of the helmet in question.

The first aim of the study was to estimate the head acceleration when the helmet is experiencing the drop test. Three drop conditions were adopted to simulate the impact from the top, rear and side of the helmet [18]. The second aim investigates the impact response of the helmet in terms of the stress distribution of each main element of the helmet, which are the outer shell and the inner liner. The identification requires to be performed since the helmet has a hole to place an electronic device. The helmet is intended to still satisfactory to sell to the market. Therefore, this identification is a preliminary analysis of whether the helmet is acceptable for the local impact test of a helmet prior to the mass production from the local standard testing requirements.

2. Material and Method

2.1. Electronic device integration in helmet

The helmet is designed for innovation to attach an additional electronic device for riding assistance. Therefore, it is necessary to attach an electronic device by still keeping the appearance of the helmet to become a normal-looking helmet as the ones have been in the market. The decision is to keep the electronic part internally attached to the inner liner of the helmet. Figure 1 (e) shows the location of the hole in which the electronic device is mounted. The location choice considers the lowest potential location for a helmet to endure an impact on an accident [9]. Since the electronic device is integrated into the inner liner, the outer shell (Figure 1 (a)) is then covering the inner liner to protect the electronic device. The main helmet construction consists of an outer shell, inner liner (Figure 1 c) with an electronic device (Figure 1 b) integrated into it, and the headform (Figure 1 (d)) representing the human’s head.

![Figure 1](image)

2.2. Finite Element Models
The helmet model involving in the study consists of the outer shell, inner liner, and headform, as shown in Figure 1. In this case, the comfort/fit padding that is usually placed between the head and inner liner is removed from the simulation for simplification. Moreover, the absence of the cheek pad, the helmet component that is mounted in the area of the cheek, is also excluded from the simulation. A similar model approach has also been employed by other researchers [16], [19]. The outer shell of the helmet uses glass (fiber) reinforced plastic that is commonly employed for a motorcycle helmet. The inner liner uses expanded polystyrene material for the main component to absorb the impact of the helmet collision. The human head is represented by the head-shaped material having the material properties in Table 1. During the impact simulation, a flat anvil is represented by structural steel as described in Table 1.

Table 1. Material properties of helmet components [10].

| Helmet component | Density [kg/m³] | Young's modulus [MPa] | Poisson ratio |
|------------------|-----------------|------------------------|--------------|
| Outer shell – Glass (fiber) Reinforced Plastic (GRP) | 1830 | 8000 | 0.1 |
| Inner liner – Expanded Polystyrene (EPS) | 59 | 19 | 0.1 |
| Headform | 1800 | 45000 | 0.35 |
| Flat anvil – Structural steel | 7850 | $2 \times 10^5$ | 0.3 |

2.3. Contact conditions
The definition of the physician contact condition for each surface of the helmet component needs to be described in the simulation. The contact condition between the headform and the inner liner is employing frictional contact with 0.3 friction coefficient [16]. Instead, the contact between the outer shell and inner liner adopts a bonded contact type. This contact condition has opted since the inner liner and outer shell is connected to each other in the real situation.

2.4. Impact test method
The testing method adopted in this study is based on the testing standard provided by Standard National Indonesia helmet testing [18]. The drop test against a flat anvil is employed in this study. The helmet is dropped from a height of 1.6 m. This condition implies that when the helmet is reaching the flat anvil, the velocity of the helmet is 5.6 m/s. Three drop position has been chosen for the test. Firstly, the drop test representing the impact from the top part of the helmet is conducted as depicted in figure 2 (a). Rear impact and side-impact are also conducted to simulate the impact loading from the back and the side of the helmet, as depicted in Figure 2 (b) and (c), respectively.

![Figure 2](image)

Figure 2. Drop condition representing the impact from the top (a), rear (b) and side impact (c).

3. Result and Discussion

3.1. Stress
Figure 3 shows the maximum stress of the helmet outer shell and the inner liner with the impact from the top. Comparing both results indicate that the stress endured by the outer shell of the helmet is far higher than the stress of the inner liner. It is quite distinctive that the stress of the outer shell is located in the area where the surface is in contact with the flat anvil. The maximum stress value of the outer shell is approximately 125 MPa. The pattern is concentrated in contact point and getting lower outer
wards. On the other hand, the resulting stress due to the top impact of the inner shell is merely about 7.1 MPa. However, the peak stress location is not located at the point of the contact area. The maximum stress, instead, is located in one of the sides of the hole where the electronic device is mounted, as depicted in Figure 3 (b).

Instead, Figure 4 depicts the maximum stress of the helmet component during the rear impact. Approximately 272 MPa of stress is undergone by the outer shell of the helmet and concentrated in the area of the impact point. Figure 4 (b) shows the maximum stress of the inner liner during the rear impact. As compared to the outer shell, the inner liner has the maximum stress in the area where the headform is touching the inner liner. The location is on the edge of the electronic device mount place. However, this result could be an evaluation for the researchers to revise the shape of the edge, so that the stress concentration is not critical in the area of the edge of the hole. This is reasonable since the shape of the headform is the same as the outer surface of the inner liner in contact with headform.

The stress due to side impact is represented by Figure 5 (a) and (b). The different results, as compared to the previous study, indicate that the side impact causes stress that is not concentrated relatively at one point. Yet, the high value of stress also occurs in the front part of the shell edge. The construction and geometry of the outer shell highly affect the results. The maximum results of the stress yield the point of approximately 110 MPa. Side impact causes the left or right side of the helmet where the cheek pad is missing to be potentially affected by the side impact. It yields in the bending loading to the outer shell in that area. The inner liner experiences the stress near the cheek of the motorcyclist. These results indicate that the presence of a cheek pad is necessary for absorbing the side impact of a motorcycle helmet. Based on the result of the inner liner, the stress is located in the lower part of the inner liner where the cheek pad should be present. Hence, the side impact causes the inner liner to have 19 MPa of stress.

Figure 3. Maximum stress experienced by the outer shell and inner liner from top impact test [MPa].

Figure 4. Maximum stress experienced by the outer shell and inner liner from rear impact test [MPa].
The impact simulation was conducted for 8 ms of the impact time in total, consisting of about 2 ms the floating time, and the rest is the impact and rebound time. Figure 1 and 2 presents the change of stress during the helmet impact in three impact positions. The peak impact stress of the inner liner occurs differently among the three impact conditions. The rear impact causes the stress of inner liner at just the beginning of the time when the helmet is touching the flat anvil, reaching about 5 MPa of stress and going down approaching zero stress. However, the stress slightly increases afterward until the end of the simulation. However, the stress due to the top impact reaches the peak at the time of 5 ms, which is rather later compared to the rear impact and decrease as the time goes. The most prominent result of the stress occurs due to a side impact that reaches a maximum nearly four times higher than rear impact results. The peak of the stress occurs at the time of approximately 6.5 ms.

The maximum value of the stress on the outer shell is nearly more than twenty-four times higher than the inner liner. The peak of stress is caused by the rear impact with the value of more than 250 MPa. However, the resulting stress due to top and side-impact is rather similar. The value is approximately half of the stress value of the rear impact. That stress peak occurs nearly at a similar time during the simulation, which happens at between 3 ms to 4 ms. All three results go down after reaching the peak and return back approaching zero value, as depicted in Figure 3.
3.2. Acceleration
This is essential to measure the headform acceleration since it represents the head's acceleration during the impact. This linear acceleration describes the translational motion of the head, which in this case, is represented by headform. This measurement is currently the common variable utilized for a helmet certification [2], [20], [21]. The results of the impact acceleration may determine whether the helmet is safe enough to be utilized by motorcycle or not. The comparison to the requirements of helmet testing standards is also presented. The lowest value of acceleration is resulted by the side impact. It reaches about more than 300 g. However, the impact duration of more than 300 g is less than 1 ms. Instead, the highest value of the acceleration occurs when the helmet is dropped at the rear part of the outer shell. It is rather fluctuating from 350 g, return to less than 100 g and surge up to nearly 600 g. A similar result can be seen from the top impact loading condition. The peak of the acceleration is more than 500 g. This value is considered enormously high as compared to the helmet testing standard requirements. The prediction of a skull fracture also uses the value of acceleration as the measurement variable. The most common magnitude of this acceleration is between 200 and 300 g [2], [22], [23], [24]. Table 2 shows the standard acceleration requirements from four different helmet testing organization. The higher results of the simulation hypothetically due to the absence of the comfort/fit padding that has the softer material. The comfort padding is attached in the inner liner to separate between the inner liner material and the headform. The inner liner material also determines to reduce head acceleration and impact protection performance [19]. The opt for the most appropriate inner liner material would be beneficial to have a reduction in the headform acceleration during the impact.

More importantly, side impact results are also higher than what is expected. The absence of a cheek pad of the helmet needs to be taken into account to criticize the results. The cheek pad material has a material that is far softer than the inner liner that could probably reduce the peak acceleration from the side impact. There is actually a suggestion saying that the outer shell made from composite can decrease the peak acceleration when the head against an impact load [14]. However, the composite helmet needs to be justified regarding the cost of the helmet, as opposed to the helmet made from the thermoplastic shell [25]. The study on other shell helmet materials is also studied as to improve the impact absorption capability of the helmet [14].

Figure 7. Maximum stress on the outer shell of the helmet.
Figure 8: Headform acceleration during all impact conditions.

Table 2. Basic requirements of motorcycle helmet safety standards [26], [18], [27], [28]

| Standard     | ECE R22.05 | Snell M2020 | DOT FMVSS 218 | SNI     |
|--------------|------------|-------------|----------------|---------|
| Allowed impact duration | N/A        | N/A         | 150 G for no more than 4 ms and 200 G for no more than 2 ms | N/A     |
| Allowed peak acceleration | 275 G      | 300 G       | 400 G          | 300 G   |

4. Conclusion
The hole position is not in the impact area of the testing conditions. The location choice is based on the minimum potential of the helmet having contact during the accident. The outer shell of the helmet experiences higher stress value than the inner liner in all testing conditions. The rear impact results in the highest value of the stress of the outer shell. Instead, the inner liner stress distribution is lower than the outer shell in all three testing conditions, and the highest value is during a side impact. The headform acceleration is higher than all mentioned testing standards for both peak acceleration and impact duration. The future works is planned to conduct an impact test simulation with the presence of all helmet component, including the cheek pad and comfort padding. The oblique impact condition is also potentially to perform. The higher results of headform acceleration lead to the study of the effect of different material properties to the maximum acceleration of headform.

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