Using High-Speed Cineradiography to Access Bicycle Helmet Internal Strain During Head Impacts: A Proof of Concept

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I. INTRODUCTION

Traumatic brain injury remains a major public health issue, particularly in sports and urban mobility accidents involving two-wheelers. Helmets play a critical role in mitigating head injuries by absorbing impact energy and reducing the linear accelerations transmitted to the head [1]. Current helmet certification procedures, such as those defined in standards like EN1078 [2], rely on drop tests in which global kinematic quantities (e.g., peak head acceleration or impact force) are used as primary performance criteria [3]. While these standardized approaches provide a robust framework for helmet certification, they are limited to global measurements and do not provide direct information on the internal mechanical response of the helmet liner during impact. As a result, the local deformation mechanisms governing energy absorption, such as foam densification or bottoming-out phenomena, remain insufficiently characterized, limiting the ability to optimize liner materials and geometries. Recent work has demonstrated the feasibility of measuring internal helmet strain using high-speed X-ray imaging and embedded markers [4]. Building on this concept, this study extends the methodology to bicycle helmets under standardized impact conditions, introduces a modified marker insertion strategy to improve marker stability and includes a dedicated comparison with control (non-instrumented) helmets to verify that the instrumentation does not significantly alter the global mechanical response.

II. METHODS

A commercially available cyclist helmet was instrumented to enable internal strain measurement during impact. The liner was sectioned along the midsagittal plane. One half was then drilled at predefined locations using a 1.5 mm drill bit to a depth of 1.5 mm to allow the press-fit insertion of 2 mm diameter spherical steel beads, ensuring secure fixation within the foam without the use of adhesive. The beads were arranged in three staggered rows within the midsagittal plane: a central row and two outer rows located near the liner extremities (Fig. 1. A). Beads in the outer rows were arranged in pairs aligned along radial directions originating from the headform center. Beads in the central row were positioned between these axes to avoid overlap with the outer bead pairs. The central row was designed to quantify in-plane strain along directions tangential to the headform surface, while the outer rows enabled measurement of compressive strain along radial directions normal to the headform surface. After bead placement, the two liner halves were aligned and reinserted back into the intact outer shell to preserve the original helmet geometry keeping the symmetry. The liner was secured in place using the residual adhesive within the shell. Impact tests were conducted following the EN 1078 European standards using a metallic EN 960 headform [3][5]. Impacts were performed at the vertex (top of the helmet) at 5.8 m/s. The helmeted headform was instrumented with a 3-axis cable-free accelerometer (DTS, TSR PRO, 10 kHz, ±250 g). A force sensor was integrated into the impact surface to monitor contact forces. A high-speed cineradiography system (OEC® 9900 Elite, GE Healthcare) modified to incorporate a high-speed camera (Phantom Miro C211, 2000 Hz) was used to capture the displacement of the internal steel beads during impact. The imaging system provided planar visualization of the midsagittal section, enabling time-resolved tracking of bead displacements. The metallic beads were tracked using a custom image-processing algorithm based on blob detection and frame-to-frame tracking. Bead positions were identified using intensity-based detection, and their trajectories were reconstructed over time using a predictive assignment approach to ensure consistent tracking throughout the impact event. Engineering strain was computed from the relative displacement between adjacent beads. For each bead pair, strain was calculated as "$\varepsilon_e = (L(t) - L_0)/ L_0$" where L_0 is the initial distance between beads and $L(t)$ is the instantaneous distance during impact.

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III. INITIAL FINDINGS

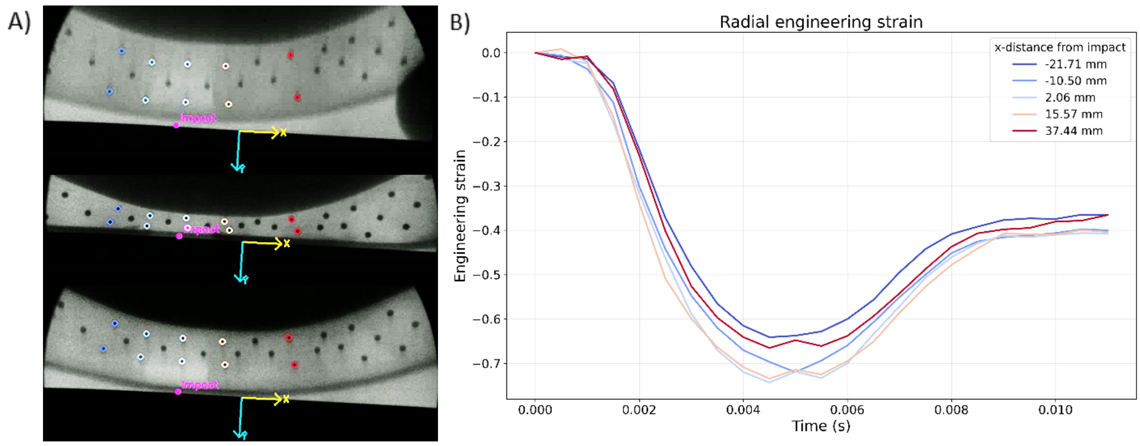

Fig. 1. A) Tracked bead pairs before, during and after impact. B) Engineering strain values measured in the vicinity of the impact point.

A total of 10 helmets were impacted, including 5 instrumented helmets and 5 control helmets. The peak impact force, peak headform acceleration and HIC values were evaluated for both helmets. For the control configuration, the average peak impact force was 13.1 ± 0.3 kN, while the instrumented configuration showed an average peak force of 13.1 ± 0.1 kN. The average peak headform acceleration was 229.0 ± 3.7 g for the control helmet and 228.0 ± 4.6 g for the instrumented helmet. The average HIC value of the headform acceleration was 1842 ± 43 for the control helmet and 1803 ± 55 for the instrumented helmet. The relative differences between the control and instrumented configurations were 0.2% for peak impact force, 0.3% for peak headform acceleration and 2% for the HIC values. In the instrumented helmets, engineering strain values were extracted in the vicinity of the impact point along the radial direction in the midsagittal plane (Fig. 1. B). At the impact location, the average peak compressive radial strain was 0.74 ± 0.03, while it was 0.60 ± 0.04 at a distance of 25 mm from the impact point. The plastic deformation after the impact was 0.40 ± 0.01, indicating significant irreversible deformation of the liner in the impacted region.

IV. DISCUSSION

The relative differences observed between the control and instrumented helmet configurations remained below 2% for the global response quantities, including peak impact force, headform acceleration, and HIC. These results indicate that the bead placement process used to enable internal measurements does not significantly change the global characteristics of the helmet, supporting the validity of the proposed experimental approach. The steel beads are denser than the foam and could have biased strain measurements if they moved independently within the liner. However, the added mass was only 0.6%, no tearing or local foam damage was observed and bead displacement remained synchronized with head motion, suggesting that the beads adequately represented the local foam displacement. The methodology demonstrated robust tracking of internal bead displacement throughout the entire impact event, with continuous displacement histories obtained for all markers without loss of visibility. This confirms the feasibility of capturing internal kinematics within the helmet liner under dynamic loading conditions. The ability to extract spatially resolved strain histories provides new insight into the deformation mechanisms governing helmet energy absorption. The current implementation is limited to partial strain information based on bead pair distances. Future work will focus on extending the methodology toward full strain tensor reconstruction. This methodology, combined with conventional experimental approaches, has potential applications in advanced helmet protection assessment, the development and validation of more realistic finite element helmet models and helmet design optimization.

V. REFERENCES AND ACKNOWLEDGMENTS

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