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Design and Development of an Experimental Setup for Large-Deflection Bending and Torsion of Highly Deformable Structural Elements

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The structural use of thin glass represents a recent and groundbreaking development in architecture and engineering. Originally developed for consumer electronics, chemically strengthened glass with a thickness of the order of 1 mm is now being explored for applications in adaptive façades and kinetic building envelopes. This has driven the need for accurate mechanical characterization under large displacement regimes. However, traditional testing methods, such as four-point bending and double-ring tests, originally conceived for stiffer materials, are inadequate due to the exceptional flexibility and high strength.

Many research efforts have been made in recent years to propose innovative methods, able to address issues such as nonlinear geometric effects, high curvature bending, and torsional instability. One of the most reliable procedures appears to be the "clamp bending"test, consisting in prescribing a rotation on two opposite edges of a rectangular thin plate, while properly adjusting the distance between the supports, so to achieve a constant-curvature deformation. In [1, 2], a tailored testing apparatus has been designed, based on the results of both analytical modelling and numerical analyses. The test bench allows to test a rectangular plate with two opposite edges inserted in steel rollers, separated by an EVA foil to prevent direct contact between steel and glass, thereby constraining the edges to remain straight. Its particular design allows to use the same test bench for both torsion and large-deflection bending tests, by making some slightly modification in constraints and actuators, so to have different constraints and allowable movements.

The test bench has been used to perform an experimental campaign, comprising 15 bending and 11 torsion destructive tests on chemically tempered thin glass plates, with thickness of 1.1 mm and 2.1 mm and length of 1 m. The comparison with the results of refined FEM analyses, accounting for the real constraint conditions, allowed to estimate the thin glass strength. This turns out to be up to 400 MPa, significantly higher than the characteristic value of 150 MPa usually assumed for chemically tempered glass. The extreme deformability of the thin glass specimens allowed to reach torsion angles of approximately 50° and bending curvatures with radii on the order of 1 m.

However, the experimental campaign carried out has highlighted that the proposed test bench should be improved to be used to better assess the thin glass strength. For bending tests, the major limitation is that the motors/actuators governing the translation and the rotation of the extremities of the thin glass element must be perfectly synchronized to obtain a deformed shape with constant curvature. This limitation can be overcome by designing an innovative setup, employing a mechanical/cinematic interconnection of the moving components [3]. The concept is based on the use of toothed contact profiles on properly-designed pitch profiles, to prescribe translation as a function of rotation, or vice-versa. As a result, only one degree of freedom has to be controlled when performing the test, i.e., only one actuator is necessary. The new setup can be manufactured via 3D printing or CNC milling, and it results in a compact device made with robust and reliable components, which can be scaled up to accommodate specimens of any size.

We believe that the proposed system, based on simple mechanisms, can contribute to the development of standardized test procedures, which are still lacking not only for thin glass, but more generally for highly deformable structural elements. This class of elements is increasingly attracting the interest of researchers, since their high flexibility, generally coupled with low weight and high strength, makes them suitable for a wide range of applications. These range from crash absorption plates for automotive use, to vibration damping plates, to morphing wing skin plates and flexible thermal protection plates used in aerospace engineering. Other potential applications include deployable space structures, adaptive and active surfaces, stretchable and flexible electronics, biomedical devices, and soft robotics.

[1] Galuppi, L., & Riva, E. (2022). Experimental and numerical characterization of twisting response of thin glass. Glass Structures & Engineering, 7(1), 45-69.

[2] Galuppi, L., & Riva, E. (2024). Constant-curvature bending response of thin glass: Analytical, numerical

and experimental study of "clamp-bending"tests. Glass Structures & Engineering, 9(2), 99-116.
[3] Boni, C., & Galuppi, L. (2024). A kinematics-based single-actuator setup for constant-curvature bending tests in extremely large deformations. Extreme Mechanics Letters, 73, 102259.

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