# Morphing in aerospace:
# aims, challenges and current showstoppers

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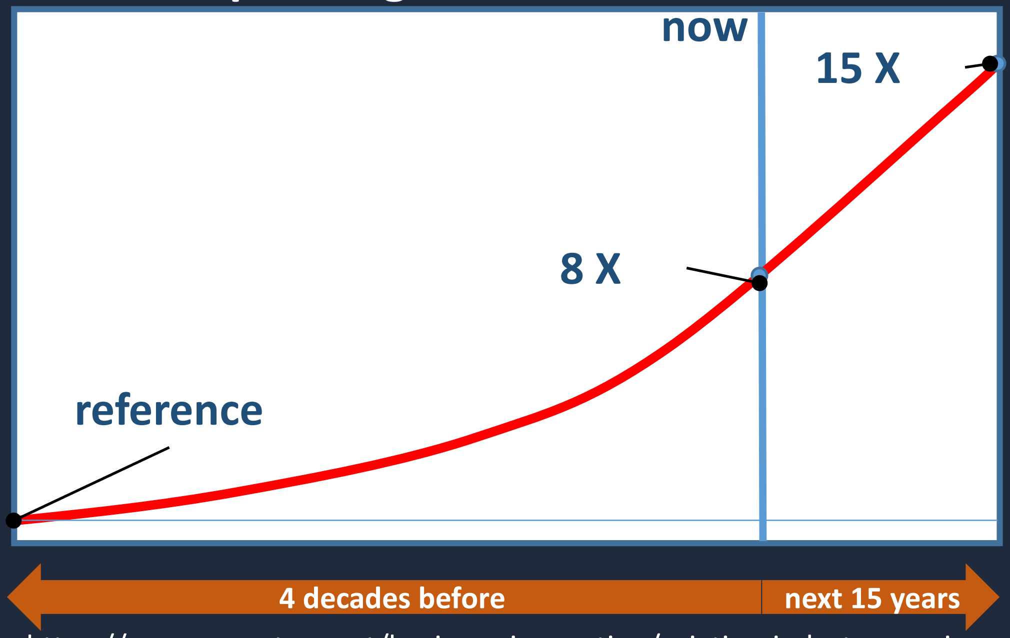
# Let’s start with… MOTIVATION

# MARKET

## Revenue passenger kilometers




https://www.raconteur.net/business-innovation/aviation-industry-soaring-into-the-future

- air navigation agencies employ 7.6 million people
- aviation supports 58 million jobs and contributes $2.4 trillion to the world economy

# MARKET

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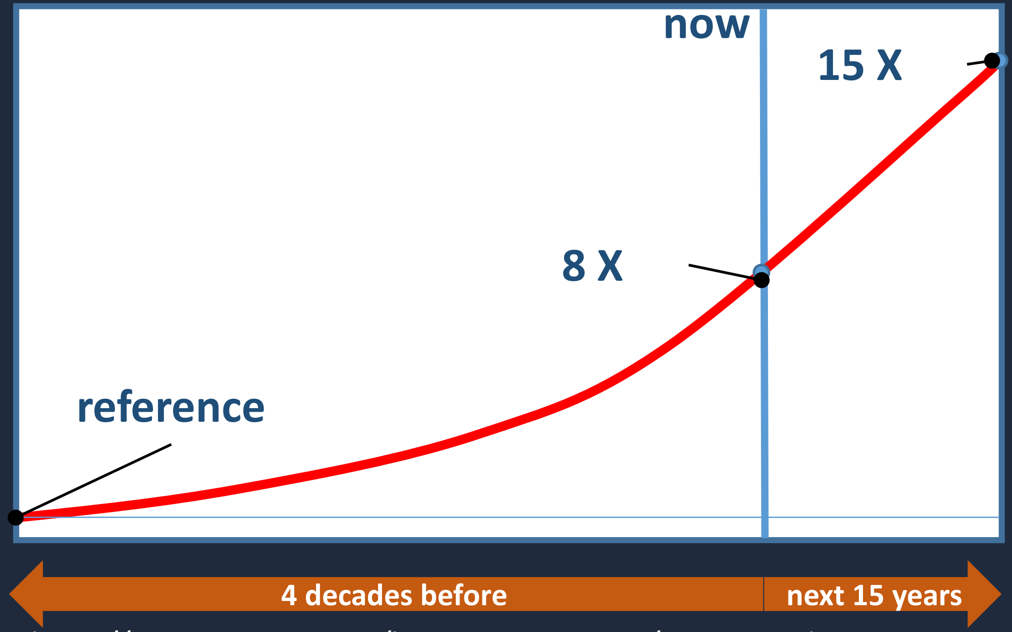


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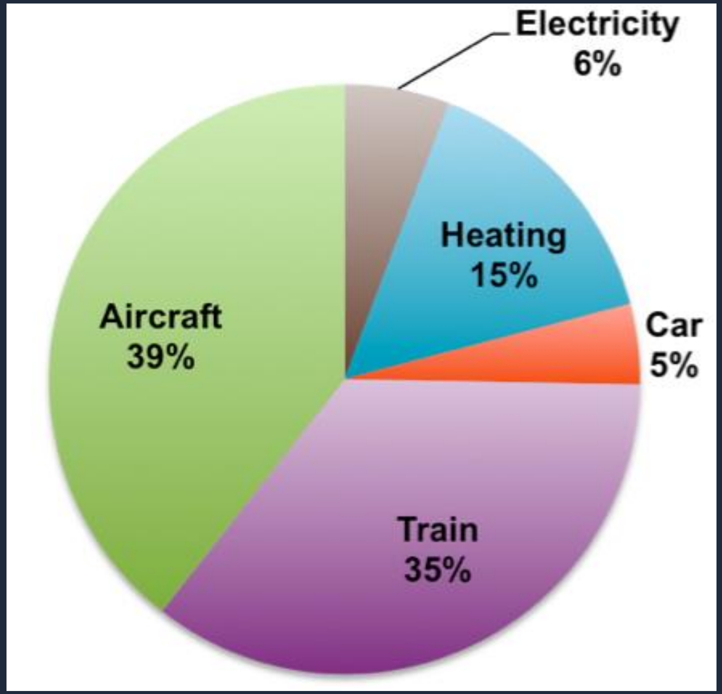
# ENVIRONMENT

## Environmental impact goals for the 2050 (ACARE agenda):

- Cutting CO2 emission by 75%
- Reducing NOx by 90%
- Reducing perceived noise levels by 65%




*https://theicct.org/blogs/staff/carbon-diary-reluctant-traveler*


What should I do now?

AERODYNAMICS


PROPULSION

ON-BOARD SYSTEMS

STRUCTURES AND MATERIALS

# among the other technologies… morphing…

# among the other technologies… morphing… why?

***"a multidisciplinary technology that combines integrated aerodynamic, structures and on-board systems knowledge"***

# among the other technologies… morphing… why?

- Higher L/D → fuel saving → lower costs and emissions
- High lift generation → take-off/landing performance
- LC&A → reduced stress level → more safety, lighter main structure, lower running costs
- Lighter, less complex and more reliable architectures

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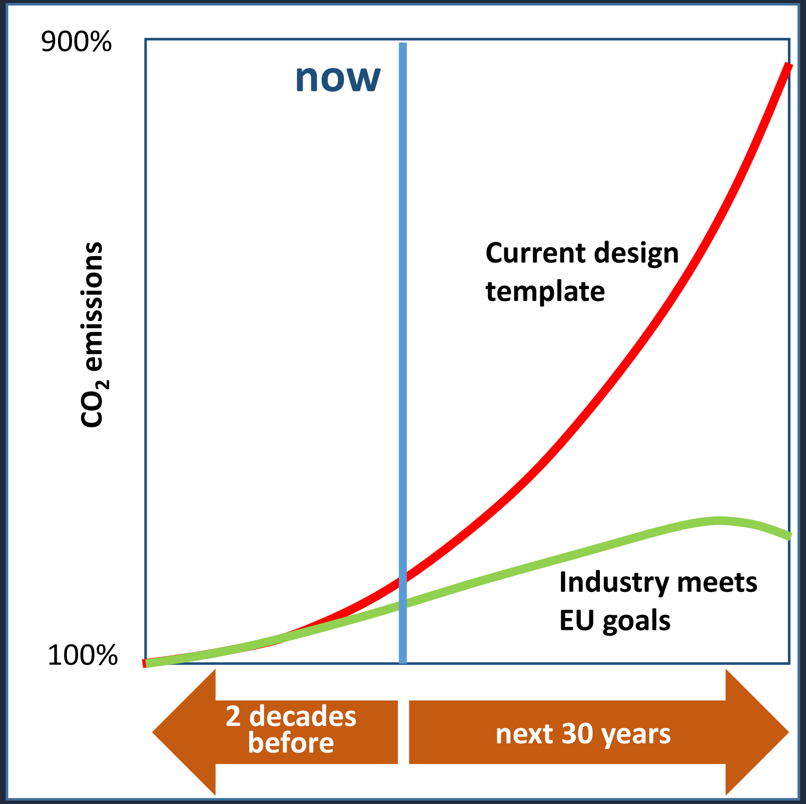


*http://theconversation.com/morphing-is-one-way-to-make-aircraft-more-efficient-23683*

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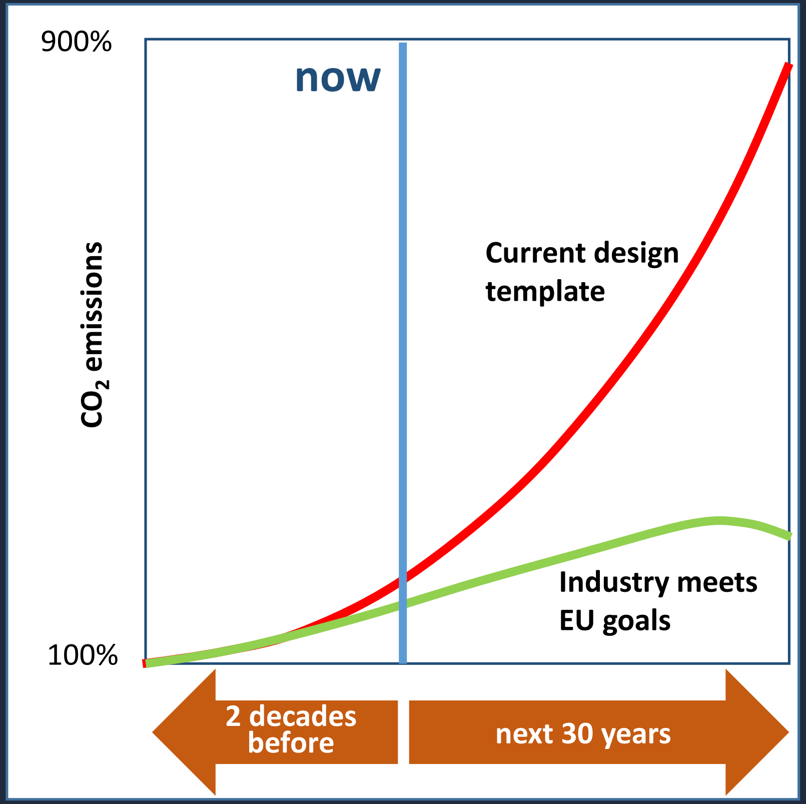



*http://theconversation.com/morphing-is-one-way-to-make-aircraft-more-efficient-23683*

**Efficiency increase higher than 20%, in synergy with other technologies**

# Unfortunately… not all that glitters is gold!

Herein some relevant problems are shown:

**Load transmission to the supporting structure**

**Scalability**

**Strength vs flexibility skins**

**Dynamic/aeroelastic response**

**Load transmission to the supporting structure**

**Scalability**

**Strength vs flexibility skins**

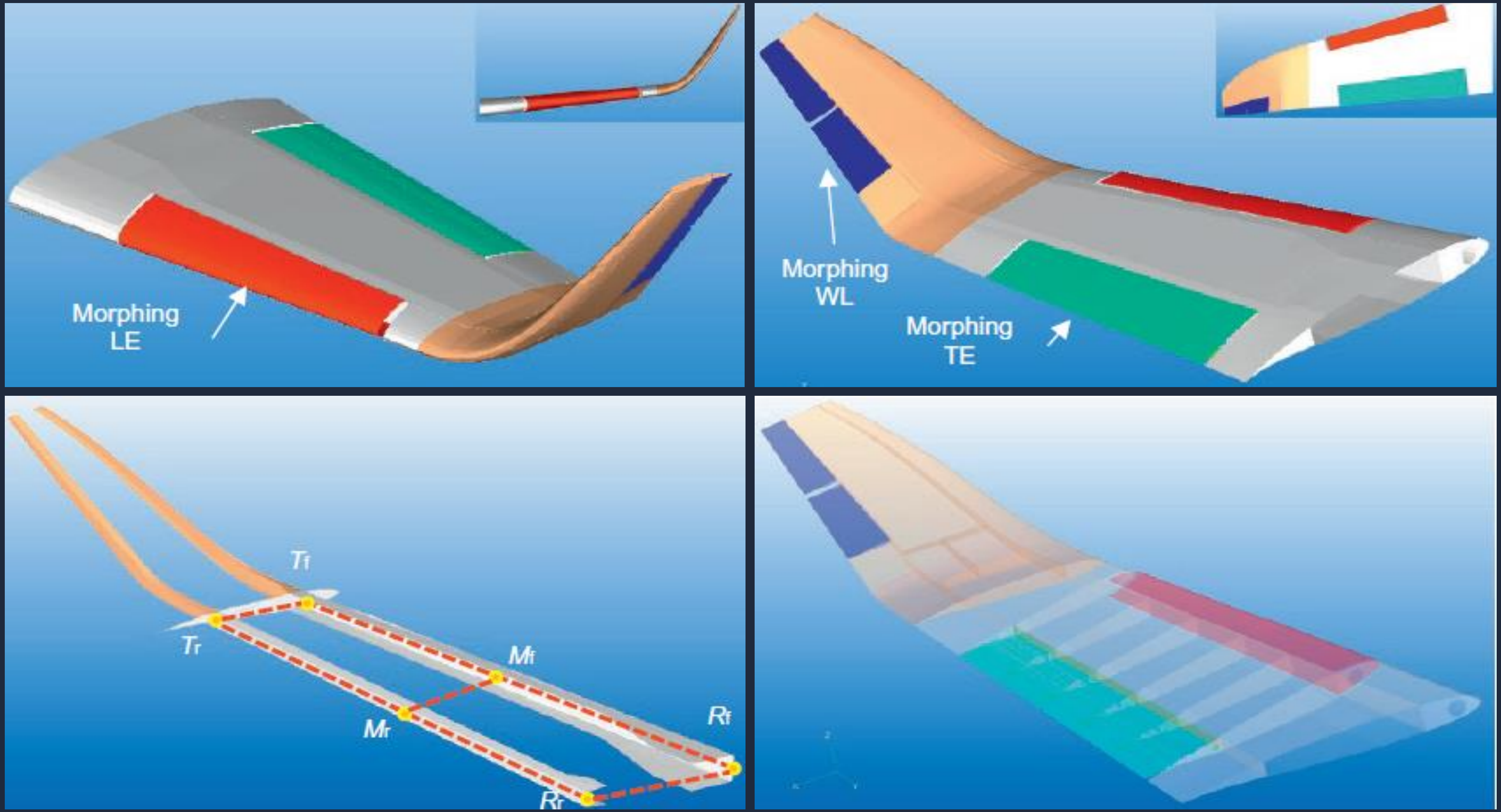
**Dynamic/aeroelastic response**

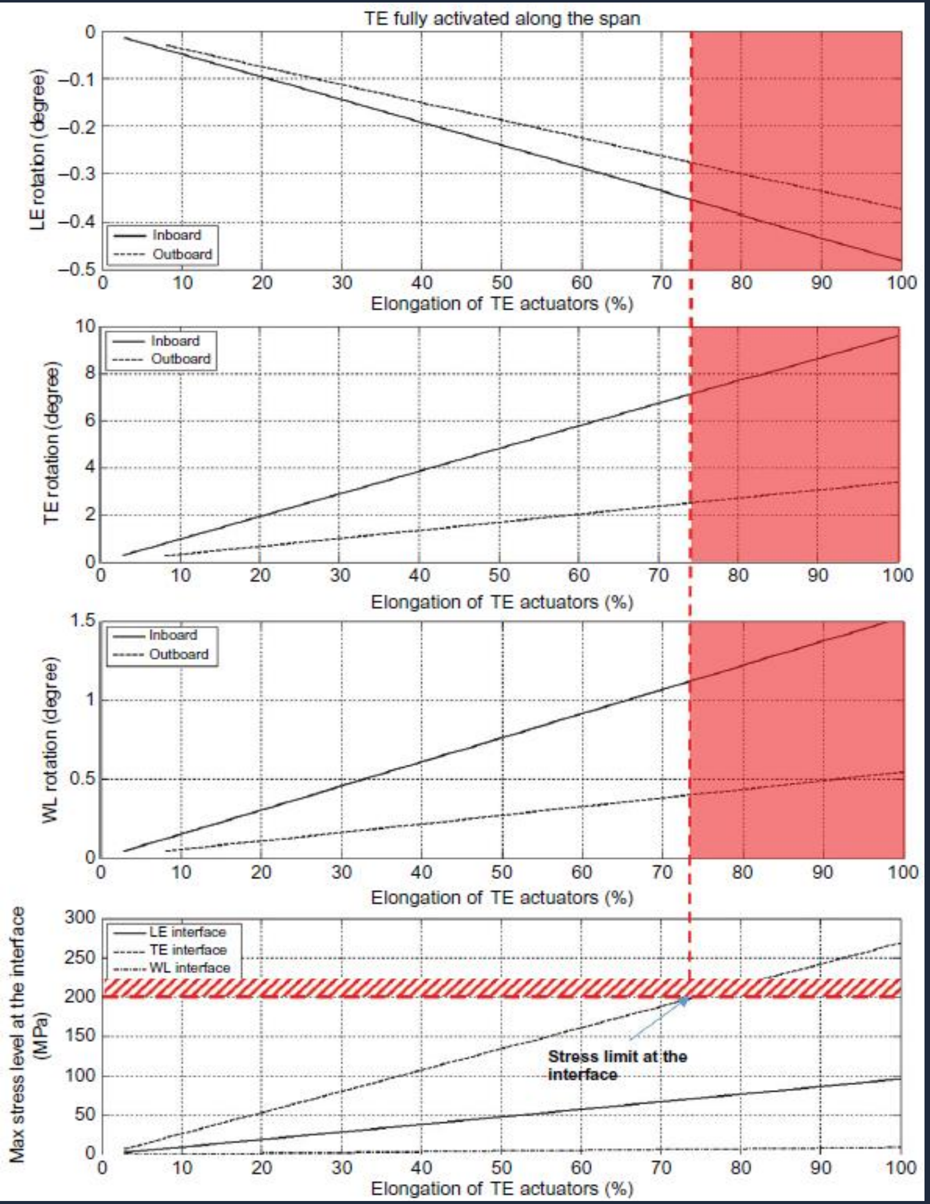
Morphing systems may be classified as **kinematics and compliant**, each with its own characteristics and peculiarities. For instance, kinematic systems are usually related to a larger number of parts and components (architectural complexity), while compliant systems generates larger localized stress and strain fields (design, materials).

In spite the different issues herein addressed should be specialised for each of the abovementioned classes, the main features shall have a general validity unless explicitly stated.

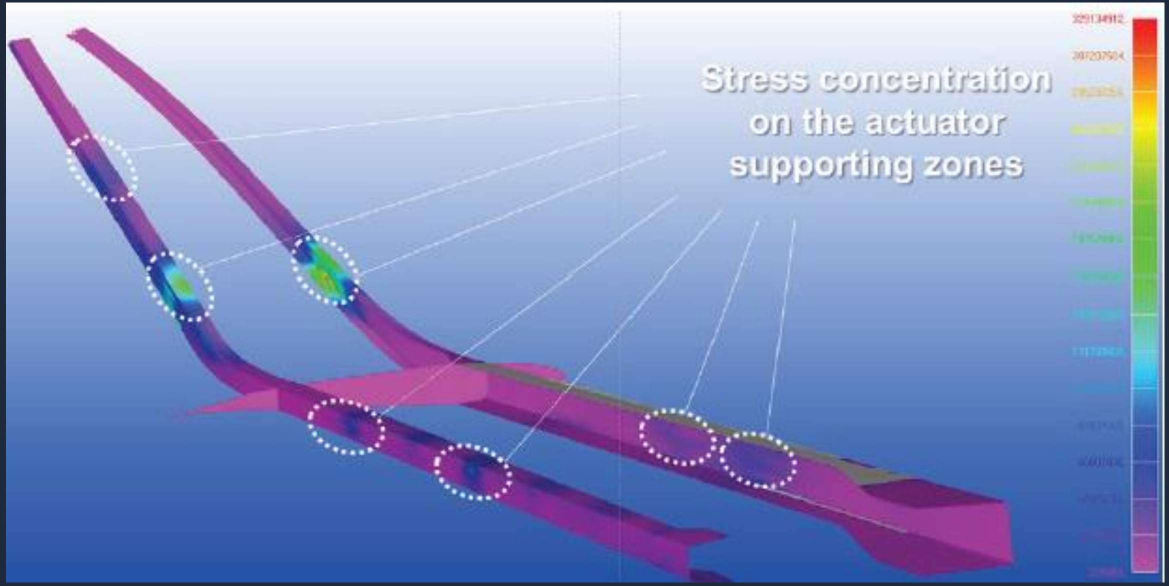
# Load transmission to the supporting structure

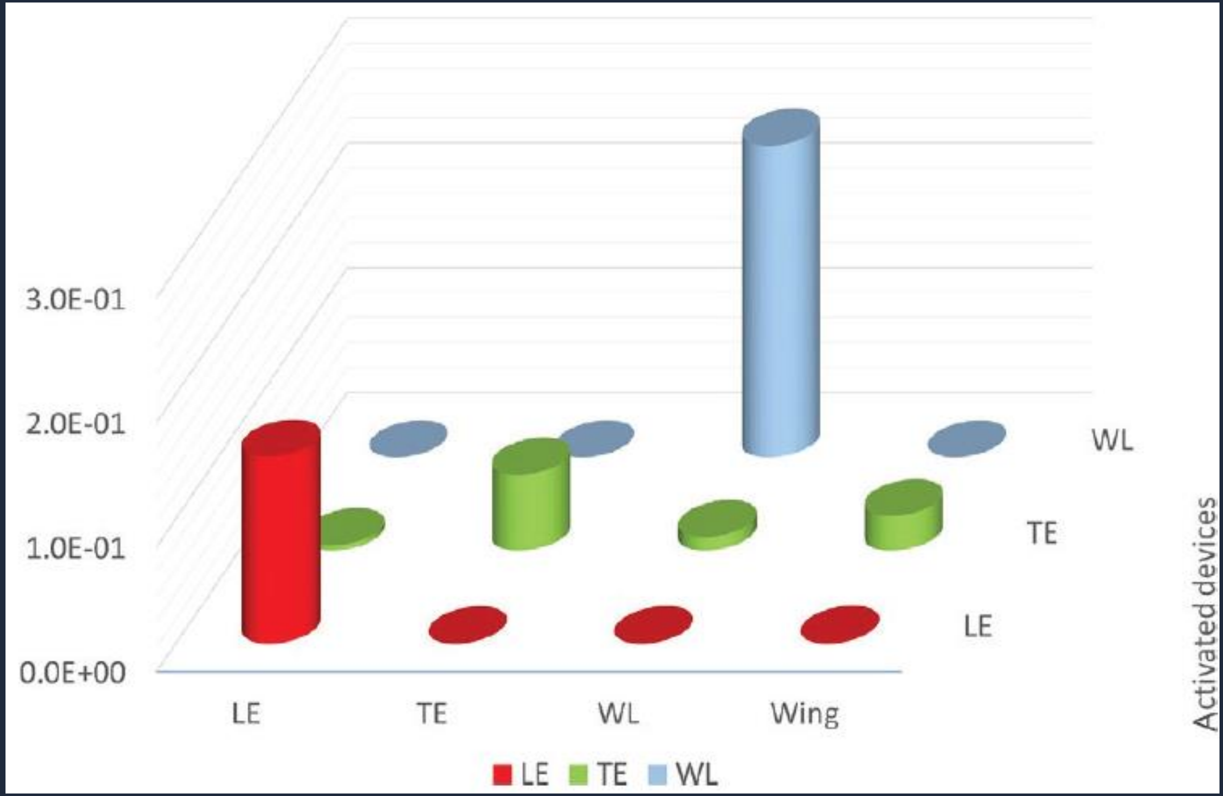
## Wing layout, SARISTU






## Effect of the elasticity of the interface and cross related deflections

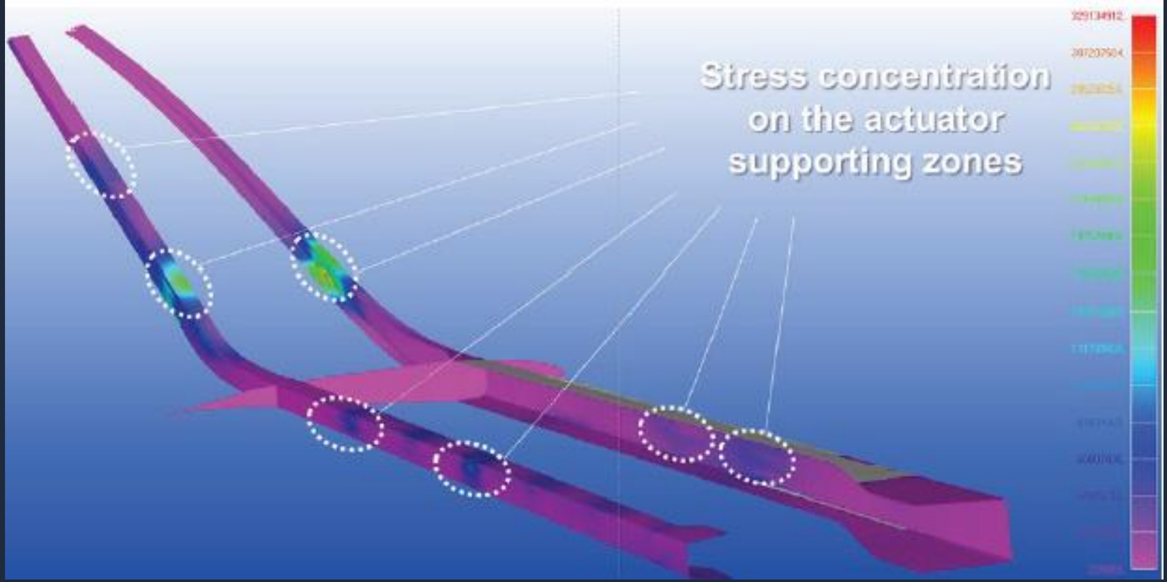


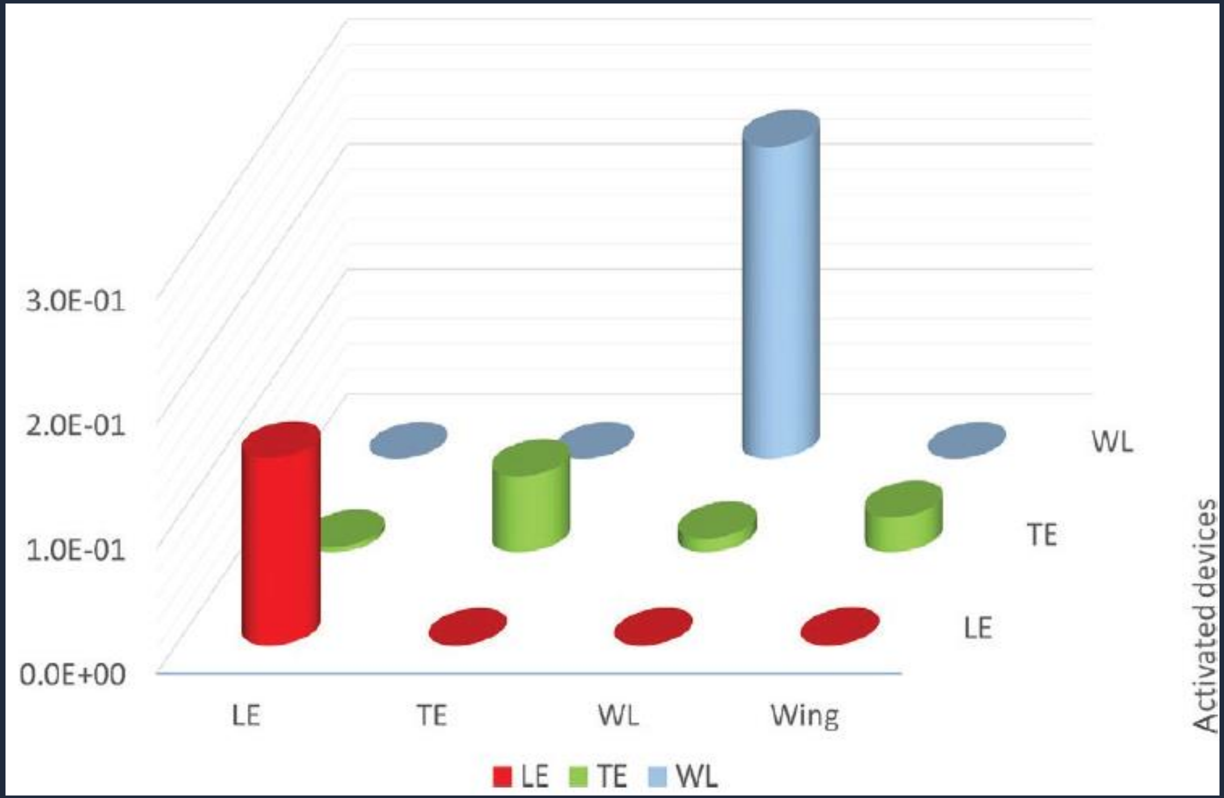



*Ameduri S. (2018), "Influence of the elastic constraint on the functionality of integrated morphing devices", Ch.13, In: Morphing Wing Technologies, pp. 401-428, Elsevier-Butterworth-Heinemann: Concilio A., Dimino I., Lecce L., Pecora R.*

Relative Ratio between Induced and Actuation Rotations %, for each Morphing Device

| | Actuated | | |
|---|---|---|---|
| | **LE** | **TE** | **WL** |
| LE | 1.00E+00 | 7.05E−02 | 3.33E−08 |
| TE | 5.52E−04 | 1.00E+00 | 5.48E−08 |
| WL | 2.19E−03 | 1.76E-01 | 1.00E+00 |
| Wing | 3.93E−03 | 4.53E−01 | 1.38E−04 |



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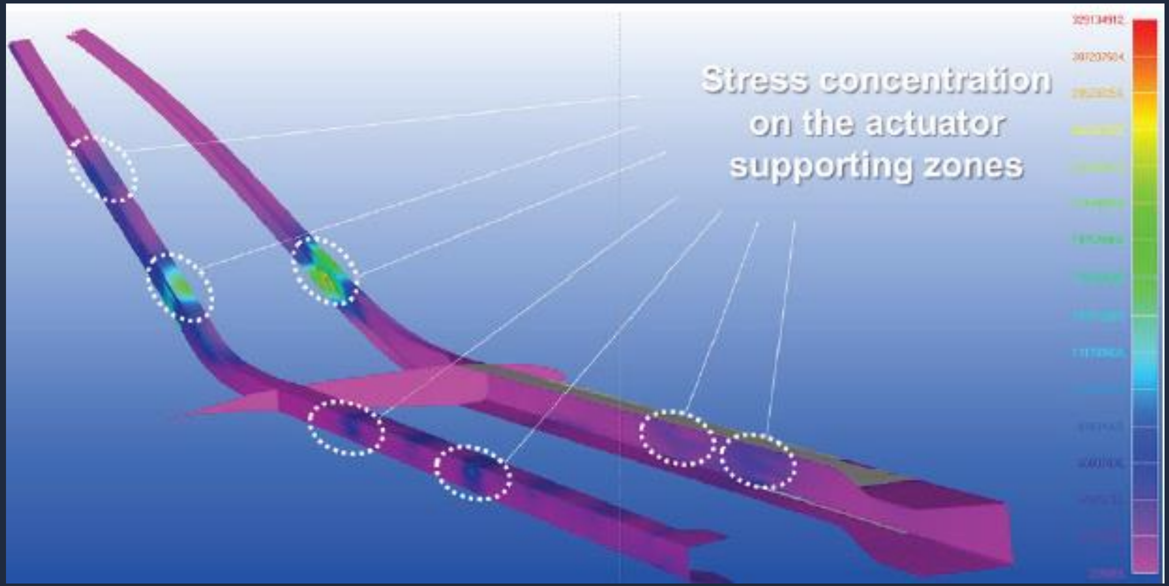

# Load transmission

- Adaptive structures transmit significant loads at the interfaces
- Part of those loads comes from the elastic reaction of the structure when deformed
- This aspect has impact in terms of:
  - stress accumulation at the interfaces
  - losses of functionality of the morphing device
  - alteration of the functionality of other attachments

# Strength vs flexibility

- Different parts of a morphing structure undergo large deformations and, at the same time, must withstand high loads

- Among the other components the skin is particularly impacted… in fact:
  - it is the most centrifuged component with respect the others with a consequent amplification of displacements and deformations
  - it must keep its shape under the aerodynamic loads

# Strength vs flexibility

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  - it must keep its shape under the aerodynamic loads

thus let's just focus on the **SKIN**

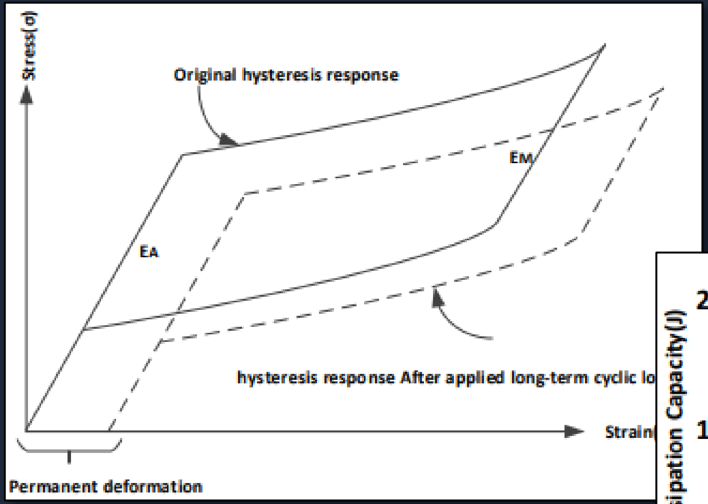
# Skin requirements

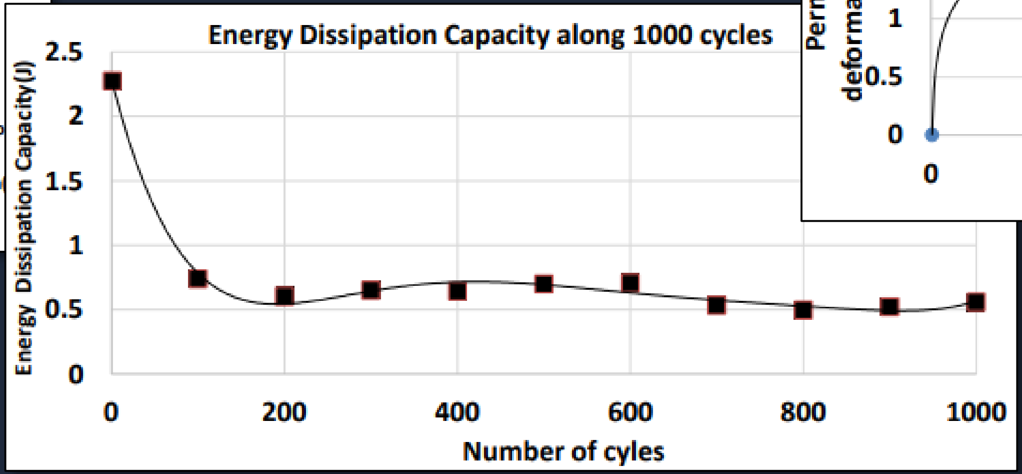
- **elastic/flexible in chordwise direction** to allow low force actuation
- **stiff in spanwise direction** to withstand aerodynamic and inertial loads
- **toughness**
- **abrasion and chemical resistant**
- resistant to **weather agents**
- **high strain** capability → superleasticity
- **Aging and fatigue** resistant

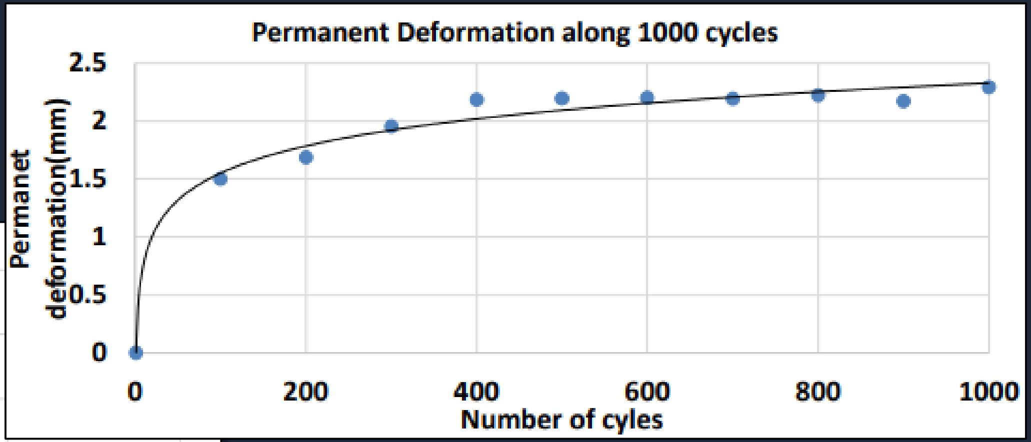

- *Kikuta, M.T. Mechanical properties of candidate materials for morphing wings, 2003, p 123, Department of Mechanical Engineering, Virginia Polytechnic Institute and State University*
- *C. Thill, J. Etches, I. Bond, K. Potter and P. Weaver, "Morphing skins", THE AERONAUTICAL JOURNAL, No. 3216*

# Candidate materials and architectures

## Superelastic materials… SMA



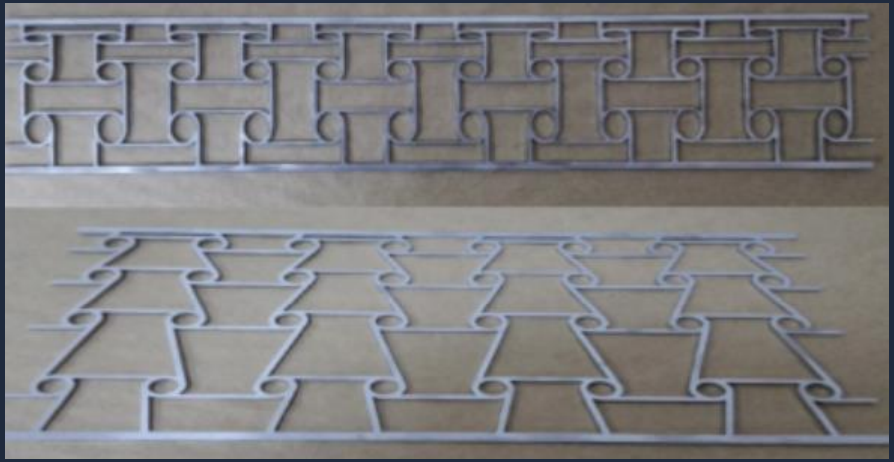



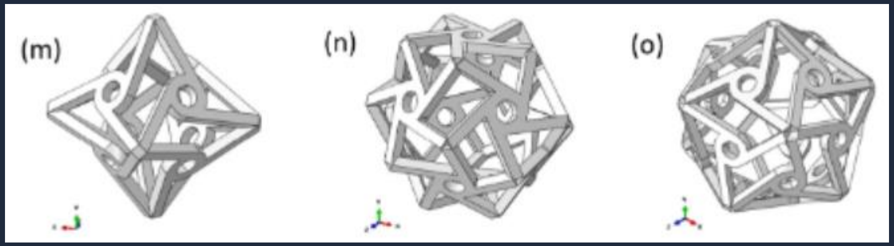

*S Zareie, MS Alam, RJ Seethaler, A Zabihollah, "Effect of cyclic loads on shape memory alloy-based component of cable-stayed bridge", CSCE Annual Conference, Laval (Greater Montreal), June 12 - 15, 2019*

# Candidate materials and architectures

## Auxetic materials

- **advanced manufacturing techniques** are needed for fabrication of composites based on chiral metamaterials
- research attainments on **design optimization does appear still limited**, especially for 3D chiral metamaterials
- **mechanical properties of 2D and 3D chiral mechanical metamaterials under larger deformations** should be further investigated
- **more theoretical models** should be proposed for catching the multifunctional performances of 2D and 3D chiral metamaterials, such as: impact energy absorption
- **more experimental verifications** should be performed for assessing potential industrial applications






*W Wu, W Hu, G Qian, H Liao, X Xu, F Berto, "Mechanical design and multifunctional applications of chiral mechanical metamaterials: A review" Materials & Design, 2019 - Elsevier*

# Candidate materials and architectures

## Laminated composites

### EMC

- Supporting structure required
- Low out-of-plane stiffness

### Fiber reinforced with SMPs

- Low actuation performance

### Honeycombs between stretchable laminae

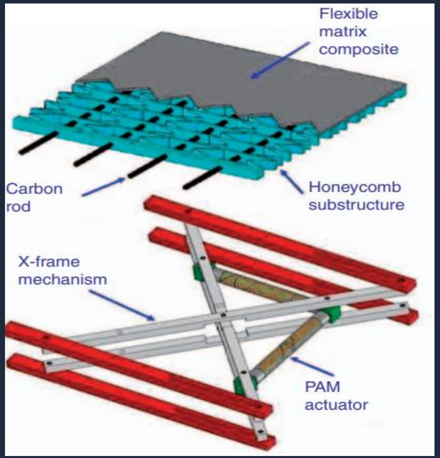
- Composite thickness

### Compliant laminae with sandwiched corrugations

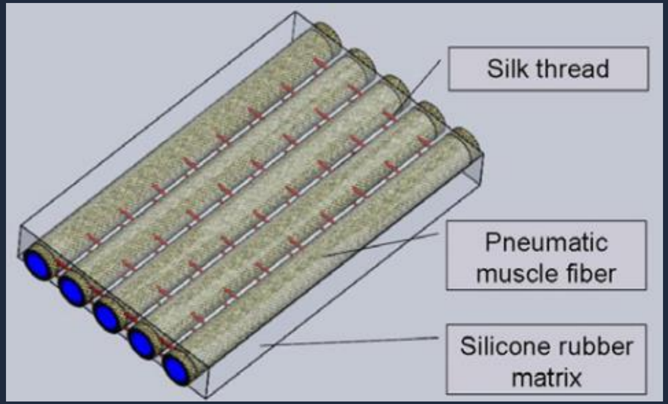
- Composite thickness

### Fluid channels between compliant media

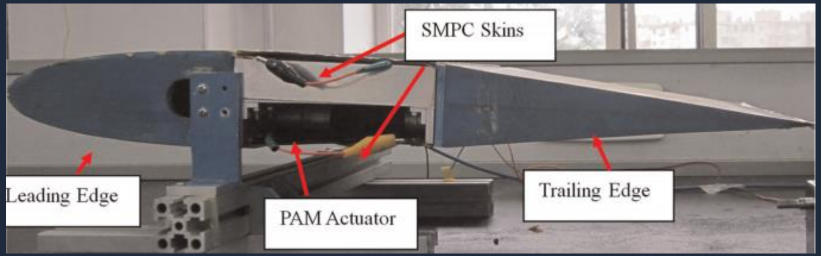
- Bulky fluid sources




*E.A. Bubert, B.K.S. Woods, K. Lee, C.S. Kothera , N.M. Wereley, "Design and Fabrication of a Passive 1D Morphing Aircraft Skin", J. of Intelligent Material Systems and Structures, Vol. 21—November 2010*




*Yijin Chen, Weilong Yin, Yanju Liu , Leng Jinsong, "Structural design and analysis of morphing skin embedded with pneumatic muscle fibers", Smart Materials and Structures 20(8):085033*

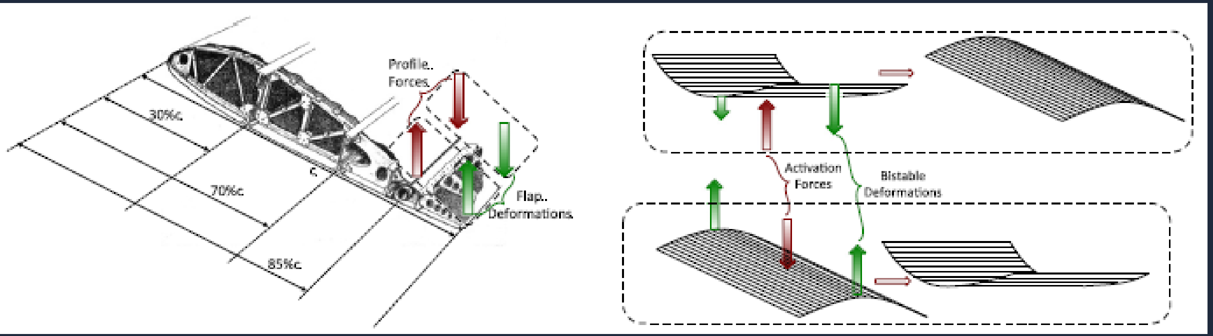



*Jian Sun, Yanju Liu, Jinsong Leng, "Mechanical properties of shape memory polymer composites enhanced by elastic fibers and their application in variable stiffness morphing skins", Journal of Intelligent Material Systems and Structures, 2015, Vol. 26(15) 2020–2027*

*V. S. C. Chillara, M. J. Dapino , "Review of Morphing Laminated Composites" Applied Mechanics Reviews, JANUARY 2020, Vol. 72 / 010801-1*

# Candidate materials and architectures

## Multi-stable composites





- *F. Nicassio, G. Scarselli, F. Pinto, F. Ciampa, O. Iervolino, M. Meo, "Low energy actuation technique of bistable composites for aircraft morphing", Aerospace Science and Technology 75 (2018) 35–46*
- *Y. Cui, " Adaptive multistable flexible composite structures", PhD thesis, Department of Aeronautics Imperial College London, 2015*
- *S. A. Emam, D. J. Inman, " A Review on Bistable Composite Laminates for Morphing and Energy Harvesting", Applied Mechanics Reviews · November 2015*


- low load bearing capability of some stable states
- temperature-dependence of material properties NON-UNIFORM temperature environment
- accurate mathematics modeling of complex nonlinear small- and large-amplitude dynamics
- control of snap-through and snapback motions
- optimizing stiffness in load and actuation directions to ensure structure compliance

# Scalability


- For the sake of clearness we will assume a geometric scale factor of 1/1000, thus passing from m to mm
- If we want to have the same stiffness for the original and scaled structures the relation $K = \frac{F}{x}$ must hold for both of them
- However, for the present case, $K = \frac{EA}{L}$… this means that keeping constant the material, there is a factor of 1000 between the original and scaled structure

*S. Ameduri, A. Concilio, "A shape memory alloy torsion actuator for static blade twist", Journal of Intelligent Material Systems and Structures,2019, Vol. 30(17) 2605–2626*

# Scalability


- Finally, dynamic behaviour: $\omega = \sqrt{\frac{E}{\rho L^2}}$
- Referring to the same material, the ratio $E/\rho$ does not change, while the length is reduced by 3 magnitudes
- Consequently, the frequency of the scaled structure is 1000 times the original one

*S. Ameduri, A. Concilio, "A shape memory alloy torsion actuator for static blade twist", Journal of Intelligent Material Systems and Structures,2019, Vol. 30(17) 2605–2626*

# Scalability

## Another example… compliant mechanism vs size/weight/load

| Parameter | Herti / AR4 (ref) |
|---|---|
| Size (chord) | ~8 |
| Wing loading | 3 |
| MTOW | 160 |

Considering a metallic honeycomb filler for the wing and the limitations given by the wing depth and chord, a weight ratio of **500** results between the two wings

*R. M. Ajaj, C. S. Beaverstock, M. I. Friswell, "Morphing aircraft: The need for a new design philosophy", Aerospace Science and Technology, Vol 49,  2016, Pages 154-166*

# Scalability

- Morphing structures are very scale-dependent
- Different architectures must be adopted to actuate the same functionality on geometrically similar models
- For WT tests, it is not possible to define a unique scale factor for geometry elasticity and aerodynamics (…and aeroelasticity…)
- Compliant mechanisms appear non-convenient as the aircraft size arises

# Aeroelastic behavior of morphing systems

- Morphing systems enable more DOFS with benefits in terms of LCA efficiency

- However
  - Due to the intrinsic non linearity (large displacements and related stress accumulation) dedicated modeling approaches are needed, encompassing clean and deformed configurations
  - More distributed dofs → higher modal density → higher probability of bending and torsional modes coupling and higher probability of failures

*Claudia Y. Herrera, Shun-fat Lung, Gregory Ervin, Peter Flick, "Aeroelastic Airworthiness Assessment of The Adaptive Compliant Trailing Edge Flaps", SFTE 2015 Symposium*

*Maria Chiara Noviello, Ignazio Dimino, Antonio Concilio, Francesco Amoroso, Rosario Pecora, "Aeroelastic Assessments and Functional Hazard Analysis of a Regional Aircraft Equipped with Morphing Winglets", Aerospace 2019, 6, 104*

# Conclusions

An overview of the challenges and current showstoppers of the morphing technology was provided; we found that:

- Morphing systems exhibit an unconventional transmission modality of loads, due to the elastic reaction of the deformed structure
- The strength-flexibility paradox primed the development of different types of skins, characterized by specific limits
- Morphing systems cannot be easily scaled → no immediate transportation of the technology to different aircraft classes and dedicated/partial requirements for WT tests
- Morphing systems exhibit specific aeroelastic behavior, due to their intrinsic non-linearity and the higher dofs with respect to conventional systems

# References

## Aerospace growth and environmental impact and morphing expectation


- https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg111-115.pdf
- F. Previtali, A. F. Arrieta and P. Ermanni, "Performance of a Three-Dimensional Morphing Wing and Comparison with a Conventional Wing", https://doi.org/10.2514/1.J052764
- https://www.atkinsglobal.com/~/media/Files/A/Atkins-Corporate/aviation-trends-white-paper-digital.pdf
- https://www.raconteur.net/business-innovation/aviation -industry-soaring-into-the-future
- http://forhumanliberation.blogspot.com/2018/02/2825-air-travel-and-climate-change.html
- https://www.prescouter.com/2018/01/ technologies-improving-aircraft-fuel-efficiency/
- https://www.ansys.com/blog/5-trends-aerospace-industry-multiphysics-simulation
- http://theconversation.com/morphing-is-one-way-to-make-aircraft-more-efficient-23683
- M.L. Wilbur, M.P. Mistry, P.F. Lorber, R. Blackwell Jr., S. Barbarino, T. H.Lawrence, U. T.P. Arnold (2018). “Rotary Wings Morphing Technologies: State of the Art and Perspectives”, Ch.24, In: Morphing Wing Technologies, pp.759-797, Elsevier Butterworth-Heinemann, A. Concilio, I. Dimino, L. Lecce, R. Pecora
- https://www.aia-aerospace.org/issue/environment/
- F. Moens, "Augmented Aircraft Performance with the Use of Morphing Technology for a Turboprop Regional Aircraft Wing", Biomimetics (Basel). 2019 Sep; 4(3): 64
- S. Barbarino, O. Bilgen, R. M. Ajaj, M. I. Friswell, D. J. Inman, “A Review of Morphing Aircraft”, Journal of Intelligent Material Systems and Structures, Vol. 22—June 2011
- J. E. Green, "Civil aviation and the environmental challenge", THE AERONAUTICAL JOURNAL, 281-299, 2003

# References

## Aerospace growth and environmental impact and morphing expectation


- https://www.industryweek.com/supply-chain/supplier-relationships/article/21972312/5-key-trends-impacting-the-aerospace-sector-and-what-they-mean-for-growth
- N. S. Chandra, N. V. Raghavendra, G. L. Shekar, "Aerospace industry of India: Analysis of strengths, weaknesses, opportunities and threats", 2016 7th International Conference on Mechanical and Aerospace Engineering (ICMAE)
- https://www.accenture.com/_acnmedia/accenture/redesign-assets/dotcom/documents/global/1/accenture-commercial-aerospace-insight-report.pdf
- M. Anderson, "The Role of Collaborative Integration in Industrial Organization: Observations from the Canadian Aerospace Industry", Journal Economic Geography Vol. 71, 1995 - Issue 1:Pages 55-78
- M. Su, D. Tsang, "Entrepreneurial judgment and re-combinative innovation: the emergence of the Chinese aerospace industry", Advances in Economics, Business and Management Research, 31. pp. 1418. ISSN 23525428 doi:https://doi.org/10.2991/msmi17.2017.4
- K. Domae, H. Matsumoto, "Spatial Concentration of Aerospace Industry and Agglomerations Economies in Aircraft Parts Industry: A Case Study in Japan", Asian Transport Studies, Volume 5, Issue 4 (2019), 635–652
- J. Luna, S. Addepalli, K. Salonitis, H. Makatsoris, "Assessment of an emerging aerospace manufacturing cluster and its dependence on the mature global clusters", 6th International Conference on Through-life Engineering Services, TESConf 2017, 7-8 November 2017, Bremen, Germany
- https://www.aef.org.uk/uploads/RCEP_Env__Effects_of_Aircraft__in__Flight_1.pdf

# References


## Load transmission to the supporting structure

- S. Ameduri (2018). “Influence of the elastic constraint on the functionality of integrated morphing devices”, Ch.13, In: Morphing Wing Technologies, pp.401-428, Elsevier Butterworth-Heinemann: A. Concilio, I. Dimino, L. Lecce, R. Pecora
- M. Bellucci, M. C. Noviello, F. Amoroso, R. Pecora, I. Dimino, A. Concilio (2018). “Stress Analysis of a Morphing System”, Ch. 15, In: Morphing Wing Technologies, pp.451-488, Elsevier Butterworth-Heinemann: A. Concilio, I. Dimino, L. Lecce, R. Pecora
- S. K. Patiballa , G. Krishnan, "Estimating Optimized Stress Bounds in Early Stage Design of Compliant Mechanisms", J. Mech. Des. Jun 2017, 139(6): 062302 (12 pages)
- P. C. Wölcken, A. Kötter, B. Newman, R. Wadleich, K. Genzel, SARISTU: Six Years of Project Management, Smart Intelligent Aircraft Structures (SARISTU) pp 1-40

## Stress vs flexibility - skins

- H. You, W. Y. Joe, G. Yun, "New Concept for Aircraft Morphing Wing Skin: Design, Modeling, and Analysis", March 2019, AIAA Journal, DOI: 10.2514/1.J058102
- MORPHING SKIN: FOAMS 7 pp. 207-230 Oliver Schorsch, Christof Nagel, Andreas L€uhring, Fraunhofer IFAM, Bremen, Germany)
- W. Wu, W. Hua, G. Qian, H. Liao, X. Xud, F. Berto, "Mechanical design and multifunctional applications of chiral mechanical metamaterials: A review", Materials and Design 180 (2019) 107950
- W. A. Chapkin, P. Walgren, G. J. Frank, D. R. Seifert, M. R. W. Rashidi, D. J. Hartl, J. W. Baur, "Bending mechanics of cylindrical skins for morphing aerospace applications", Materials and Design 186 (2020) 108316
- W. A. Chapkin, P. Walgren, G. J. Frank, D. R. Seifert, D. J. Hartl, J. W. Baur, "Design and optimization of high-strain, cylindrical composite skins for morphing fuselages", https://doi.org/10.1016/j.matdes.2019.108395

# References

## Stress vs flexibility - skins


- J. Qiu, C. Wang, C. Huang, H. Ji, Z. Xu, "Smart skin and actuators for morphing structures", 23rd International Congress of Theoretical and Applied Mechanics, IUTAM 10 ( 2014 ) 427 – 441
- K. R. Olympio, F. Gandhi, "Zero Poisson's Ratio Cellular Honeycombs for Flex Skins Undergoing One-Dimensional Morphing", Journal of Intelligent Material Systems and Structures, Vol. 21—November 2010, pp. 1737-1753
- W. Raither, E. Furger, M. Zu¨ndel, A. Bergamini, P. Ermanni, "Variable-stiffness skin concept for camber-morphing airfoils", Journal of Intelligent Material Systems and Structures 2015, Vol. 26(13) 1609–1621
- F. Previtali, A. F Arrieta and P. Ermanni, "Double-walled corrugated structure for bending-stiff anisotropic morphing skins", Journal of Intelligent Material Systems and Structures 2015, Vol. 26(5) 599–613
- J. Sodja, M. J Martinez, J. C Simpson, R. De Breuker, "Experimental evaluation of a morphing leading edge concept", Journal of Intelligent Material Systems and Structures 2019, Vol. 30(18-19) 2953–2969
- C. Wang, H. Haddad Khodaparast, M.I. Friswell, A. Magrini, R. Ponza, E. Benini, V. Landersheim, D. Laveuve, C .C. Asins, "Conceptual-level evaluation of a variable stiffness skin for a morphing wing leading edge", Proc IMechE Part G:J Aerospace Engineering 2019, Vol. 233(15) 5703–5716
- J. Sun, Q. Guan, Y. Liu, J. Leng, "Morphing aircraft based on smart materials and structures: A state-of-the-art review", Journal of Intelligent Material Systems and Structures 1–24, 2016
- B. Alsaidi, W. Y. Joe, M. Akbar, "Simplified 2D Skin Lattice Models for Multi-Axial Camber Morphing Wing Aircraft", Aerospace 2019, 6, 90; doi:10.3390/aerospace6080090
- S. Emam, D. Inman, "A Review on Bistable Composite Laminates for Morphing and Energy Harvesting", Applied Mechanics Reviews, november 2015, Vol. 67 / 060803-1

# References

## Stress vs flexibility - skins


- K. Yu, W. Yin, Y. Liu, J. Leng, "Application of SMP composite in designing a morphing wing", Proceedings Volume 7375, ICEM 2008: International Conference on Experimental Mechanics 2008; 737560 (2009) https://doi.org/10.1117/12.839363
- Q. Ai, P. M.Weaver, M. Azarpeyvand, "Design and mechanical testing of a variable stiffness morphing trailing edge flap", Journal of Intelligent Material Systems and Structures, 29(4), 669-683
- E. A. Bubert, B. K.S. Woods, K. Lee, C. S. Kothera, N.M. Wereley, "Design and Fabrication of a Passive 1D Morphing Aircraft Skin", Journal of Intelligent Material Systems and Structures 2010 21: 1699
- C. K. Khoo, F. Salim, J. Burry, "Designing Architectural Morphing Skins with Elastic Modular Systems", international journal of architectural computing issue 04, vol 09
- A.D. Shaw, I. Dayyani, M.I. Friswell, "Optimisation of composite corrugated skins for buckling in morphing aircraft", Composite Structures 119 (2015) 227–237
- E. P. Koumoulos, A. F. Trompeta, R. M. Santos, M. Martins, C. M. dos Santos, V. Iglesias, R. Böhm, G. Gong, A. Chiminelli, I. Verpoest, P. Kiekens, C. A. Charitidis, "Research and Development in Carbon Fibers and Advanced High-Performance Composites Supply Chain in Europe: A Roadmap for Challenges and the Industrial Uptake", J. Compos. Sci. 2019, 3, 86
- F. Nicassio, G. Scarselli, F. Pinto, F. Ciampa, O. Iervolino, M. Meo, "Low energy actuation technique of bistable composites for aircraft morphing", Aerospace Science and Technology 75(2018)35–46
- C. Thill, J. Etches, I. Bond, K. Potter and P. Weaver, "Morphing skins", The Aeronautical Journal, Paper No. 3216
- S. Zareie, M. S. Alam, R. J. Seethaler, A. Zabihollah, "Effect of Cyclic Loads on Shape Memory Alloy-based Component of Cable-stayed Bridge", CSCE Annual Conference 2019

# References

## Scalability


- S. Ameduri, A. Concilio, “A shape memory alloy torsion actuator for static blade twist”, Journal of Intelligent Material Systems and Structures, 2019, Vol. 30(17) 2605–2626
- R. M. Ajaj, C. S. Beaverstock, M. I. Friswell, "Morphing aircraft: The need for a new design philosophy", Aerospace Science and Technology, Vol 49, 2016, Pages 154-166


## Aeroelastic behavior of morphing systems


- H. Ren, Q. Zhiping, "Transient aeroelastic responses and flutter analysis of a variable-span wing during the morphing process", Chinese Journal of Aeronautics, (2013),26(6): 1430–1438
- C. Huang, C. Yang, Z. Wu, C. Tang, "Variations of flutter mechanism of a span-morphing wing involving rigid-body motions", Chinese Journal of Aeronautics, (2018), 31(3): 490–497
- A. De Gaspari, S. Ricci, L. Travaglini, "Aeroelastic analysis of a regional aircraft with morphing wing using PyPAD framework", 4th SCAD, Symposium on Collaboration in Aircraft Design, 25-27 November 2014, ONERA, Toulouse
- L. Unlüsoy, Y. Yaman, "Aeroelastic behaviour of UAV wings due to morphing", Aircraft Engineering and Aerospace Technology: An International Journal, Vol. 89 · Number 1, 2017, pp, 30–38
- D. P. Holmes, "Elasticity and Stability of Shape Changing Structures", Current Opinion in Colloid and Interface Science, September 14, 2018
- V. C. de Sousa, C. De Marqui Jr, "Effect of pseudoelastic hysteresis of shape memory alloy springs on the aeroelastic behavior of a typical airfoil section", Journal of Intelligent Material Systems and Structures 2016, Vol. 27(1) 117–133

# References

## Aeroelastic behavior of morphing systems


- F. Rea, R. Pecora, F. Amoroso, M. Arena, M. C. Noviello, "Aeroelastic Stability Analysis of a Wind Tunnel Wing Model Equipped with a True Scale Morphing Aileron",International Journal of Mechanical Engineering and Robotics Research Vol. 6, No. 6, November 2017
- M. C. Noviello, I. Dimino, A. Concilio, F. Amoroso, R. Pecora, M. C. Noviello, I. Dimino, A. Concilio, F. Amoroso, R. Pecora, "Aeroelastic Assessments and Functional Hazard Analysis of a Regional Aircraft Equipped with Morphing Winglets", Aerospace 2019, 6, 104
- S. Courchesne, A. V. Popov, R. M. Botez, "New aeroelastic studies for a morphing wing", INCAS BULLETIN, Volume 4, Issue 2/ 2012, pp. 19 – 28 ISSN 2066 – 8201
- R. De Breuker, M. Abdalla, Z. Gurdal, D. Lindner, "Energy-Based Aeroelastic Analysis of a Morphing Wing", Modeling, Signal Processing, and Control for Smart Structures 2007, Proc. of SPIE Vol. 6523, 652308, (2007)

# Thank you for your kind attention!

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