ENHANCING HELMET SAFETY: DEVELOPMENT OF A NOVEL TANGENTIAL IMPACT ABSORPTION SYSTEM USING SHEAR THICKENING FLUIDS.

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ABSTRACT

Rotational accelerations in head impacts are critical contributors to traumatic brain injuries (TBIs) and concussions, driving advancements in helmet safety standards. Current anti-rotational systems, such as MIPS and 6D Helmets, predominantly use mechanical sliding layers to mitigate rotational forces, yet their integration into helmet structures limits the ability to isolate and test these systems. This study introduces O-DAMP, an innovative anti-rotational system based on non-Newtonian fluids, designed to assess and dissipate tangential impact forces. Utilizing polyborodimethylsiloxane (PBDMS) as a shear-thickening non-Newtonian fluid, we investigated its performance with a dedicated tangential impact comparator, which simulates tangential forces separate from orthogonal components at the helmet interface.

Through repeated impact tests, we evaluated six candidate fluids, determining which one exhibited optimal energy dissipation, based on its peak and initial force characteristics. Additional linear impact tests on helmet segments confirmed that the integration of the O-DAMP system did not compromise the helmet's compliance with regulatory standards. The O-DAMP system showed improved energy absorption, particularly under concentrated impact scenarios, such as with hemispherical and kerb anvils. These findings suggest that non-Newtonian fluid-based systems like O-DAMP offer a promising pathway to enhancing helmet safety in tangential impact scenarios, with potential applications across various helmeted activities.

1. INTRODUCTION

Rotational accelerations in head impacts have been a significant focus of research due to their association with traumatic brain injuries (TBIs) and concussions [1] [4]. Various safety regulations have emerged in response, aimed at addressing these hazardous forces in helmet designs. Standards such as the Fédération Internationale de Motocyclisme (FIM) [5] and the more recent ECE 22.06 have incorporated oblique impact tests, which account for rotational forces during crashes.

Tangential impacts, distinct from direct linear impacts, are the primary source of rotational accelerations. These impacts generate forces that current helmet safety system may not effectively mitigate. While several anti-rotational systems like MIPS [6] (Multi-directional Impact Protection System) and 6D Helmets [7] have been developed, they predominantly rely on mechanical sliding layers or similar mechanisms to reduce rotational forces. However, these systems are integrated into complete helmet setups, limiting the ability to test the anti-rotational capabilities in isolation from the helmet structure.

In this study, we propose an innovative approach that eliminates the need for full helmet integration during testing. By isolating the anti-rotational mechanism, our goal is to evaluate the system’s effectiveness independently of the helmet's design or material composition. Furthermore, we introduce a novel anti-rotational solution, O-DAMP, which leverages non-Newtonian fluids to dissipate tangential energy. Unlike conventional materials, non-Newtonian fluids exhibit properties that allow for energy dissipation under variable stress conditions [3], making them highly suitable for managing the forces generated by tangential impacts [8].

2. MATERIALS AND METHODS

2.1 Non-Newtonian Fluids

For our study, we explored several non-Newtonian fluids to identify the best candidate for impact attenuation. Our primary fluid of interest was polyborodimethylsiloxane (PBDMS), synthesized using a hydroxy-terminated polydimethylsiloxane (PDMS) precursor and boric acid. This fluid exhibits shear-thickening behavior, meaning its viscosity increases under stress, which is essential for impact absorption. The rheological properties of PBDMS were characterized using an Anton Paar EC-Twist 502 rheometer, performing frequency-sweep tests to assess its viscosity under different shear conditions. In addition to PBDMS, we tested commercially available non-Newtonian fluids, such as both shear-thinning and shear-thickening silicone gels, comparing their performance to PBDMS to identify the most effective fluid for our application. The evaluation criteria focused on viscosity variation under shear, energy dissipation capacity, and compatibility with the O-DAMP system structure.

2.2 O-DAMP System Configuration

The O-DAMP system is a novel anti-rotational mechanism designed to reduce rotational accelerations caused by tangential impacts. Mechanically, it consists of a fluid-based module placed between layers of Expanded Polystyrene (EPS) foam within the helmet. The system leverages the unique properties of non-Newtonian fluids, which increase their viscosity under stress, providing enhanced energy dissipation during impacts. In a previous article, an initial version of the O-Damp system was presented [2]. The updated configuration introduced in this study builds upon previous designs by improving fluid containment and optimizing the mechanical interaction between the fluid and the surrounding materials. The O-DAMP module is composed of sealed chambers filled with non-Newtonian fluid, strategically placed to optimize rotational energy dissipation without compromising the helmet's structural integrity. This design ensures that the fluid can move freely during impacts, while the increasing viscosity of the fluid under stress helps to absorb the energy from tangential impacts more effectively.

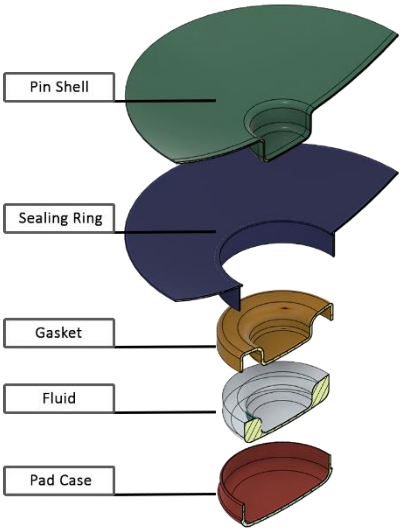


Figure 1 *O-Damp system components*

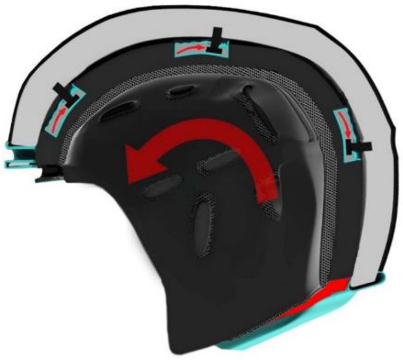


Figure 2 *Movement of the pins in the fluid*

2.3 Tangential Impact Comparator

To accurately assess the performance of various fluids in dissipating tangential impact forces, we developed a custom tangential impact comparator [fig.3.a]. The core idea behind this system is to conceptually and practically separate the orthogonal and tangential components of the force generated at the interface between the helmet and the impact surface during a tangential impact. The system is designed to replicate only the tangential force component, focusing on a specific localized area of the helmet.

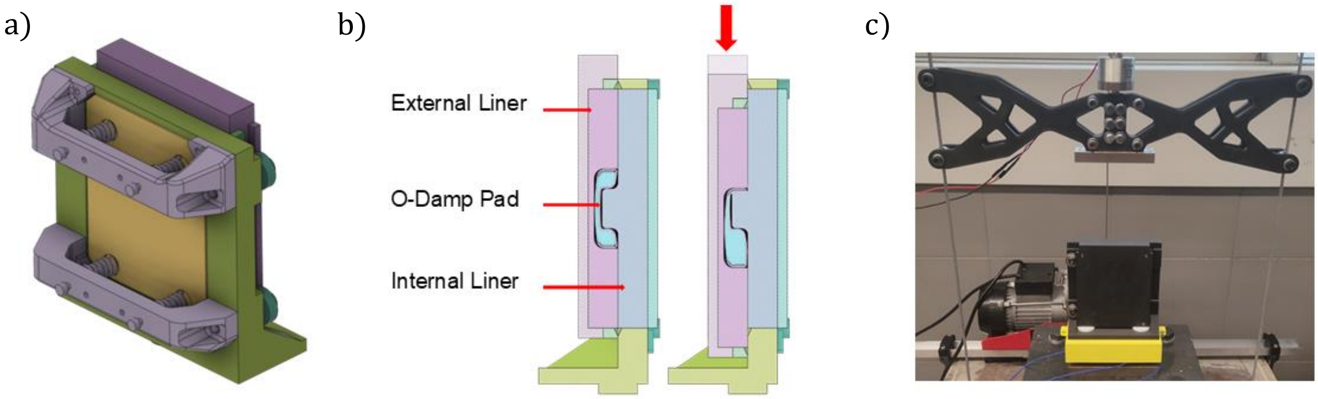


Figure 3 *a) Assonometric view of the comparator device. b) Section of the inner of the device in which is possible to view the PAD between the liners. c) Dropweight machine test setup*

All anti-rotational systems function through relative sliding between elements. Our approach isolates this sliding interface and subjects it to the tangential energy portion from the helmet's impact. The tangential force is replicated and simplified as a linear component by considering the curvature of the helmet at that point as having an infinite radius, allowing us to work with flat surfaces. Upon impact, the two surfaces are forced to slide against each other using a drop tower setup. The anti-rotational device is placed between the sliding elements [fig.3.b], and a system of load cells measures the force transmitted downstream of the device [fig.3.c]. This setup enables us to determine which fluid or anti-rotational device dissipates the most energy.

2.3.1 Fluid study

The study aimed to evaluate the performance of different non-Newtonian fluids integrated into the O-DAMP system, focusing on their ability to dissipate energy during tangential impacts. For this purpose, a drop tower setup was employed, built in compliance with the ECE 22.06 regulatory standards for helmet impact testing. The comparator containing the fluids was subjected to impacts delivered by a sled with a weight of 1.65 kg, released from a height of 1 meter, resulting in an impact energy of 16.2 J and a velocity of 4.5 m/s.

Each fluid was tested through four successive impacts, during which force signals were measured by load cells installed in the testing apparatus [fig.4]. The results provided insight into the maximum forces registered during each impact, as well as average force values, standard deviations, and associated errors.

In the O-DAMP configuration, the interface between two layers of Expanded Polystyrene (EPS), which slide against each other during impact, is equipped with a pad containing a fluid that serves as a shock absorber. A rigid shell is integrated with the EPS pin, and the relative motion between the two components dissipates energy as the EPS pin slides through the fluid.

This sliding interaction was studied under the same imp0act conditions, and an additional tests were conducted using a pin made from carbon-fiber-reinforced nylon (Onyx), replacing the EPS pin. This was made for the isolation of the fluid's contribution to energy dissipation, independently from the plastic deformation of the EPS pin. Further analysis focused on the characteristics of the force signals, particularly the presence of an initial smaller peak followed by a main, larger peak. The shape of this signal provided crucial information on the fluid's efficiency in distributing impact energy over time.

The study of these fluids enabled the identification of trends in energy absorption and the evaluation of the most suitable fluid for integration into the O-DAMP system.

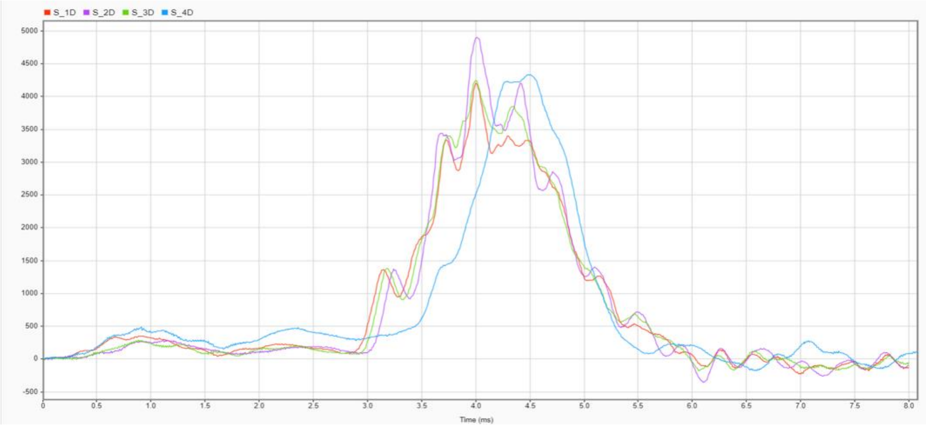


Figure 4 *Example of signals of the force transmitted to the load cells*

2.4 Helmet Segment Impact Testing

To validate that the inclusion of the O-DAMP system does not negatively impact the helmet's linear impact performance, we conducted a series of impact tests on helmet segments. These segments, equipped with the O-DAMP system, were subjected to just linear impacts. A dropweight setup was used for these tests, adhering to the ECE 22.06 and FIM standards for helmet impact testing. In the linear impact tests, the setup involved a vertical drop onto different standardized anvils, measuring peak force with a load cells system. By comparing the performance of helmet segments with and without the O-DAMP system, we evaluated the system's influence on both linear energy absorption, ensuring that the anti-rotational mechanism does not compromise the helmet’s compliance with regulatory safety standards.

We conducted the tests using samples derived from existing helmet shells. These samples were extracted with a CNC milling machine to obtain portions of the helmet's EPS (expanded polystyrene) layer beneath the outer shell. Each sample, composed of the shell plate and the corresponding EPS, was tested in two configurations: the standard configuration and a modified version where the EPS layer was split into two parts to introduce the O-DAMP system as a variable.

Figure 5 *a) Samples of portion of helmet. b) Detail of one sample containing the O-Damp system*

Each test was repeated three times on three identical samples (A, B, and C). During each test, the load curve was recorded at a frequency of 100 kHz to determine the maximum load transferred to the load cells, expressed in Newtons (N). Percentage error and standard deviation values were calculated to verify the reliability of the tests. For each test, the performance gap (%) between the two configurations (with and without the O-DAMP system) was indicated to highlight the differences.

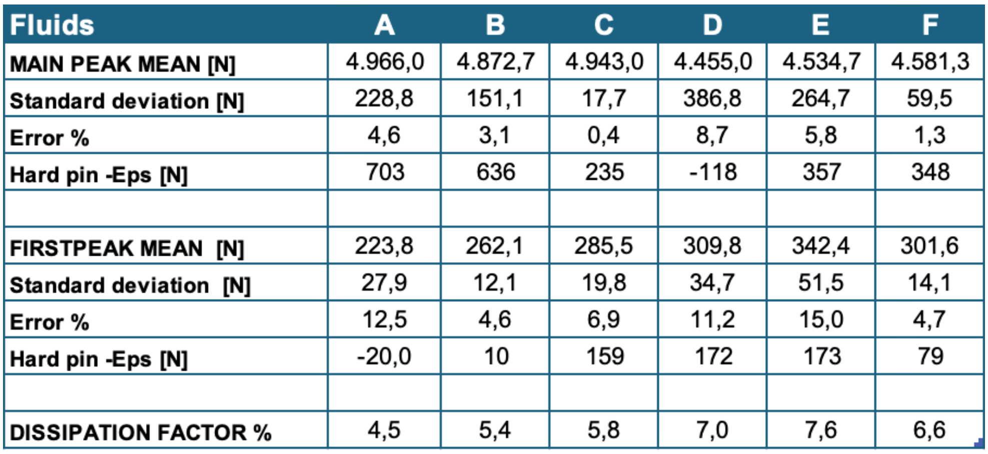
The specific tests conducted include:

- Test FRHPHe2 – Hemi – 7.5 m/s – Ambient temperature
- Test ECE 22.06 – Flat – 8.2 m/s – Ambient temperature
- Test ECE 22.06 – Kerb – 8.2 m/s – Ambient temperature
- Test ECE 22.06 – Flat – 6 m/s – Ambient temperature
- Test ECE 22.06 – Kerb – 6 m/s – Ambient temperature
- Test ECE 22.06 – Kerb – 6 m/s – 50°C temperature

3. RESULTS AND DISCUSSIONS

3.1 Fluid analysis

To determine the most effective fluid to use in the O-DAMP system, we subjected six different non-Newtonian fluids to a series of impact tests. Each fluid was tested four times under identical conditions, using a dropweight setup to simulate tangential impacts with an energy of 16.2 J, achieved through a 1.65 kg sled dropped from a height of 1 meter. The force signals were recorded via load cells, and the key performance metrics were derived from the peak forces observed during each test.



Fluids	A	B	C	D	E	F
MAIN PEAK MEAN [N]	4.966,0	4.872,7	4.943,0	4.455,0	4.534,7	4.581,3
Standard deviation [N]	228,8	151,1	17,7	386,8	264,7	59,5
Error %	4,6	3,1	0,4	8,7	5,8	1,3
Hard pin -Eps [N]	703	636	235	-118	357	348
FIRSTPEAK MEAN [N]	223,8	262,1	285,5	309,8	342,4	301,6
Standard deviation [N]	27,9	12,1	19,8	34,7	51,5	14,1
Error %	12,5	4,6	6,9	11,2	15,0	4,7
Hard pin -Eps [N]	-20,0	10	159	172	173	79
DISSIPATION FACTOR %	4,5	5,4	5,8	7,0	7,6	6,6

Table 1 *Review of the results of the fluids analysis*

For each fluid, the maximum peak force recorded in the four impact tests were averaged. This value, along with the standard deviation and percentage error, provided an initial assessment of the fluid's ability to attenuate tangential impact forces. The results showed in fig.6 and fig.7 distinct variations in peak force values across the different fluids, with some demonstrating superior energy dissipation compared to others.

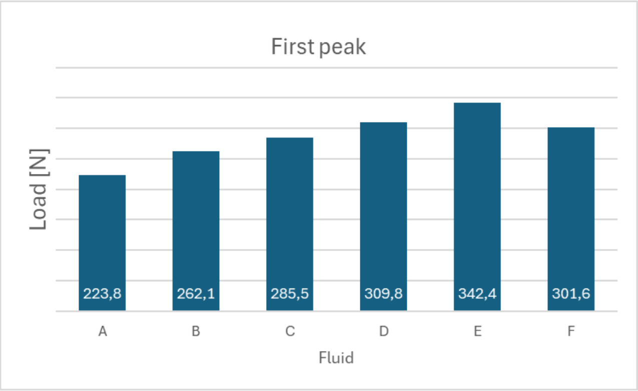


Figure 6 *Mean of the load value of the first peak*

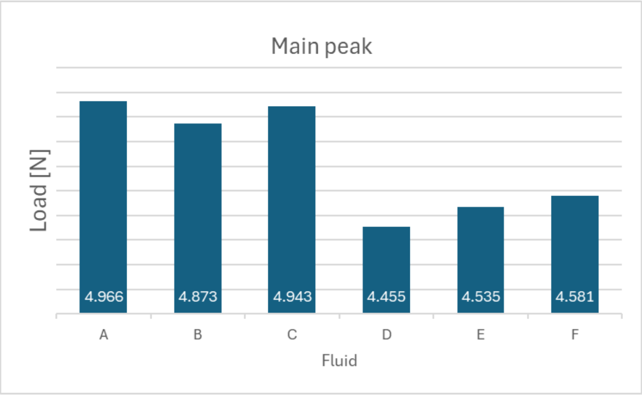


Figure 7 *Mean of the load value of the main peak*

Beyond the overall peak force, we also analyzed the initial, smaller force peak, fig.6 which corresponds to the early phase of energy dissipation in the impact. A higher first peak indicates a greater portion of the impact energy was absorbed by the fluid itself, rather than the deformation of the EPS core. This is a critical indicator of the fluid's performance, as a higher initial peak correlates with better energy distribution over time, leading to a reduction in the main peak force. We observed that fluids with higher first peak forces exhibited a more controlled dissipation of impact energy, translating into reduced acceleration values.

To quantify the efficiency of each fluid in absorbing energy, we introduced a *fluid dissipation parameter* (Df). This parameter is calculated as the ratio between the mean main peak force and the mean first peak force. A lower Df value signifies that the fluid is effectively dissipating a greater portion of the impact energy during the early phase, resulting in better overall performance. The results are indicated in fig.8

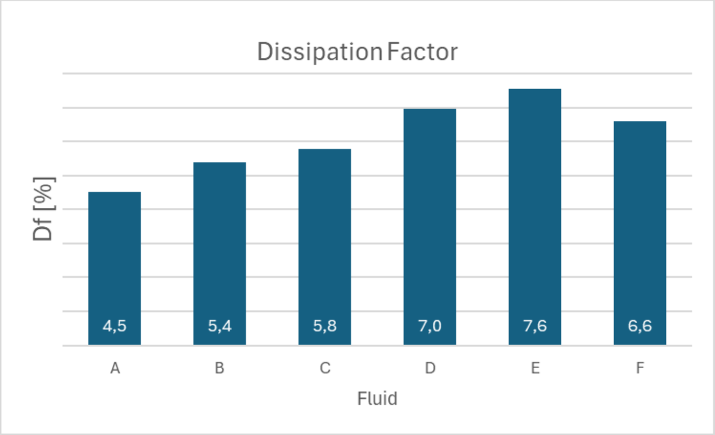


Figure 8 *Dissipation factor of the fluids*

Based on a thorough analysis of the results, including the evaluation of the maximum peak force, the initial peak force, and the ratio between these values, the decision was made to select fluid D to use in the O-DAMP system. This fluid demonstrated the most favorable balance between energy dissipation during the initial phase and overall performance in reducing tangential impact forces.

3.2 Linear impact

In this section, we present the results from the linear impact tests performed on helmet segments. The tests were conducted in accordance with ECE 22.06 and FIM regulations, using different anvil types (Flat, Hemispherical, and Kerb), impact velocities, and temperature. Each test was repeated three times on three identical samples (A, B, and C) to ensure consistency and reliability. The load transfer values were recorded for both configurations: the standard EPS and the divided EPS integrated with the O-DAMP system. For each test, we calculated the maximum load values, as well as the percentage error and standard deviation, to assess the validity of the results. In the following sections, we discuss the performance gap (%) observed between the two configurations, highlighting the impact of the O-DAMP system.

The helmet segments tested were derived from two specific areas of the helmet: the **Top**, which represents the higher and central zone of the helmet over the head, and the **Ring**, which encompasses the lateral crown and includes part of the padding.

3.2.1 Hemi Anvil Tests

The Hemi anvil tests (1-3 Top at 7.5 m/s) demonstrate the superior efficacy of the O-DAMP configuration in absorbing concentrated impacts, showing a significant performance improvement of 56% compared to the classic configuration. However, the Ring tests (2-4 at 7.5 m/s) indicate a decrease in efficacy for the O-DAMP configuration, resulting in a performance decline of 9.2% relative to the classic setup.

TEST	NORM	ANVIL	SPEED [m/s]	TEMPERATURE [°C]	PEAK CLASSIC [N]	PEAK O-DAMP [N]	GAP
1 VS 3	FRHPHe 2	Hemi	7.5	Ambient	47141	20604	56.3%
2 VS 4	FRHPHe 2	Hemi	7.6	Ambient	8032	8841	9.2%
5 VS 7	ECE 22.06	Flat	8.2	Ambient	19524	20889	6.5%
6 VS 8	ECE 22.06	Flat	8.3	Ambient	8800	9978	11.8%
9 VS 11	ECE 22.06	Kerb	8.4	Ambient	50394	22795	54.8%
10 VS 12	ECE 22.06	Kerb	8.5	Ambient	7804	9527	18.1%
13 VS 15	ECE 22.06	Flat	6	Ambient	8329	9777	14.8%
14 VS 16	ECE 22.06	Flat	6	Ambient	6558	6610	0.8%
17 VS 19	ECE 22.06	Kerb	6	Ambient	10974	9840	10.3%
18 VS 20	ECE 22.06	Kerb	6	Ambient	5918	5788	2.2%
21 VS 23	ECE 22.06	Kerb	6	50°C	14247	7069	50.4%
22 VS 24	ECE 22.07	Kerb	6	50°C	6118	9903	38.2%

Table 2 *Review of the results of linear impact*

3.2.2 Flat Anvil Tests

The Flat anvil tests yield mixed results. The Top tests (5-7 at 8.2 m/s) reveal a slight performance degradation of 6.5% in energy absorption with the O-DAMP configuration compared to the classic configuration. Similarly, the Ring tests (6-8 at 8.2 m/s) show an 11.8% decrease in performance for the O-DAMP setup. At a lower impact speed (6 m/s), the Top tests (13-15) indicate a further decline of 14.8% in the O-DAMP configuration's performance. However, the Ring tests (14-16 at 6 m/s) suggest that both configurations exhibit equivalent performance.

3.2.3 Kerb Anvil Tests

The Kerb anvil tests present a more favorable outcome for the O-DAMP configuration. The Top tests (9-11 at 8.2 m/s) demonstrate a substantial improvement in absorption performance, achieving a 54.8% enhancement over the classic configuration. Nevertheless, the Ring tests (10-12 at 8.2 m/s) indicate a performance decline of 18.1% for the O-DAMP setup compared to the classic configuration. At a lower impact speed (6 m/s), the Top tests (17-19) reveal a 10.3% improvement for the O-DAMP configuration. The Ring tests (18-20 at 6 m/s) exhibit a slight performance enhancement of 2.2% for concentrated loads with the O-DAMP configuration. Notably, the Top tests (21-23 at 6 m/s at 50°) reflect a significant improvement of 50.4% for the O-DAMP configuration over the classic setup, while the Ring tests (22-24 at 6 m/s at 50°) indicate a marked performance decline of 38.1% for the O-DAMP configuration in absorbing concentrated impacts compared to the classic configuration.

3.2.4 Discussion

The impact test results indicate that the difference in technology and in the configurations of EPS used in the O-DAMP setup differ significantly from those employed in the classic configuration. It is important to note that not all samples in the O-DAMP configuration included a pad; some merely featured the expanded foam divided into two halves with specific design modifications.

While the specific model of the helmet referenced and the corresponding compositions and densities of the foams cannot be explicitly detailed at this stage, the findings reveal a general trend: the O-DAMP configuration drastically improves linear impact results in certain cases, particularly for tests involving concentrated loads (Kerb and Hemi anvil tests).

In contrast, for tests under distributed loads (Flat anvil), the classic configuration exhibited slight performance improvements. However, during regulatory testing, this difference should not pose significant issues, as it remains within an acceptable safety range, especially considering the advantages that the O-DAMP system brings to inclined anvil tests and concentrated loads.

The most critical challenges arose during the tests with the Ring at low speed using the Kerb impactor. We anticipate that this discrepancy is attributable to the slight gap introduced in the O-DAMP configuration to allow for relative movement between the two concentric liners. Furthermore, the O-DAMP configuration employs a different density combination compared to the classic setup, and specifically for this test, we expected some performance degradation as a result.

It is hoped that minor modifications in geometry and/or density could resolve this issue, which has proven to be the sole concern for the system to date.

Overall, the results demonstrated that the inclusion of the O-DAMP system did not compromise the ability of the helmet to absorb linear impacts effectively, maintaining compliance with the required standards.

4. CONCLUSION

In this study, we successfully developed and improved an innovative anti-rotational system, O-DAMP, designed to enhance helmet safety during tangential impacts. The implementation of this system was accompanied by the creation of a standardized test method, allowing for the comprehensive evaluation of tangential performance and the determination of the optimal fluid for maximizing energy absorption.

We also conducted an in-depth analysis of non-Newtonian fluids, defining the lecture of the mechanisms of energy dissipation in our system and examining how these influence the impact curves. This research led to the identification of the most suitable fluid to use in the O-DAMP system.

Finally, the results from the linear impact tests confirmed that the integration of O-DAMP does not compromise the performance in absorbing linear impacts. In fact, it has demonstrated to maintain, and in some cases, improve the overall safety of the helmet, particularly in concentrated impact scenarios.

These promising results open new avenues for the implementation of O-DAMP in the market, with the potential to elevate safety standards in motorcycle helmets.

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