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APPLICATION OF CARBON FIBER REINFORCED POLYMER SANDWICH STRUCTURES IN MULTIAXIAL TESTING MACHINES

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1. INTRODUCTION

Hardware-in-the-loop (HWIL) simulations of inertial navigation systems, gyroscopes and accelerometers commonly employ highly-dynamic multiaxial testing machines (MATMs). The development progress of the systems to be tested is driving the demand for better performing testing machines, achieving higher angular accelerations and velocities without precision and stability losses. Strict requirements for the eigenfrequencies have to be fulfilled, as the tests must not be influenced by the natural vibrations of the testing machine. So far, the moving machine axes are mostly shaped as aluminum or magnesium classic box beam designs. This article investigates the potential and challenges of the application of carbon fiber reinforced polymer (CFRP) sandwich structures for the moving structural parts of MATMs.

2. REFERENCE SYSTEM

The testing machine under study consisted of a steel base structure on which three aluminum cardanic axes were mounted as can be seen in Fig. 1(a). The outer and middle axes are hydraulically-driven, whereas the small inner axis is driven by an electric motor. In order to analyze the dynamics of the machine, a parameterized rigid body model was created and calibrated by experimental modal analysis data. A subsequent sensitivity analysis revealed the outer cardanic axis (OCA) to be the most influencing substructure for the lowest eigenfrequencies of the machine. As a consequence, the OCA was primarily targeted for the machine optimization that is presented in the following.

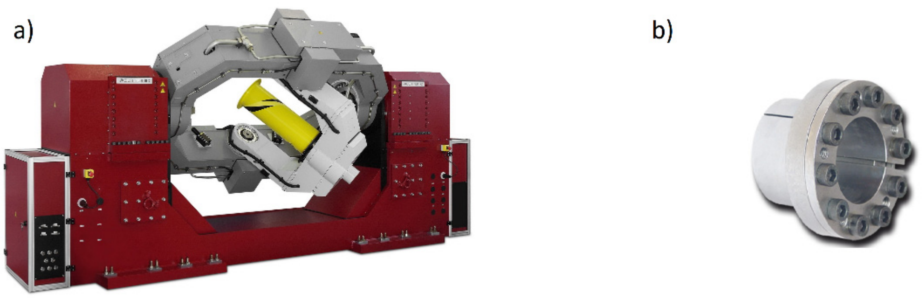

Fig. 1: (a) Reference aluminum testing machine, (b) Cone clamping element (Ringspann GmbH).

3. STRUCTURAL CONCEPT

The existing aluminum OCA design was not a convincing structural concept for a CFRP component. FRPs are typically processed in a mold-based manufacturing process. This allows for much higher freedom of design regarding geometrical complexity. According to [1], the introduction of curvatures into a structure leads to a significant increase of stiffness and buckling strength. The same was found for the reinforcement of free edges or the stiffening of large-area shells by ribs and stringers, as stated by [2]. Thus, by carrying out a systematic concept study, a structural model is presented, which exploits the geometrical potential of the FRP approach better than the reference design.

The first step included the development, analysis and assessment of design concepts of lightweight beams, shells and framework structures. After assessing these designs in terms of mechanical performance and expected manufacturing effort, curved sandwich shell concepts were identified as the most promising.

The second step aimed at investigating the effect of design parameters such as shell curvature and thickness, position and configuration of stiffeners, and material distribution. Thereafter, weaknesses in the design were systematically eliminated. As a final design, visible in Fig. 2(a), a double-curved sandwich shell was obtained, which offered a promising combination of high performance and reasonable manufacturing effort. The sandwich shell shape was based on an ellipsoid and flat surfaces were introduced at the flange areas to allow for the mounting of the motors. The shell structure was carried out as a sandwich with a foam core of 50 mm thickness. The stiffness was enhanced by introducing edge stiffeners. The foam runs out at the shell edge, as can be seen in the section view in Fig. 2(a). The face sheets followed a 90° bend to the inside of the shell and were joined to form a thick edge reinforcement of the shell.

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In a third step, laminate optimization of the CFRP sandwich shell structure was carried out. Optimization target was a maximum lowest eigenfrequency, while constraints on laminate thickness and the inertia of the structure were applied. After the optimization run, the element-wise optimal results were transferred to a producible layup solution. Local layups acting as reinforcements of critical areas of the sandwich were created, mainly the flanges and the edge stiffeners. The total thickness distribution after post-processing the optimization result is shown in Fig. 2(b).

As a result of the redesign of the outer cardanic axis of the MATM, a fundamental frequency of 139.1 Hz was measured for the optimized CFRP sandwich shell structure, whereas the aluminum reference structure showed a lowest eigenfrequency of 78.6 Hz. The frequency-to-inertia ratio of the system could be increased from 1.52 to 3.93 Hz/kg m^2 (+160%). A significant improvement of stiffness and margin of safety against structural failure of the structure could be guaranteed as well.

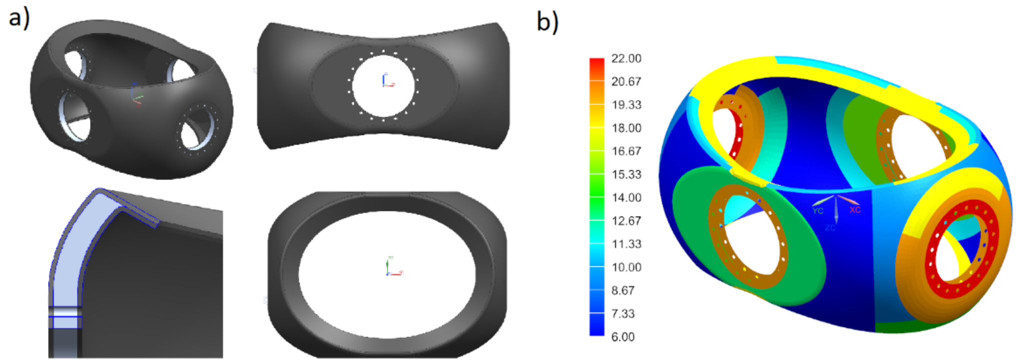

Fig. 2: (a) Double-curved CFRP sandwich structure for the outer cardanic axis, (b) laminate thickness of optimized sandwich shell structure [mm].

4. LOAD INTRODUCTION AND INSERTS DEVELOPMENT

The sandwich structure lacks inherently of precision in thickness, and its core is unable to bear large local pressures. Therefore, the load introduction in the CFRP tub lead to considerable difficulties. Flanges and cone clamping elements (Fig.1(b)) are the most common way of load introduction and transfer between elements. However, they are disadvantaged when a lower weight, adjustability and scalability are required, caused by their massive and specific design for each application. Hence, inserts have been developed to satisfy the need of more compact dimensions, lower mass and higher freedom of design [3]. Stiffness and strength can be easily adjusted by varying the type and number of the inserts. As the inserts were originally developed in the aerospace and automotive industry [4], the precision of the parts was an order of magnitude lower than required for precision machines, typically in the 10 µm range. Besides, as safety has priority in aerospace and automotive applications, the design of the original inserts followed a design for strength rather than for stiffness. These two main differences induced the development of a new insert type for precision machines, object of this chapter.

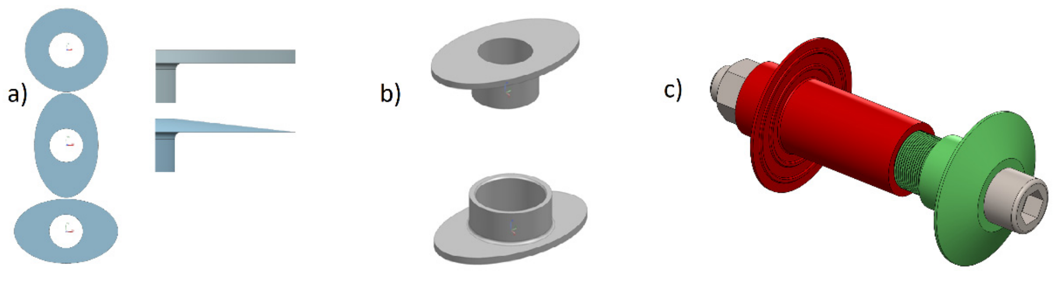

Fig. 3: (a) Design variation of the inserts, (b) Prototype inserts, (c) Prestressed stiffness optimized inserts.

The development of these new inserts was stiffness-driven with minimum strength requirements in the case of a 4 kN in-plane shear load case. The inserts are made of steel (42CrMo4) due to its high strength and stiffness, can be manufactured through an economic, automated turning process, and are of the through-the-thickness type. They consist of two pieces with concentric tubes and external flanges at both ends. The flanges distribute the load more evenly on the sandwich structure, thus preventing premature failure according to [5]. An increase of the loads with reduced stress concentrations is possible by implementing the geometry optimization of the inserts carried out by Shipsha et al [6].

Analytic considerations and FEM software allow for accurate and reliable stiffness calculations, whereas strength simulation is more complex and requires failure criteria and validation. Consequently, right from the beginning, it was fundamental to first of all guarantee the minimum strength requirement and understand how the different geometry variations influence the strength of the whole element. If the bonding fails, the whole solution would fail, causing the optimization regarding stiffness to be useless. In this first phase, preliminary sandwich samples and prototype inserts were manufactured, and the most influential geometric parameters for strength were experimentally determined through pull-out testing. As depicted in Fig. 3(a), circular, oval parallel and oval perpendicular to the load case direction flanges were employed. Two thickness variations of the flanges were also tested: constant flange thickness and linear thickness variation. The pull-out results indicated that the flange thickness variation leads to a considerably better load (+25%) introduction in the structure. Oval shaped flanges showed just a minor advantage (7%). Thus, a circular shape was favored, due to advantages in manufacturing and assembly.

Following the minimum strength requirements, a stiffness optimization was carried out. In this second phase, the results from the previous study were applied to a parametrically designed insert, employing the Design Step SolidWorks algorithm. The inserts were developed with respect to high stiffness, low mass, scalability, adjustability, ease of manufacture, and cost effectiveness. A first addition to the prototype design includes a fine thread connecting the bolt prestressed tubes, as visible in Fig. 3(c). This ensures a precise axial compensation for the CFRP sandwich thickness variation, and predominantly protects the sandwich core from damaging. Other additions include millable overhangs for further axial compensation and improved mating with other components, as well as back spacers on flanges to guarantee an optimal bonding layer thickness with the CFRP sandwich.

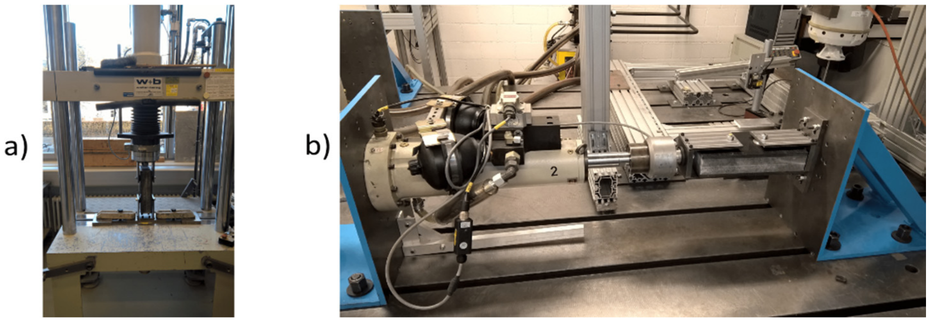

Fig. 4: (a) Static and (b) Fatigue testing in the hydropulser machine.

In the last development phase, static and dynamic characteristics of the stiffness-optimized through-the-thickness stainless steel inserts for CFRP sandwich structures with a foam core were investigated. A conclusive pull-out test with a load of 45 kN was passed in order to ensure the essential strength requirement (Fig. 4(a)). As shown in Fig. 4(b), fatigue tests at room temperature with a 2 Hz sinusoidal load were also successfully conducted in a hydropulser machine: the first round comprised of one million cycles with a +/-2.5 kN load, followed by another half a million cycles at +/-5 kN load.

ACKNOWLEDGEMENT

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Fig. 5: (a) CFRP MATM, (b) Newly developed inserts.

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