SHORT COMMUNICATION: STAPP CAR CRASH CONFERENCE

Validation of impact-absorbing pavement under head oblique impacts

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ABSTRACT – Head injuries are an increasing public health concern. Although motor-vehicle injuries have steadily declined in Sweden, casualties among vulnerable road users (VRUs) continue to rise. Inspired by playground surfaces, impact-absorbing pavement (IAP) has been developed to enhance public safety, mitigate injury severity, and promote sustainable reuse of end-of-life tires. This study developed and validated a finite element (FE) model of IAP to evaluate head response during oblique impact. Compression tests at multiple strain rates and 45° oblique impact tests using a Hybrid III headform were conducted. Simulations showed strong agreement with experimental peak angular velocity (PAV) while the peak linear acceleration (PLA) was overestimated. Under the constraints of lab setup, small-scale IAP samples exhibited promising head protection, and a further 10% reduction in PLA with increased diameter indicates that IAP could provide better head protection under real-world conditions.

INTRODUCTION

Traumatic brain injury (TBI) remains a growing public health challenge worldwide. Although motor vehicle injuries have steadily declined in Sweden, the number of injuries and fatalities among vulnerable road users (VRUs) continues to rise (Hurtig et al., 2023). These trends underscore the need for more effective protective measures for VURs who are highly exposed to severe injury in traffic environment.

Currently, most road surfaces are constructed from stiff asphalt, which provides little protection for VRU during impact. Inspired by playground surfaces, impact-absorbing pavement (IAP) has been developed by incorporating rubber granules from recycled tires into asphalt mixtures (Makoundou et al., 2023). IAP integrates a high content of crumb rubber and retains a mineral aggregate skeleton, balancing impact absorption with structural integrity. This approach aligns with urban safety and sustainability goals, encouraging active mobility while reducing VRU injury risk (Makoundou et al., 2025).

Despite its potential, IAP is still experimental. There is also a lack of a finite element (FE) model of the IAP material to systematically evaluate its protective performance. Real-world oblique cyclist head impacts are more complex than the current surfaces test standard which involves flat surface and evaluates critical fall height for radial impact. Previous experimental studies (Makoundou et al., 2025) demonstrated that IAP can achieve head protection comparable to helmets under oblique impacts according to multiple brain injury metrics. However, those samples were constrained by laboratory conditions, fixed in a small C-shaped holder that limited shear and boundary deformation. This raises an important question: can such small samples tested under controlled laboratory conditions reliably represent the head protection performance of IAP in real-world scenarios?

Therefore, this study aims to address this gap through three objectives: (1) to validate the FE model of IAP under oblique impact; (2) to examine the influence of sample diameter and friction beyond experimental limitations; and (3) to explore the potential of IAP in enhancing head protection performance and provide insights for future optimization.

METHODS

Impact-absorbing pavement material

The IAP samples were provided by the University of Bologna, Italy. Details of the material and manufacturing process are reported in previous studies (Makoundou et al., 2023).

***Figure 1**. The impact-absorbing pavement material components and the samples.*

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In brief, the mixture comprises 56% rubber particles by volume (with particle size under 4 mm), 22% aggregate and filler, 21% SBS-modified bitumen emulsion, and 1% cement acting as an emulsion breaking agent (see Figure 1).

Compression tests

Uniaxial compression tests were performed using an Instron ElectroPuls E3000 testing instrument at three strain rates: 0.01/s, 1/s, and 10/s (Venturucci, 2020). Three replicates were planned for each strain rate condition. The samples were prepared with a diameter of 38 mm and a thickness of 44 ± 2 mm. The average stress-strain responses are summarized in Figure 2.

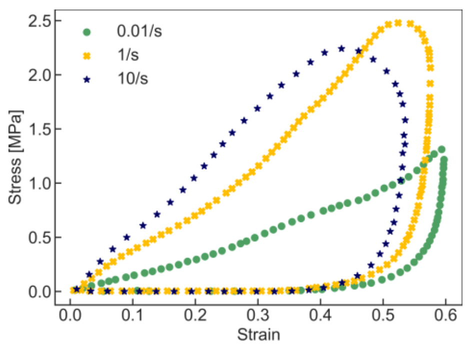

Figure 2. *Mean stress-strain curves of IAP under three strain rates (0.01 /s, 1 /s and 10 /s) compression tests.*

Oblique drop tests

The oblique test setup contains an aluminum column, a fixed concrete base, a 45° angled anvil, and a Hybrid III (HIII) headform. The headform was placed on a free-falling trolley. Details of the setup can be found in the previous study (Fahlstedt et al., 2021). The IAP were modeled as cylindrical samples with a diameter of 100 mm and a thickness of 46 mm and were fixed on the angled anvil by a C-shaped holder. The bare headform was dropped from a height of 205 cm (6.0 m/s) at three directions (X/Y/Zrot, see Figure 3).

The HIII FE model was used in simulations. The IAP sample was modeled as the same thickness of 46 mm, oriented at a 45° angle, and constrained its lower boundaries via a C-shaped holder. The IAP was modeled using MAT_SIMPLIFIED_RUBBER, with a density of 1.4 g/cm^3, a Poisson's ratio of 0.35, and hysteretic parameters (HU and SHAPE) of 0.01 and 5, respectively. In addition, the stress-strain curves under three strain rates were defined based on the compression data.

The coefficient of friction between headform and the IAP surface was initially set as 0.5. The kinematics were recorded at the center of gravity (CG) of the headform model. All simulations lasted the same duration as the input kinematics (30 ms) and were conducted using an explicit dynamic solving method (LS-DYNA, r13).

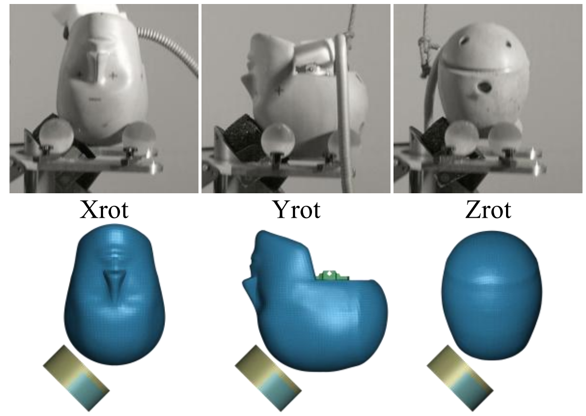

Figure 3. *High-speed video and finite element simulation of HIII head oblique impacts at three directions (X/Y/Zrot).*

RESULTS

A comparison of experimental and simulated kinematic responses at headform CG is presented in **Figure 4**.Overall, the simulations overestimated the linear acceleration in all impact directions, with the resultant peak linear acceleration (PLA) values differing by 48%, 23%, and 26% for X/Y/Zrot, respectively. Rotational kinematics were more closely matched, the resultant peak angular velocity (PAV) differed by 7%, 34%, and –15% for X/Y/Zrot, respectively.

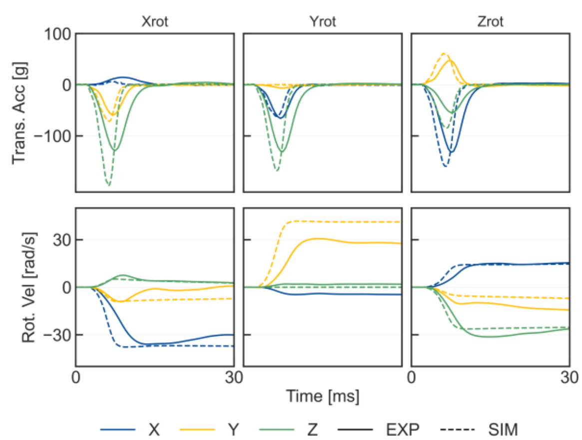

Figure 4. *Linear and rotational kinematics of headform in the drop oblique tests at three directions (X/Y/Zrot).*

Figure 5 illustrates the effect of IAP sample diameter on peak kinematic responses. The resultant PLA in the simulations remained largely constant across different sample diameters but was overestimated by approximately 30-40% compared with experiments. However, as the diameter increased, the errors in the

X/Y/Zrot impact decreased by around 10%. In contrast, the resultant PAV showed errors within 10% relative to the experiments and exhibited minimal variation with increasing diameter.

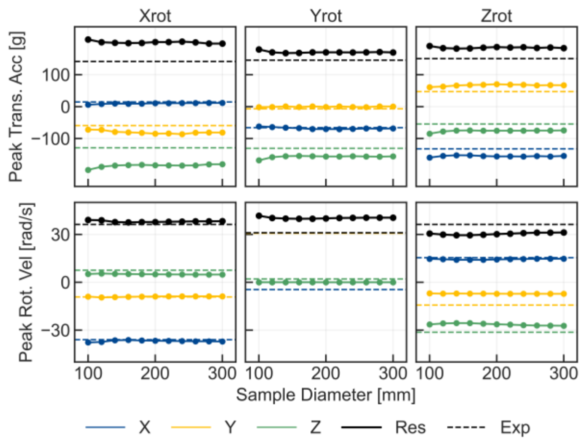

Figure 5. *Effect of IAP sample diameter on peak kinematics for head oblique impacts at X, Y, and Zrot.*

Figure 6 illustrates the effect of the coefficient of friction (COF) between headform and IAP. As the COF decreased, the errors in the resultant PLA were reduced by approximately 20–30% compared with the experimental results. The rotational kinematics were more sensitive: the X/Yrot impacts significantly affected related PAV components (X/Y branches), while the other two components were almost unaffected. For Zrot impacts, low-friction conditions even induced rotational reversal.

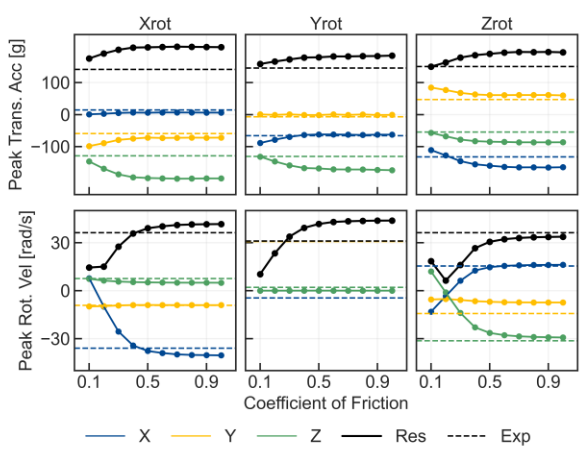

Figure 6. *Effect of friction between IAP sample and headform on peak kinematics at X, Y, and Zrot.*

DISCUSSION

This study developed and validated a FE model of impact-absorbing pavement, with a specific focus on its head protective performance under oblique impacts at 6 m/s. Comparisons between experimental and simulated kinematics showed strong agreement in rotational kinematics across all three directions under the oblique impact conditions. However, the linear acceleration was overestimated, indicating a need for model improvements such as the head-pavement interface and bio-fidelity of the HIII headform.

The validated model overcomes key limitations of prior IAP oblique-impact experiments, which were restricted to small samples by the free-fall trolley geometry. This restriction limited IAP shear deformation and edge effects. Parametric simulations show that edge effects have a small influence on PLA (around 10%) while friction significantly affects PAV. The observation of friction is consistent with prior studies showing that surface friction strongly influences rotational kinematics during oblique head impacts. For example, Trotta et al. (2018) reported that lower friction conditions between the head and helmet attenuate rotational acceleration and thereby reduce the likelihood of brain injury. Considering the pavement is built on large surfaces so the demonstration of the size and friction influence should be verified also on site.

Several limitations should be noted. First, only one impact condition was considered, which may not encompass the full range of real-world impacts. Second, the bio-fidelity (material, inertial and friction) of the headform is limited, which may affect the head kinematics. Third, modeling the rubberized asphalt as a homogeneous material neglects its composite nature, which influences mechanical behavior. Future work is required for systematic evaluation.

CONCLUSION

This study modeled and validated the FE model of IAP. Simulations showed strong agreement with experimental PAV, while the PLA was overestimated. Under the constraints of laboratory testing, small-scale IAP samples exhibited promising head protection performance, and a further 10% reduction in PLA with increased diameter indicates that IAP could provide better head protection under real-world conditions. It also demonstrated that IAP has significant potential to reduce head injuries among VRUs and contribute to a safer traffic environment.

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