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Variable Stiffness Wing Structures with Compliance for Aeroelastic Morphing

Paolo Ermanni
Eidgenössische Technische Hochschule ETH
Rämistrasse 101
Zurich, 8092
CH

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14. ABSTRACT Conformal shape adaptation of aerospace systems, widely known as morphing, offers the potential for achieving optimal performance across a wide range of operational conditions. This research project investigated different purely passive shape adaptation techniques for wings, exploiting the tailored behaviour resulting from structural components purposely undergoing elastic instability. This unconventional technique is the key to the unique mechanical characteristics of the proposed shape adaptation mechanisms, extending the capabilities of structural members beyond the mere load-carrying functionality. Morphing is achieved by leveraging the significantly different mechanical responses of structural components in the linear (pre-buckling) and in the nonlinear postbuckling regime. Our approach significantly differs from existing morphing techniques as it does neither require external actuators nor conventional discrete mechanisms to achieve shape adaptation, but relies on the external loads (air pressure) for actuation. The resulting purely passive shape adaptation has thus the potential of altering the aerodynamic shape when a specific load level is reached. Owing to the actuator-free design and to the lack of discrete elements, its long-term behaviour is not affected by otherwise common problems, such as energy consumption, friction, wear, need for lubrication and adjustments. The morphing techniques investigated in this project are primarily studied for passive load alleviation, exploiting the aerodynamic loads to achieve required variations in shape to reducing the lift and root bending moment.					
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Final Report - FA8655-13-1-3057

Project Grant Number FA8655-13-1-3057 “Variable stiffness wing structures with compliance for aeroelastic morphing”

1. Project Description and Aims

Conformal shape adaptation of aerospace systems, widely known as morphing, offers the potential for achieving optimal performance across a wide range of operational conditions. This research project investigated different purely passive shape adaptation techniques for wings, exploiting the tailored behaviour resulting from structural components purposely undergoing elastic instability.

This unconventional technique is the key to the unique mechanical characteristics of the proposed shape adaptation mechanisms, extending the capabilities of structural members beyond the mere load-carrying functionality. Morphing is achieved by leveraging the significantly different mechanical responses of structural components in the linear (pre-buckling) and in the nonlinear postbuckling regime. Our approach significantly differs from existing morphing techniques as it does neither require external actuators nor conventional discrete mechanisms to achieve shape adaptation, but relies on the external loads (air pressure) for actuation. The resulting purely passive shape adaptation has thus the potential of altering the aerodynamic shape when a specific load level is reached. Owing to the actuator-free design and to the lack of discrete elements, its long-term behaviour is not affected by otherwise common problems, such as energy consumption, friction, wear, need for lubrication and adjustments. The morphing techniques investigated in this project are primarily studied for passive load alleviation, exploiting the aerodynamic loads to achieve required variations in shape to reducing the lift and root bending moment.

2. Detailed Task Description and Work Accomplished

In this Section, the detailed task description and project aims, as defined in the Technical Supplement Full Proposal Application Grant Number FA8655-13-1-3057 “Variable stiffness wing structures with selective compliance systems for aeroelastic morphing”, are stated. For each subtask, the research results are briefly explained.

The results dissemination by means of conference contributions and journal papers (accepted and currently undergoing the review process) is provided in Section 3.

2.1. First Year

- i. Understanding of the buckling phenomena for simple engineering structures.
- ii. Structural tailoring of wing box elements for selective buckling at a prescribed load level.
- iii. Aeroelastic model for an aerofoil incorporating a wing box with buckling webs.

A: Research Results

Subtasks i) and ii)

The morphing mechanism based on buckling-induced twisting is investigated for a simplified wingbox geometry (Figure 1). Our novel approach exploits shear buckling of one wingbox web – in form of a diagonal tension field in the postbuckling regime – to vary its effective torsional stiffness and shear centre location, in turn affecting the twisting response of the wing structure. To increase even further the stiffness variation, we exploit the anisotropy offered by composite materials enabling to augment the tailorability. For variations in fibre orientation, thickness and choice of composite material of the shear web design, the attainable twisting response is investigated, also considering a potential buckling-induced increase in susceptibility to failure.

The working principle for this simplified wing box structures is demonstrated by studying the buckling-induced twisting of composite beams analytically, numerically and experimentally. Figure 2 shows the experiment of a composite beam structure under bending and shear loads. For loads significantly exceeding the buckling load, diagonal tension field develops as shown in Figure 2. The local buckling-induced deformations of the shear web are captured with the digital correlation technique (DIC). Figure 3

shows the tip twist angle obtained for the analytical and finite elements solution. The loads are applied in the initial shear centre location of the composite beam, therefore leading to a zero twist in the prebuckling regime. In the postbuckling regime, the buckling-induced shear centre relocation induces a moment which leads to a twisting response of the beam. The results of the experiment, illustrated by dots in Figure 3, show very good agreement with the numerical analytical predictions.

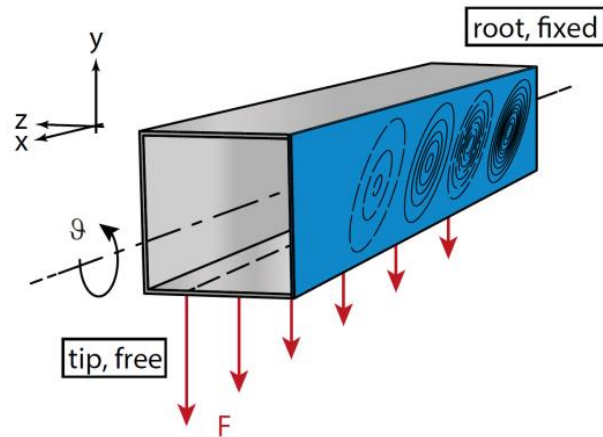


Figure 1 - Rectangular wing box with one web undergoing elastic instability. Diagonal tension field illustrated schematically.

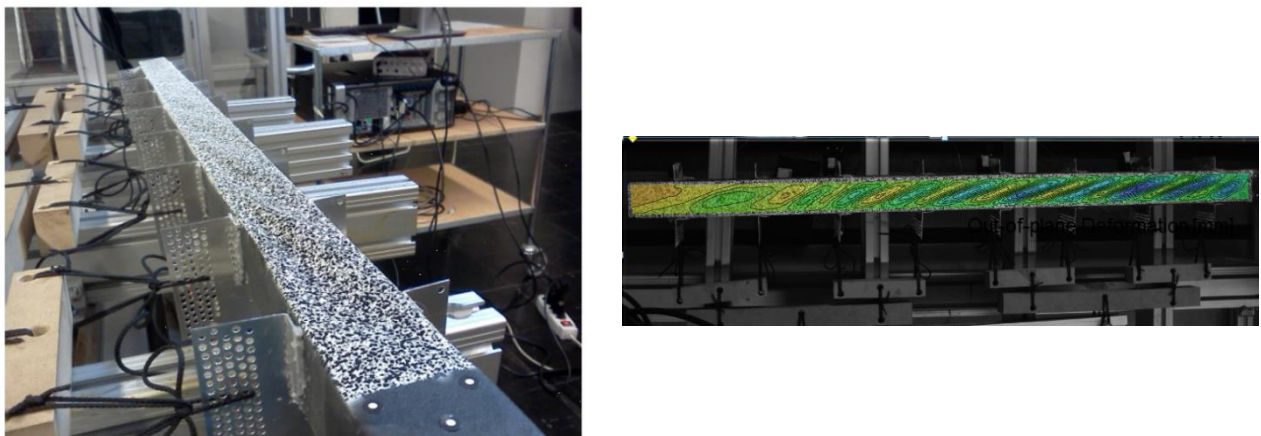


Figure 2 – Experiment – Composite beam applied to shear and bending loads. Development of diagonal tension field. Speckle pattern on shear web utilised to capture local deformations (right Figure) by digital correlation technique (DIC).

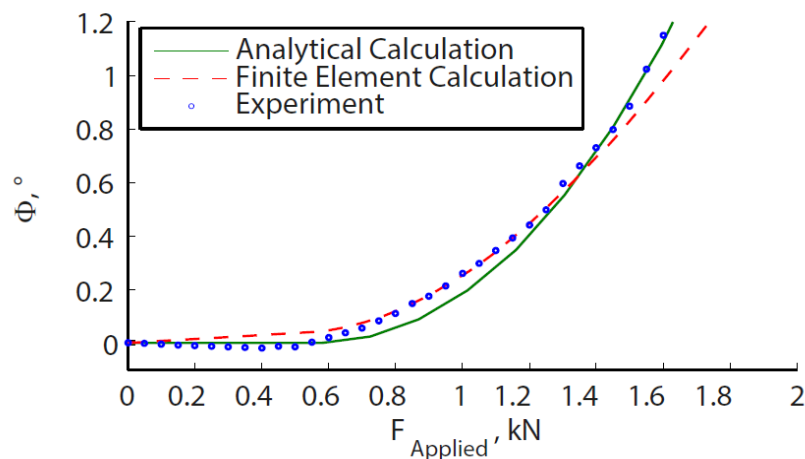


Figure 3 - Comparison of analytical, numerical and experimental solutions for buckling-induced tip twist angle of the wing box structure under loading conditions as defined in Figure 1. In the undeformed state, the load is applied in the shear centre of the wing box, resulting in a zero twist in the prebuckling regime.

Subtask iii)

To enable the application of the buckling-induced morphing technique to realistic wing structures, adequate analysis tools and numerical models have been developed to capture and assess the aeroelastic behaviour of such designs. For the 3D aeroelastic analysis technique, a nonlinear lifting line method is utilised to calculate the spanwise lift distribution on the wing structure. The structure is designed such that the torsional response is dominated by the wing box, allowing to compare the results with the preliminary investigation (performed by only considering the simplified box geometry). Figure 4 shows the aerodynamic loads on a wing structure with one web undergoing diagonal tension.

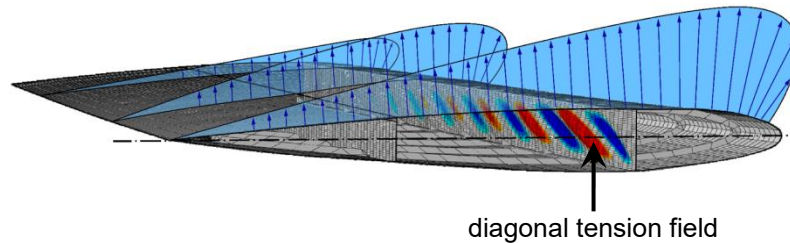


Figure 4 - Aerodynamic loading on a representative wing structure with one spar undergoing diagonal tension

2.2. Second Year

- i. Post-buckling structural tailoring of aeroelastic morphing for designed aerofoil with buckling webs.
- ii. Structural tests of aerofoil with wing box incorporating buckling elements.
- iii. Design of buckling elements in leading and trailing edges for aeroelastic cambering of morphing aerofoil.

A: Research Results

Subtasks i) and ii)

The tools developed in Subtask iii) of the first year are utilised to investigate the twisting response of finite wing structures under aerodynamic loads. Material anisotropy and wing component dimensions are utilised to structurally tailor the aeroelastic morphing response, in particular in the post-buckling regime. Parametric studies were performed for shear web designs made of unidirectional (UD-) fibre reinforced composites and glass weave fabrics, studying the impact of the fibre orientation and shear web thickness on the resulting twisting behaviour. For a wind speed of 45m/s and a shear web thickness of $t=0.19\text{mm}$, the attainable twist angles obtained for the linear and nonlinear solution are shown in Figure 5 for variations in the fibre orientation. For one specific shear web design, the development of the buckling-induced twist angle is shown in Figure 6 as a function of the external airflow velocity. Purely passively achieved airfoil nose-down effects are exploited for load alleviation purposes. The downwards airfoil twist reduces the root bending moment owing to a redistribution of the aerodynamic loads towards the wing root. For one specific wing design, the reduction in lift and root bending moment are shown in Figure 7.

Next steps for the presented concept should focus on the long-term fatigue behaviour of the composite wing. Furthermore, the dynamic response of the structure will be of interest, studying flutter and additional aeroelastic instabilities to further advance the proposed morphing technique for applications in wing and rotor blade morphing. Following research tasks will focus on the optimization of the wing design for achieving the required load alleviation capabilities. Next step could then include the design and conduction of experimental wind tunnel tests for wings specifically designed for a specific buckling speed and buckling-induced twisting response.

This morphing technique is particularly suited for structures of high aspect ratio, such as wind turbine blades and high-altitude long-endurance (HALE) aircraft. We envision to exploit the proposed purely passive load alleviation technique as a safety mechanism, allowing to attain a required nose-down twist for airspeeds significantly exceeding the nominal operational conditions. Mitigating the impact of rare, but decisive, load cases through the proposed purely passive morphing technique promises to enhance the structural efficiency of wing structure and rotor blades, reducing the number of actuators and structural mass otherwise required to withstand the critical load cases during operation.

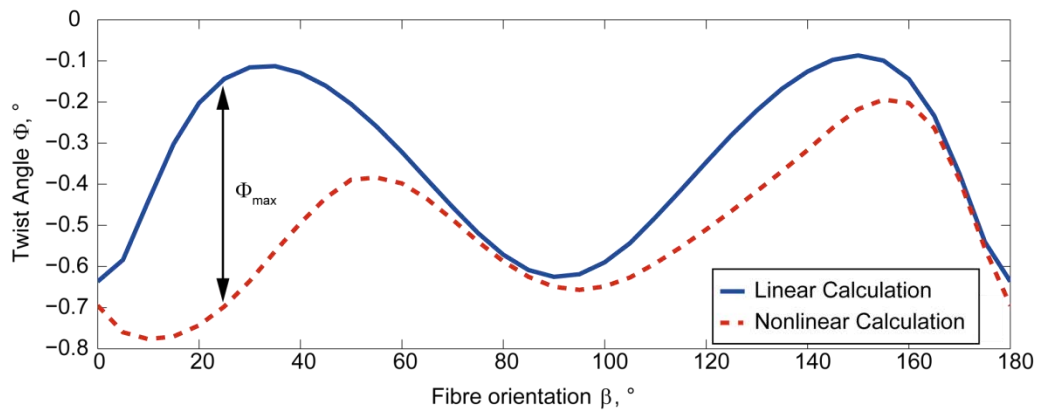


Figure 5 - Twist angle as a function of fibre orientation of shear web - $\Phi_{\max}$ represents the twist obtained solely due to the occurrence of the diagonal tension field

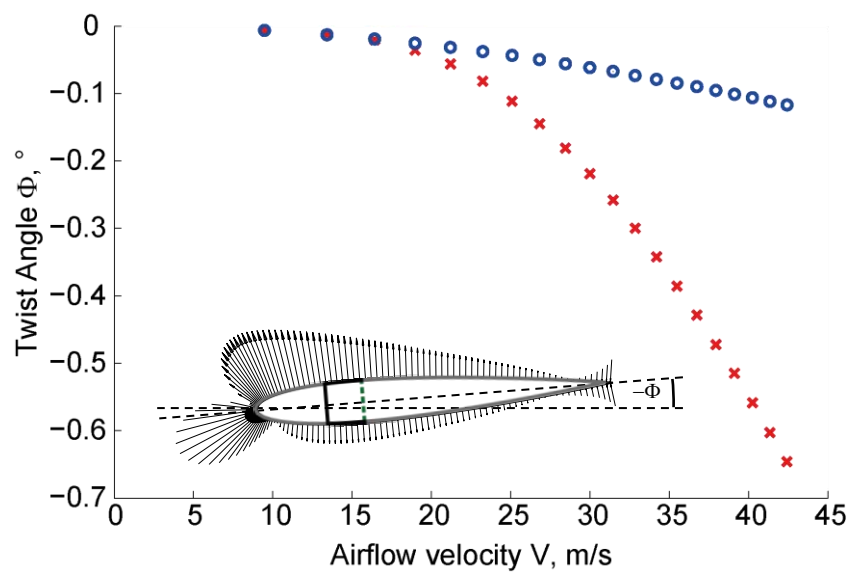


Figure 6 - Twist angle as a function of the airflow velocity – Buckling speed $V=15\text{m/s}$

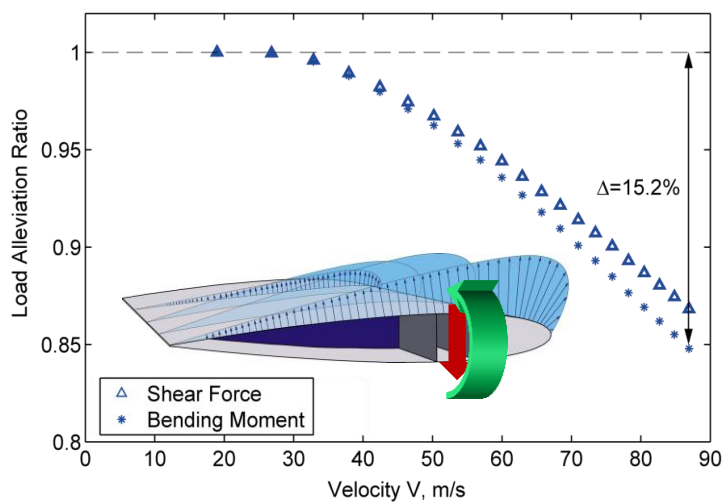


Figure 7- Load alleviation due to buckling-induced nose-down twist

Subtask iii)

The investigation of camber morphing represents the second part of the research project, and follows the same principle introduced for the bending-twisting shape adaptation: passively-induced elastic instabilities are exploited to achieve shape adaptation; in this case, camber morphing along the chord of wing profile sections.

The initial approach, proposed in the Project Task Description, was to include buckling elements on the leading and trailing edges of the wing. This approach, however, showed limitations in the achievable morphing capabilities and was therefore replaced by a more promising technique, relying on structural metamaterials for the wing rib design. For this purpose, we have devised a novel lattice topology based on chiral honeycomb designs, capable of exhibiting large shape changes owing to their unique micromechanical deformation behaviour. The design space of these periodic assemblies is significantly augmented by introducing an additional geometrical degree of freedom, defined as the ligament eccentricity (Figure 8). As a result, the macroscopic mechanical response of the lattice structure can be significantly altered, permitting to tailor the global stiffness-strain relation. Furthermore, the occurrence of buckling in the continuous medium at a particular level of strain is exploited for achieving drastic variations in local stiffness. Preliminary studies for simplified triangular chiral structures, illustrated in the initial and deformed state in Figure 9, were conducted to assess numerically and experimentally the mechanical behaviour. The significant tailorability of the response of the proposed buckling elements includes zero- and negative stiffness phases. The investigation represents a preliminary study of the mechanical response of the chiral lattice with transversely curved ligaments.

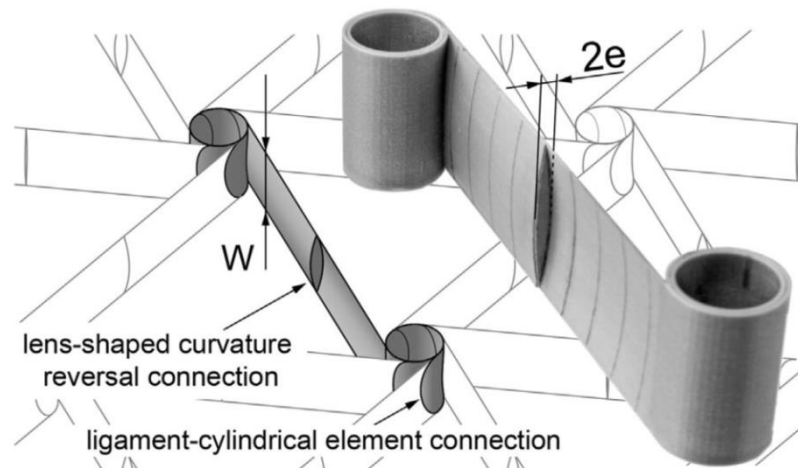


Figure 8 - Novel chiral structure with curved ligaments. Eccentricity ϵ defines the curvature of the ligament ($\epsilon=e/W$).

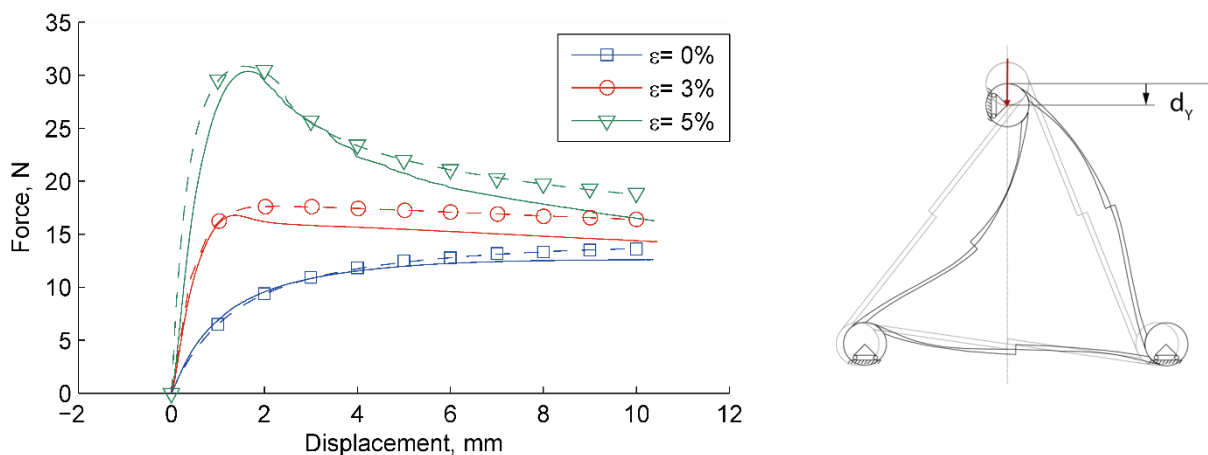


Figure 9 - Force-displacement curves for triangular samples under the load case shown in the right illustration. Dashed lines show numerical results, solid lines show experimental results. Ligament eccentricity ϵ as defined in Figure 8.

2.3. Third Year

- i. Structural tailoring for aeroelastically aided cambering for the leading and trailing edges of morphing aerofoil for the post-buckled regime.
- ii. Optimisation of the complete aerofoil combining twisting and cambering morphing capabilities.
- iii. Manufacturing of final demonstrator and experimental verification of designed morphing aerofoil with variable stiffness buckling elements.

A: Research Results

Subtask i)

The mechanical characteristics response of the proposed lattice structure have to be determined as a function of its numerous design parameters in order to be able to attain the required morphing behaviour. The characterization has been performed through a homogenization technique, indicating that the mechanical behaviour can be divided into two significantly different responses.

- for *slightly curved* ligaments, the response of the structure under pure compression loads is stable, resulting in a homogeneous distribution of the global strains and a microstructural deformation behaviour similar to conventional chiral structures with flat ligaments (bottom right illustration in Figure 10). The additional design parameter can be exploited to increase the effective modulus and the absorbed strain energy of the periodic structure under compression (Figure 10)
- for *strongly curved* ligaments, local buckling in the lattice occurs, leading to an inhomogeneous strain distribution (top right illustration in Figure 10). Collapse of elements exhibiting a negative stiffness phase leads to a sudden macroscopic load reduction, resulting in the unique force-displacement relation illustrated in Figure 10 for chiral structure with ligament eccentricity $\epsilon=5\%$.

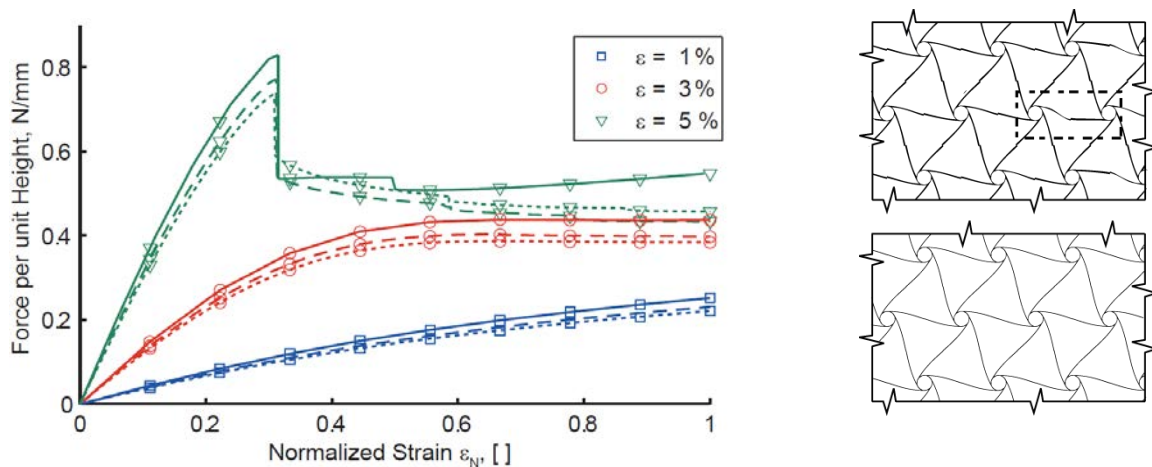


Figure 10- Force-strain curves of chiral lattices with different ligament eccentricities, subjected to axial compression in horizontal direction. Ligament design with eccentricity $\epsilon=3\%$ represents transition between stable and unstable responses

Subtask i) Part 1 - Structural Analysis

The significant tunability of the mechanical response is the chiral cell, namely changing ligament length, width and thickness, radius of the cylindrical elements and assessed by means of finite elements analysis, relying on variations in the design parameters defining the novel design parameter ligament eccentricity. For variations in the radius of the cylindrical nodes, the resulting strain-dependent stiffness is shown in Figure 11. It is shown that the strain leading to buckling, determining the transition from positive to negative stiffness regimes, can be largely tuned through this design parameter. For variations in ligament eccentricity and thickness, Figure 12 shows the attainable stiffness reduction, comparing the stiffness obtained at 2% compressive strain to the initial stiffness of the chiral lattice. The transition between the regimes is highlighted, allowing to design the chiral cell to exhibit a stable or unstable response for strains up to 2%. Applying a blocking mechanism by means of parallel cylindrical structures with radii R_c (Figure 13) generating contact at a specific macroscopic strain, the attainable force-displacement curves are shown in

Figure 13. The drastic stiffness increase at the contact of all supporting elements leads to a macroscopic response characterized by an effective zero-stiffness region delimited by regimes of significantly larger stiffness. This allows, for the case of force-controlled deformations, to attain hysteresis in the structural response, showing potential for structural damping and shock absorption applications.

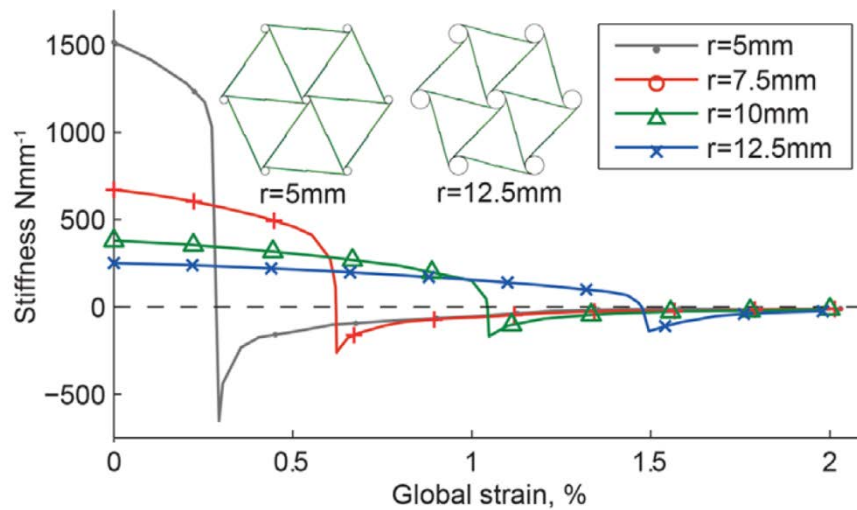


Figure 11- Strain-dependent stiffness: Tunability by radius of cylindrical elements

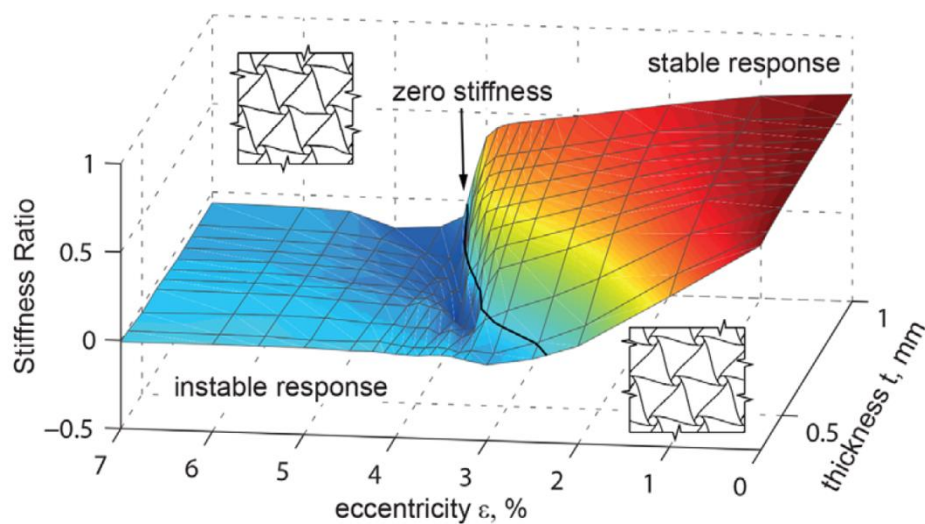


Figure 12- Ratio between stiffness at 2% global strain and initial stiffness of lattice structures

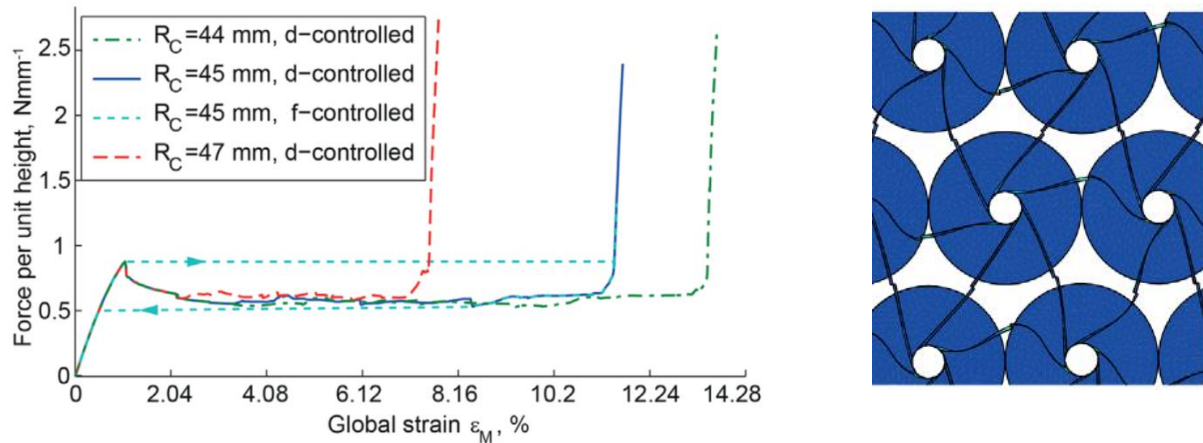


Figure 13- Left: Attainable force-displacement curves (force- and displacement-controlled) utilising external blocking mechanisms for large strains Right: Chiral lattice with parallel blocking mechanisms designed as cylindrical elements establishing contact at a specific macroscopic strain

Subtask i) Part 2 - Utilization of novel chiral structures for achieving wing morphing

Based on the results obtained through the structural analysis of chiral honeycombs with transversely curved ligaments, different wing-rib designs with chiral rib designs are developed. Their aeroelastic behaviour is assessed through finite elements calculations and aerodynamic tools established in the first part of the project. For these studies, we focused on typical wing profiles, such as a NACA0012 and Selig1223 (shown in Figure 14).

The additional shape adaptation capability offered by the proposed concept is evaluated, showing a significant buckling-induced augmentation of the total wing rib compliance for increased aerodynamic loads. This is exploited for achieving purely passive load alleviation. Figure 15 enables to assess the influence of ligament eccentricity on the resulting shape adaptation performance. The trailing edge displacements of identical wing structures, solely differing in the value of ligament eccentricity and thickness of the chiral honeycomb rib design, is shown at different levels of aerodynamic loads, corresponding to different levels of airspeed. The line with circular markers represents a chiral honeycomb with flat ligaments. The solid line represents a chiral honeycomb with curved ligaments exhibiting a similar initial response for small airspeeds, and therefore loads acting on the structure. The thickness of the flat ligaments is therefore larger compared to the thickness of the curved ligaments to provide a similar bending stiffness of these structural members for initial microstructural deformations. For increased loads, the buckling-induced stiffness reduction of the chiral rib design with curved ligaments leads to a larger compliance of the wing section, and consequently to larger trailing edge displacements compared to the conventional chiral wing rib design.

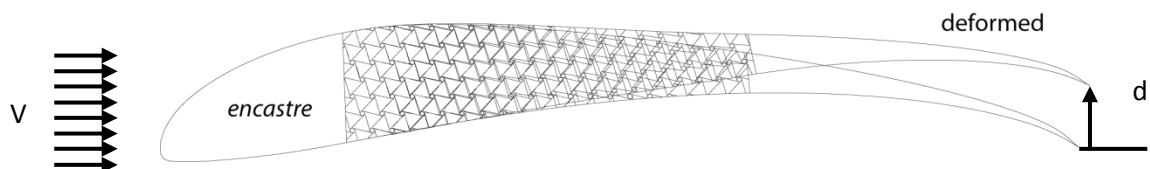


Figure 14 - Selig profile with internal wing rib structure consisting of chiral lattices with curved ligaments

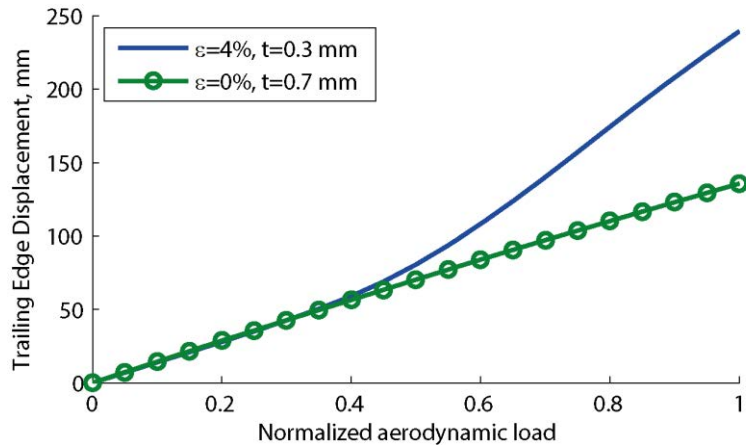


Figure 15 - Trailing edge displacement for wing structures under aerodynamic loads. Solid line shows result of a chiral geometry with curved ligaments and small ligament thickness. Line with circular markers shows results for chiral geometry with flat ligaments and larger ligament thickness. Both designs show a similar initial mechanical response before the onset of instability (at a normalized load of 0.4). Buckling of the curved ligaments leads to a significant increase in compliance for larger aerodynamic loads, hence significant load-alleviation capabilities.

Subtask ii)

The novel approach of utilising metamaterials exploiting buckling – proposed for achieving camber morphing in the second part of the project – was applied to other morphing concepts, specifically the bending-twist coupling technique investigated in the first part of this project. Wing structures with one shear web constituting of chiral elements were investigated for the resulting buckling-induced twist variations. Figure 16 shows the structural model of the wing box (compare Figure 1 showing wing box with one web undergoing diagonal tension). The load application is simplified using a transverse force applied at the tip of the wing box, while the root is fixed. Preliminary results show that two drastically different mechanical responses are attained, corresponding to the stable and unstable regimes exhibited by the chiral web. Figure 17 shows the development of the tip twist angles attained at different levels of applied load for a linear and nonlinear solution. It can be observed that initially both solutions lead to the same result, while for loads exceeding the critical value significantly larger twist angles are attained for the nonlinear solution which predicts ligament buckling and the resulting softening response of the chiral web.

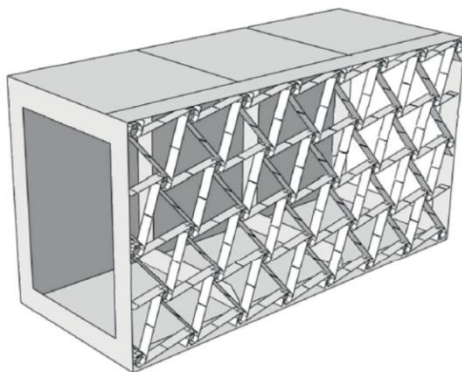


Figure 16 – Wing box design with one shear web consisting of a chiral honeycomb structure

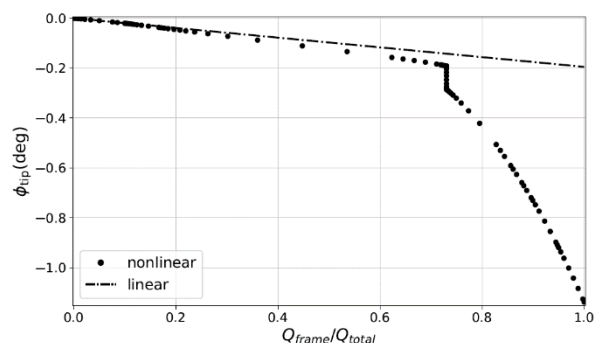


Figure 17– Tip Twist Variation for linear and nonlinear solutions as a function of applied shear force

Subtask iii)

Experimental mechanical assessments were performed in parallel to the finite elements analyses to validate the numerical predictions and to correlate the model, ensuring it can capture all relevant phenomena. For the experimental analysis, we focused on the in-plane load cases of tension, compression and shear. The left illustration in Figure 18 shows a finite lattice structure under boundary conditions for the load cases of tension and compression. A vertical deformation is imposed on the most upper row of cylindrical elements. The lowest row is not allowed to displace in vertical direction. All other degrees of freedom are not constrained. All other cylindrical nodes of the lattice are free to deform. The right illustration in Figure 18 shows the load case of shear. Deformations are imposed onto the outer cylinders of the chiral lattice by virtue of connecting their in-plane deformations to the displacements of a rigid frame (illustrated in Figure 18). The frame is hinged at its corners, and the deformation is applied at the upper right corner such that the chiral structure embedded in the frame exhibits pure shear.

The samples used for the experimental validation were manufactured by means of 3D printing (fused deposition molding). This allows to manufacture the comparatively complex shapes of chiral structures with transversely curved ligaments. The printing material is polylactide (PLA). Figure 19 shows two basic elements of the chiral structure which were connected at the rigid nodes to generate the larger lattice structure. The test samples and setups for the compression/tension and shear tests are shown in Figure 20. The force-displacement curves are attained applying displacement-controlled deformations to the lattice structure (load applied as shown in Figure 18). Local deformations and rotations of the cylindrical nodes are captured utilising the digital image correlation technique (DIC).

The left illustration in Figure 21 shows the force-displacement loading and unloading curves obtained in the experiment and the results of finite elements analysis, showing good agreement for small and large displacements. The right illustration in Figure 21 shows the reaction force-shear angle response of the lattice loaded in in-plane shear. Although the finite elements results predict a larger stiffness for the small displacement regime, the overall structural response, exhibiting regimes of drastically different stiffnesses, is verified.

To experimentally investigate the numerically studied shape adaptation techniques, downscaling of the chiral lattices is required. For this reason, additional manufacturing techniques – already described in literature for the design of conventional chiral structures – should be studied in future projects related to the proposed morphing technique. In addition, the studies should focus on suitable connection strategies for assembling the lattice and generating the contact of the lattice to a (compliant) wing skin. Preliminary studies were conducted in the framework of this project investigating the connection between the cylindrical nodes of the lattice and different skin designs. Figure 22 shows two possible solutions for the design of a compliant wing skin. Axial and bending compliance of specific deformation modes is provided through the utilization of corrugated structures. The left illustration in Figure 22 shows a trapezoidal-shaped corrugation, and the right figure shows a sinusoidal-shaped corrugation. The preliminary studies show that the stiffness of the wing skin significantly influences the deformation behaviour of the connected, -adjacent chiral cells. For the applicability of the chiral structure in the design of morphing wings, considering the presented camber morphing and twisting morphing approaches, the structural interaction of rib/web and skin must be considered in the design. This is particularly important if the number of chiral unit cells in the wing is comparatively small. In this case, the chiral lattices exhibits a mechanical response on a structural level, and boundary effects cannot be neglected for the resulting deformation behaviour.

In addition to the presented morphing ideas, we see potential in exploiting the unique mechanical responses permitted by the novel chiral topology for additional applications. This metamaterial can be applied for structural concepts which rely on selective compliance to achieve additional functionality, such as smart skins, deployable systems, compliance based robotics, and wave propagation tunability. The high hysteresis in the buckling-induced microstructural deformation, in combination with zero-stiffness phases over a large range of deformations, is beneficial for energy dissipation with applications in structural damping, shock absorption, protective systems, and vibration and noise control.

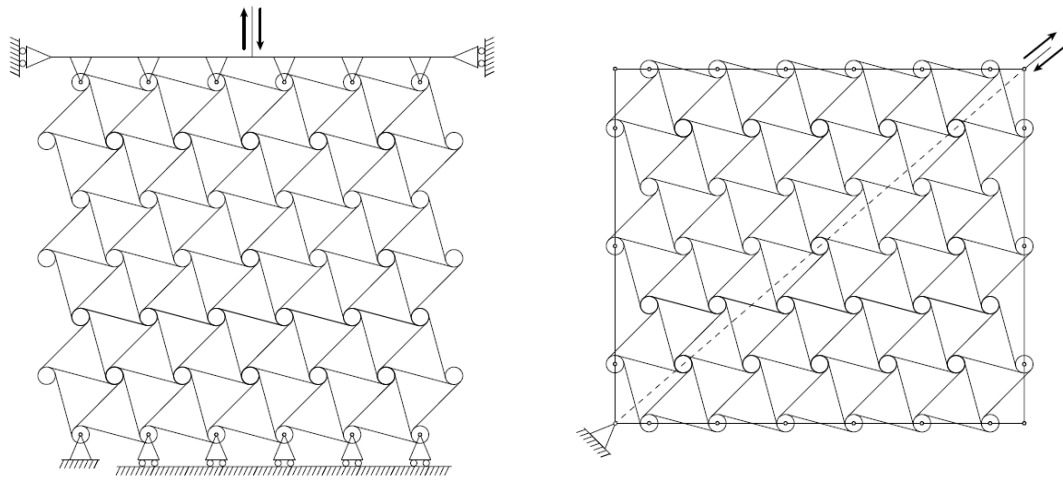


Figure 18– Tensile and compressive (left Figure) and shear loading (right Figure) on finite lattice structures



Figure 19 – Manufactured basic elements. Left sample directly after 3D printing, right sample prepared for the experiment

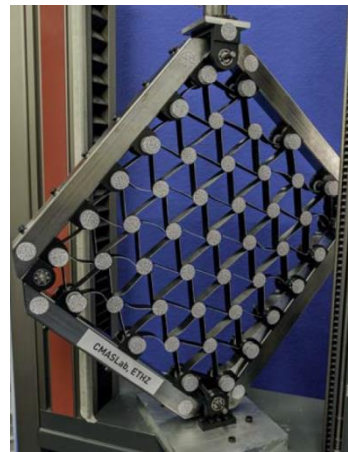


Figure 20 – Tensile and compressive (left Figure) and shear loading (right Figure) on finite lattice structures – Experimental setups. White markers with speckle pattern utilised to capture the individual deformation of the cylindrical nodes by means of Digital Image Correlation (DIC)

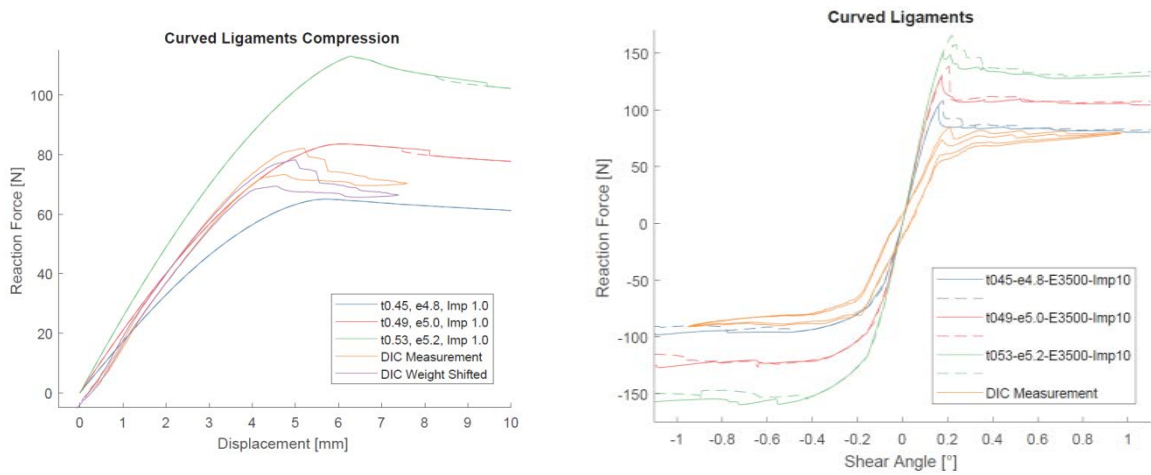


Figure 21 – Force-displacement curves for compressive (left Figure) and shear loading (right Figure)

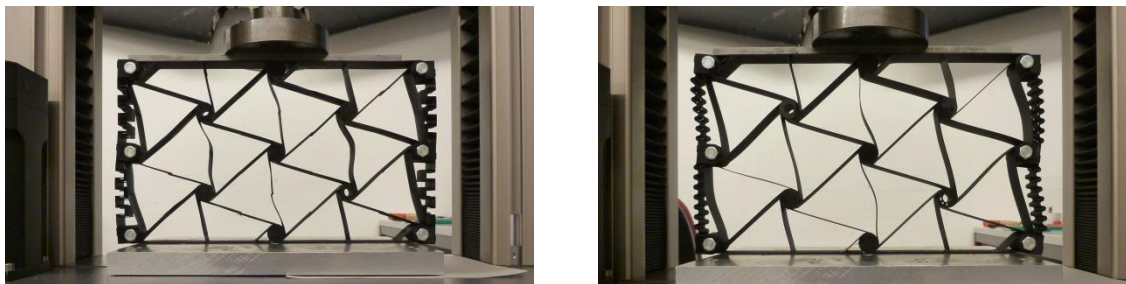


Figure 22– Connection of chiral lattice to compliant skins. Left figure shows a trapezoidal-shaped corrugation and right figure shows a conventional sinusoidal-shaped corrugation.

3. Results Dissemination

The team members involved in the research project were Prof. Dr. Paolo Ermanni (ETH Zurich), Prof. Dr. Andres Arrieta (Purdue University, former ETH Postdoc) and Falk Runkel (PhD candidate). The research results – given in the detailed project summary – have been presented at various scientific conferences, such as AIAA SciTech, SMASIS17, ECCM17 and ICCM20.

Additionally, the content of this research project was presented at the “Multi-Scale Structural Mechanics and Prognosis Program Review” of the AFOSR and at the Airforce Research Laboratory (AFRL) in Dayton, Ohio, by invitation of Dr. Gregory Reich.

F. Runkel, A. F. Arrieta, P. Ermanni. *Conference on Buckling and Postbuckling Behaviour of Composites*, Braunschweig, 2015.

F. Runkel, A. F. Arrieta, P. Ermanni. Design of passive morphing wing structures using elastic instabilities, *ICCM20*, Copenhagen, 2015.

F. Runkel, A. Reber, G. Molinari, A. F. Arrieta, P. Ermanni, *Composite Structures*, 2016.

F. Runkel, U. Fasel, G. Molinari, A. F. Arrieta, P. Ermanni, Bending-Twist Coupling Mechanism by Elastic Instability: Aeroelastic Study, *ECCM Munich, Germany*, 2016.

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