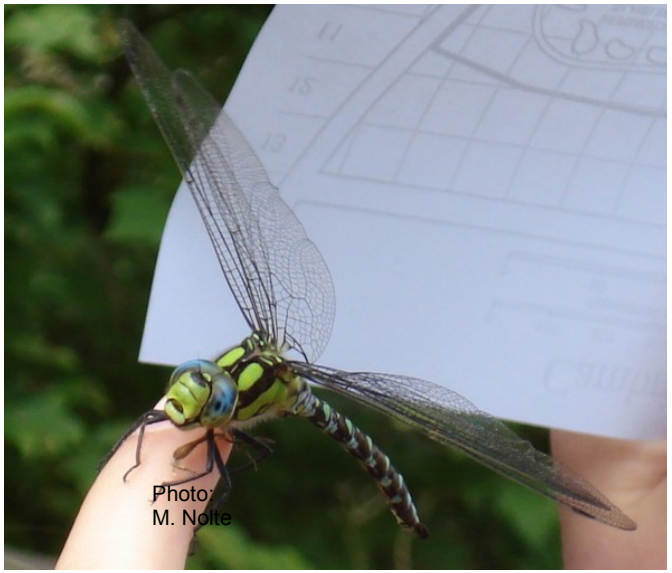
Measuring wing elasticity in insect wings - problems and solutions

Henja Wehmann

Different species have been investigated

- Dragonflies and damselflies (Newman & Wootton 1986, Combes & Daniel 2003a, Combes & Daniel 2003b, Wang et al. 2008, Chen et al. 2008, Chen et al. 2013, Talukder & Shivakumar 2016)
- Butterflies and moths (Steppan 2000, Combes & Daniel 2003, Combes & Daniel 2003a, Combes & Daniel 2003b, Mengesha et al. 2011)
- Flies (Ganguli et al. 2010, Lehmann et al. 2011)



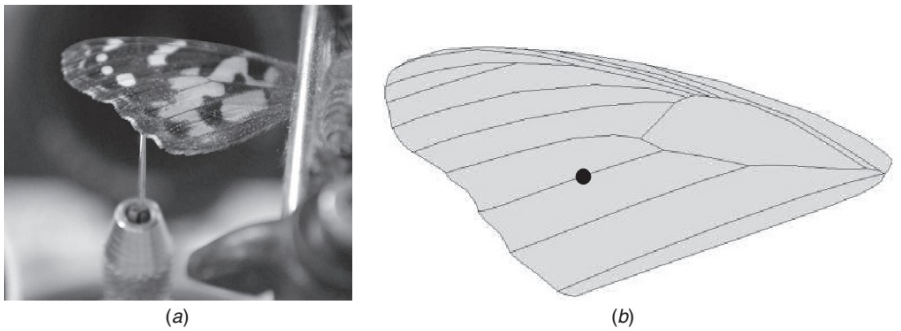
What is stiffness?

- Elastic modulus/Young's modulus *E* (Pa) describes relationship between stress and strain in a material
- Stiffness (N/m): indicator of how much something resists deformation (https://en.wikipedia.org/wiki/Stiffness)
- Flexural stiffness (Nm²) of an object as *EI/L* or *EI* (*E*: elastic modulus, *I*: second moment of area, *L*: length of member) (https://en.wikipedia.org/wiki/Moment_distribution_method#Flexural_stiffness,https://de.wikipedia.org/wiki/Biegesteifigkeit#Biegesteifigkeit)
- Extensional stiffness (N) as *EA* (*A*: cross-sectional area) (https://de.wikipedia.org/wiki/Biegesteifigkeit#Dehnsteifigkeit)
- Bending stiffness *K(E,I,L,boundary conditions)* (https://en.wikipedia.org/wiki/Bending_stiffness)

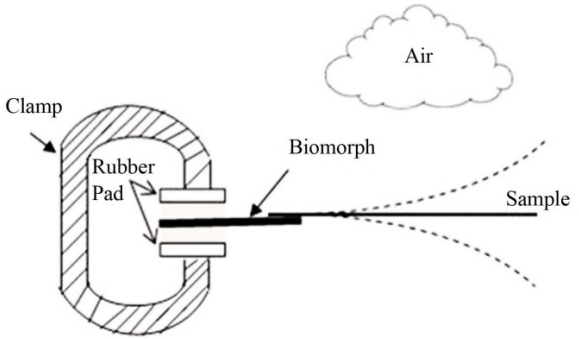
Many terms and definitions
and not always used in a very ordered manner.

Measuring stiffness (N/m)

- Mostly cantilever beam tests with point loads (Newman & Wootton 1986, Wang et al. 2008, Ganguli et al. 2010, Mengesha et al. 2011)
  - Leads to values around 1 to 50 N/m depending on species, state of the wing, bending direction, …
- Vibrating cantilever test (Talukder & Shivakumar 2016)
  - Values on the order of 0.1 N/m in damselfly wings



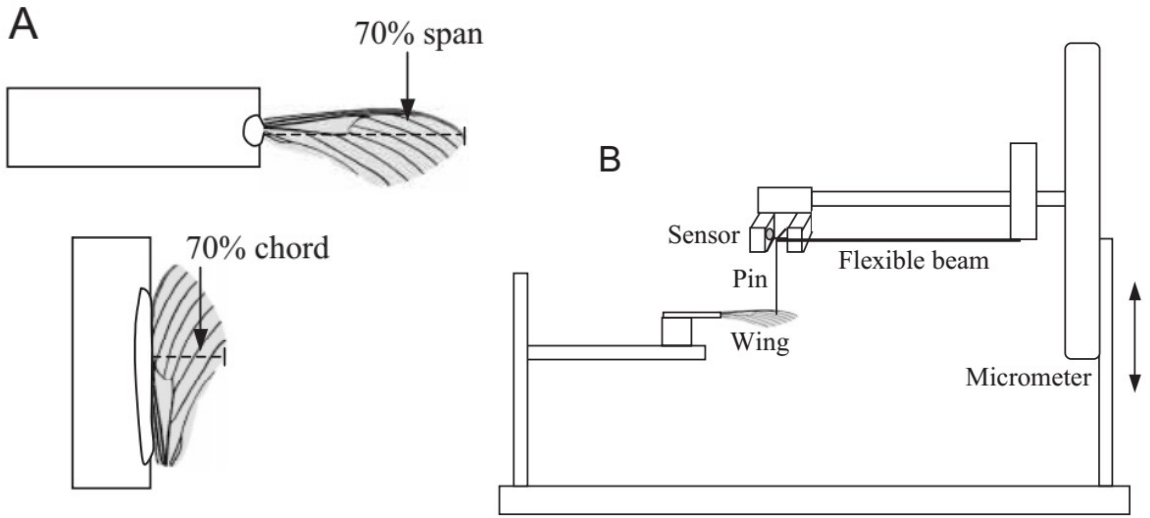
Mengesha et al. (2011), Bioinsp. Biomim. 6:014001, figure 2.



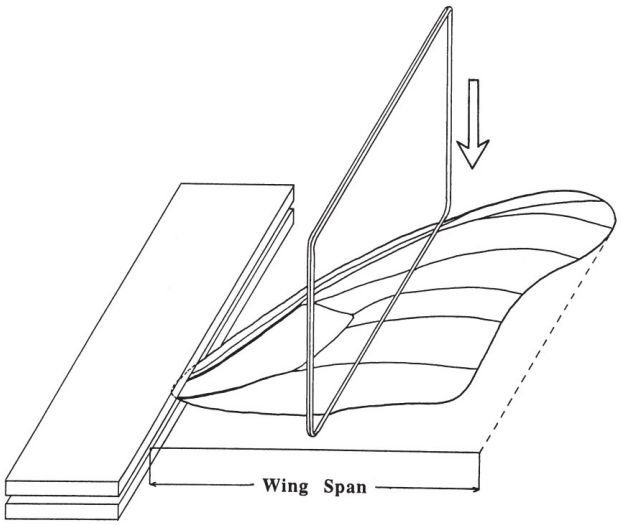
Talukder & Shivakumar (2016), J. Biomat. Nanobiotech. 7:127-141, figure 4.

Measuring flexural stiffness

- Mostly cantilever beam tests with line or point loads (Steppan 2000, Combes & Daniel 2003a, Combes & Daniel 2003b, Ganguli et al. 2010, Lehmann et al. 2011)
  - Usually at different distances from fixed end
  - Usually results in values of integrated stiffnesses up to where the load is positioned
  - Values around 0.1μNm² (between 0.01 and 600μNm²), depending on species, state of wing, position on chord/span, ...



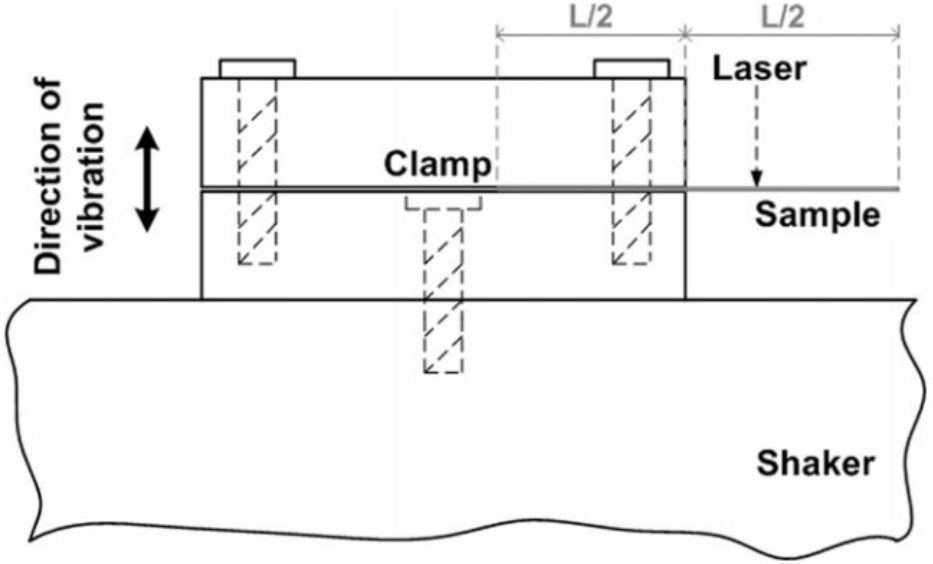
Combes & Daniel (2003), JEB 206:2979-2987, figure 2.



Steppan (2000), J. Res. Lepid. 35:61-77, figure 1.

Measuring Young's modulus

- 3-point-bending test (Wang et al. 2008)
  - Dragonfly *Pantala*
  - Forewing: 24 to 32 GPa
  - Hindwing: 60 to 80 GPa
- Vibrating cantilever beam test (Chen et al. 2013)
  - Leading edge vein of dragonfly *Sympetrum* only
  - 30MPa (fresh) to 615MPa (dry)



Chen et al. (2013), MatLetters 97:166-168, figure 1.

Other things to measure and keep in mind

- Natural frequencies (Chen et al. 2008, Talukder & Shivakumar 2016)
  - Dragonflies/damselflies, frequencies between 120 and 270 Hz
- Mode shapes (Chen et al. 2008, Talukder & Shivakumar 2016)
  - Bending and twisting
- Damping of air and material (Combes & Daniel 2003, Chen et al. 2008, Talukder & Shivakumar 2016)
  - No consensus on the importance of damping
- State of the wing matters: Desiccation increases stiffness (Steppan 2000, Chen et al 2013)
- Is only part or all of the wing being measured?

Questions to ask:

- What exactly do we mean by 'stiffness'?
- What and how can we measure?
- What assumptions underlie our experiments? Are the justified?
  - e.g. homogeneous beams of rectangular cross-section

References

- Chen, J.-S.; Chen, J.-Y. & Chou, Y.-F. (2008): On the natural frequencies and mode shapes of dragonfly wings, *Journal of Sound and Vibration* 313: 643-654.
- Chen, Y. H.; Skote, M.; Zhao, Y. & Huang, W. M. (2013): Stiffness evaluation of the leading edge of the dragonfly wing via laser vibrometer, *Materials Letters* 97: 166-168.
- Combes, S. & Daniel, T. (2003): Into thin air: contributions of aerodynamic and intertial-elastic forces to wing bending in the hawkmoth *Manduca sexta*, *JEB* 206: 2999-3006.
- Combes, S. & Daniel, T. (2003a): Flexural stiffness in insect wings I. Scaling and the influence of wing venation, *JEB* 206: 2979-2987.
- Combes, S. & Daniel, T. (2003a): Flexural stiffness in insect wings II. Spatial distribution and dynamic wing bending, *JEB* 206: 2989-2997.
- Ganguli, R.; Gorb, S.; Lehmann, F.-O.; Mukherjee, S. & Mukherjee, S. (2010): An experimental and numerical study of *Calliphora* wing structure, *Experimental Mechanics* 50: 1183-1197.
- Lehmann, F.-O.; Gorb, S.; Nasir, N. & Schützner, P. (2010): Elastic deformation and energy loss of flapping fly wings, *JEB* 214: 2949-2961.
- Mengesha, T. E.; Vallance, R. R. & Mittal, R. (2011): Stiffness of desiccating insect wings, *Bioinspiration and Biomimetics* 6: 014001.
- Newman, D. J. S. & Wootton, R. J. (1986): An approach to the mechanis of pleating in dragonfly wings, *JEB* 125: 361-372.
- Steppan, S. J. (2000):Flexural stiffness patterns of butterfly wings (Papilionoidea), *J. Research on the Lepidoptera* 35: 61-77.
- Talukder, R. & Shivakumar, K. N. (2016): Measurement of vibrational stiffness and air damping of damselfly wings, *Journal of Biomaterials and Nanobiotechnology* 7: 127-141.
- Wang, X.-S.; Li, Y. & Shi, Y.-F. (2008): Effects of sandwich microstructures on mechanical behaviors of dragonfly wing vein, *Composites Science and Technology* 68: 186-192.