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DESIGN AND STIFFNESS DISTRIBUTION ANALYSIS OF MOTORCYCLE SWINGARM MADE OF CARBON FIBRE COMPOSITES

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Abstract: *Swingarm, as a mechanical element, has a significant influence on overall motorcycle dynamics. Dynamics is especially influenced by stiffness, which must be at an appropriate level to provide response and stability, and also transfer vertical, lateral and torsional loads. CFRP (Carbon Fiber Reinforced Plastics) allows us to reduce weight due to high stiffness-to-weight ratio. This paper presents experimental measurement results of torsional and vertical stiffness distribution over a CFRP single side swingarm prototype. The TRITOP optical measuring system was chosen for data collection, as it allows fast and precise measurement of reference points displacement in 3D space. Several static loading conditions were then measured while loading was applied using weights on a testing jig. The results were plotted as distribution of stiffness over length to show weak spots. The gathered data will be used for numerical simulation and further layup and stiffness optimization.*

Keywords: Composite, Single side swingarm, TRITOP, CFRP, Stiffness distribution.

1. Introduction

Swingarm is the dominant type of suspension mounting for modern motorcycles. It connects the rear wheel to the motorcycle frame and accommodates the spring and shock absorber that facilitates the desired interaction with the road surface (Vlk, 2004). In this paper, we deal with a single side swingarm where due to asymmetry in wheel bearing acts considerable torsional moment and, as a result, generates a twist of the swingarm. Because torsional stiffness has a significant influence on the overall motorcycle dynamics, an inadequate level cause slower reaction during cornering and promote the creation of a weave mode. Similarly, since vertical moment is a considerable force that acts on a swingarm and stiffness has influence on the suspension setup, low stiffness value causes unpredictable behavior of the motorcycle (Cossalter, 2006, Smith, 2014). Generally, higher stiffness is preferred over lower stiffness, though each motorcycle is designed partly elastic as it helps during cornering in high tilting angles, where the conventional suspension system is not working.

Application of CFRP (carbon fiber reinforced plastics) on single sided swingarm design is still quite rare, especially in the off-road category. In comparison with conventional materials – steel or aluminum, CFRP helps us reduce weight while maintaining strength and stiffness (even with low area moment of inertia). CFRP's largest advantage is that it allows a designer to easily change the properties of the part by adjusting parameters such as material, number of layers, or the layer's orientation. CFRP is also very attractive for customers as a state-of-the-art material with pleasing aesthetics.

2. Swingarm design

A swingarm's design must satisfy several requirements. The whole part is considered as structural due to high loads transfer from wheel to frame and to the suspension system. To ensure proper functioning, adequate strength, stiffness and durability are required. For strength, the requirements are calculated using the weight of the motorcycle and the driver, with an upper limit of 250 kg. The worst dynamic loading case

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possible is a jump with a force of up to 3G overload. Minimal safety factor of 5G overload was set for quasi-static testing.

For torsional and vertical stiffness, minimal prototype values were set. In his paper, Smith (2014) cites that a swingarm is rigid enough over the torsional value of 209 Nm/°, a value first mentioned by Sharp (1974). This was set as the minimal value. Its sufficiency will be checked during driving tests. In case of vertical stiffness, it is generally claimed that for proper functioning of a suspension system, swingarm stiffness must be at least 5 times higher than the spring stiffness. Accordingly, the minimum swingarm vertical stiffness was set to 400 N/mm.

3. Manufacturing

Manufacturing technology is critical for CFRP production. All structural parts need to undergo risk minimization of potential manufacturing defects. The autoclave technology was chosen due to stable production of complex parts for series with adequate quality (Campbell, 2003). Manufacturing of the swingarm directly from the female mold is not possible as CTE (Coefficient of Thermal Expansion) of aluminum mold is one order of magnitude higher in comparison with CFRP. The part's high curing temperature would cause its clamping during cooling so an alternative process must be chosen. The aluminum master model is made for production of CFRP female mold, which is cured with significantly lower temperature. To fulfil the desired dimension tolerances of the final part, a compensation of the different CTE for master model, mold and final part material is required, similarly as Kupčák (2020) deals with. The formula below was used:

$$\Delta l = \alpha l_0 \Delta t \quad (1)$$

Where Δl [mm] is change in length, α [K^{-1}] is CTE of the tooling material, l_0 [mm] is the initial length and Δt is temperature change [K]. The final change of the dimension is the sum of cure cycles for mold and for the final part. The i represent cure cycle order in formula below.

$$\sum_{i=1}^{j} \Delta l_i \quad (2)$$

Because the strength requirements of the swingarm are higher than the stiffness requirements, the HS (high strength) fiber is chosen for production. This material is cheaper and usually stronger than HM (high module) fiber. Specifically, we also chose GG 630T twill fabric for visual layer and GG 300X biaxial for internal layers, both from the manufacturer Deltapreg.

4. Stiffness analysis

4.1. Measuring process

In the front section, the swingarm prototype is fixed to the measuring jig, which substitutes the rigid attachment of the swingarm to the frame. In the rear section, the swingarm is attached to the jig using flanges, which allows load application directly on the wheel axis, simulating real conditions (Fig. 1).

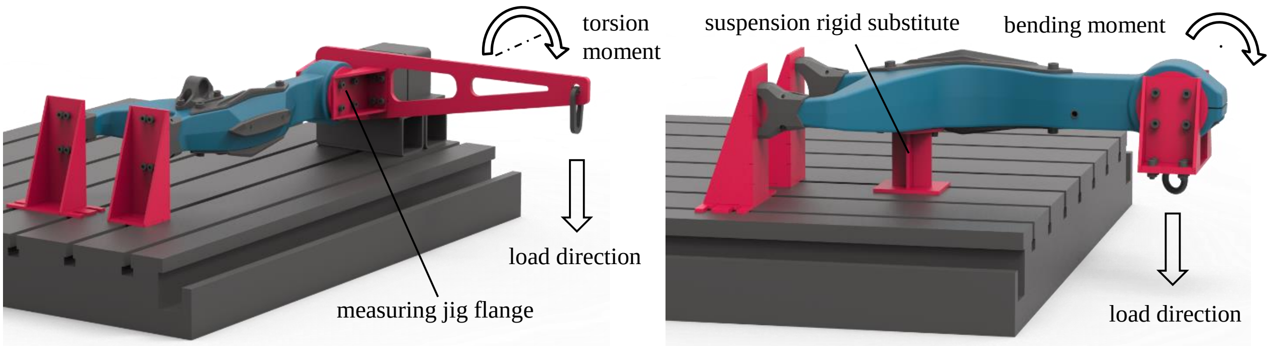

Fig. 1: Measuring setup: a) torsional stiffness measuring; b) vertical stiffness measuring.

We used the used photogrammetry device GOM TRITOP for data acquisition and evaluation, allowing measuring position of self-adhesive reference points in 3D space. From system self-check, the average reference point deviation should not be higher than 0.015 mm, and the maximum inaccuracy should not be higher than 0.025 mm·m^{-1}. The first measurement is taken unloaded to provide a reference state. Afterwards, three defined loading conditions are taken. Finally, all measured stages are aligned via rigid points and evaluated.

4.2. Torsional stiffness

Reference points are positioned directly on the measuring jig flange from both sides of the swingarm for overall torsional stiffness calculation (Fig. 1). Fitting planes and their symmetrical plane are constructed on these points. Rotation of this symmetrical plane is evaluated as twist angle θ. Torsion moment is calculated from applied load (Tab. 1) and arm length from load point to torsion twist axis. Torsional stiffness is then calculated from the derived data using the below formula:

$$K_t = \frac{M_t}{|\theta|}, \qquad (3)$$

where, K_t [N·m/°] is torsional stiffness, M_t [N·m] is torsional moment and $|\theta|$ [°] is an absolute value of twist angle. Overall results of torsion stiffness measurement are in Tab. 1.

Tab. 1: Applied load and derived data from torsional stiffness measurement.

	Load case 1	Load case 2	Load case 3
Applied weight [kg]	33.2	61	94.2
Torsion moment [N·m]	166.3	305.6	471.9
Twist angle [°]	-0.547	-1.075	-1.716
Torsional stiffness [N·m/°]	304.1	284.3	275.0

Stiffness distribution (Fig. 2) is calculated alike overall stiffness. The point twist angle is calculated as tangent of angle from the point displacement vector in Y direction and distance of the point to the parting plane of the swingarm. The inspected points for distribution are visualized as red dots in Fig. 2.

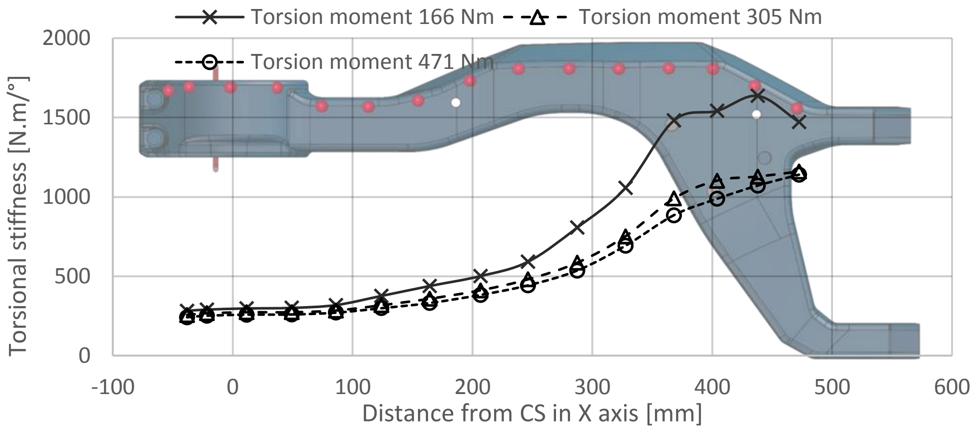

Fig. 2: Torsional stiffness distribution over the length of the swingarm.

4.3. Vertical stiffness

The same method of measurement with similar applied load was used for measuring of vertical stiffness. However, here we used a rigid substitute of the suspension system (Fig. 1) allowing for a measurement of absolute stiffness of the swingarm. The bending moment was calculated from applied load and load point distance to suspension rigid substitute centroid. The points displacement was evaluated directly from measurement as scalar value in loading direction vector.

For bending and axial vertical stiffness, we used these formulas:

$$K_v = \frac{M_v}{d_l}, \qquad (4)$$

$$K_a = \frac{F_v}{d_l}, \qquad (5)$$

where, K_v [N·m·mm^{-1}] is vertical stiffness, M_v [N·m] is bending moment and d_l [mm] is displacement. K_a [N·mm^{-1}] is the axial vertical stiffness, F_v is applied load. Overall results of vertical stiffness are in Tab. 2.

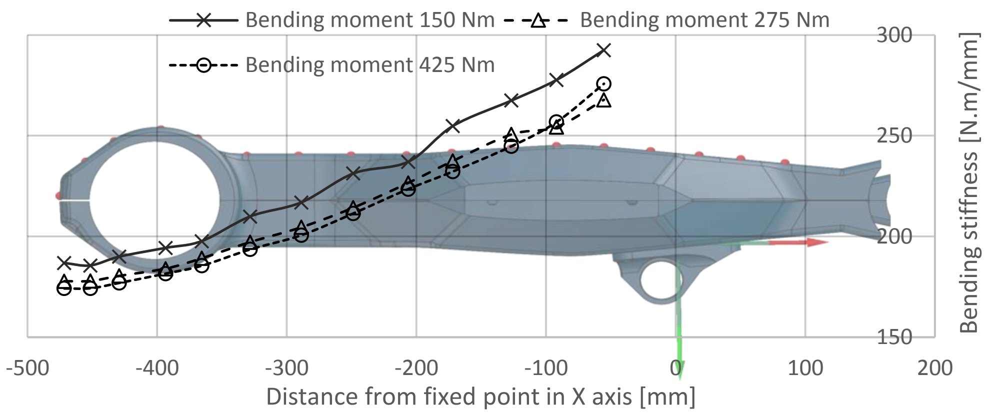

Fig. 3: Vertical stiffness distribution over the length of the swingarm.

Tab. 2: Applied load and derived data from vertical stiffness measurement.

	Load case 1	Load case 2	Load case 2
Applied weight [kg]	33.3	61.0	94.2
Bending moment [N·m]	149.9	274.5	423.9
Displacement at wheel axis [mm]	0.76	1.45	2.29
Vertical stiffness [$N \cdot m \cdot mm^{-1}$]	197.2	189.3	185.1
Axial vertical stiffness [$N \cdot mm^{-1}$]	438.2	420.7	411.4

5. Conclusion

From each measurement, it is obvious that the torsional and vertical stiffness values decrease with higher load. This is caused by clearing down the clearances on the jig. Following the results from load case 3, it is possible to accept the stiffness value as constant with increasing load. In the distribution graphs, it is clearly demonstrated which parts of the swingarm show weak spots in relation to stiffness. Our results (Tab. 3) also show that the minimum requirements set during the design phase were fulfilled. For stiffness increasing, it is possible to use IM (intermediate modulus) fiber. The measured data from this prototype could be seen as a valuable source of information for future design improvements and could be used as source for numerical simulation and validation. Future works will focus on quasi-static strength testing and driving test leading to swingarm properties improvement.

Tab. 3: Design goals fulfilment.

Parameter	Min. requirement	Measured value	Accomplishment [%]
Torsional stiffness [N·m/°]	209	280	133
Vertical stiffness [N/mm]	400	420	105

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