The statics of the maraging blades in SuperAttenuators: simulation and tests

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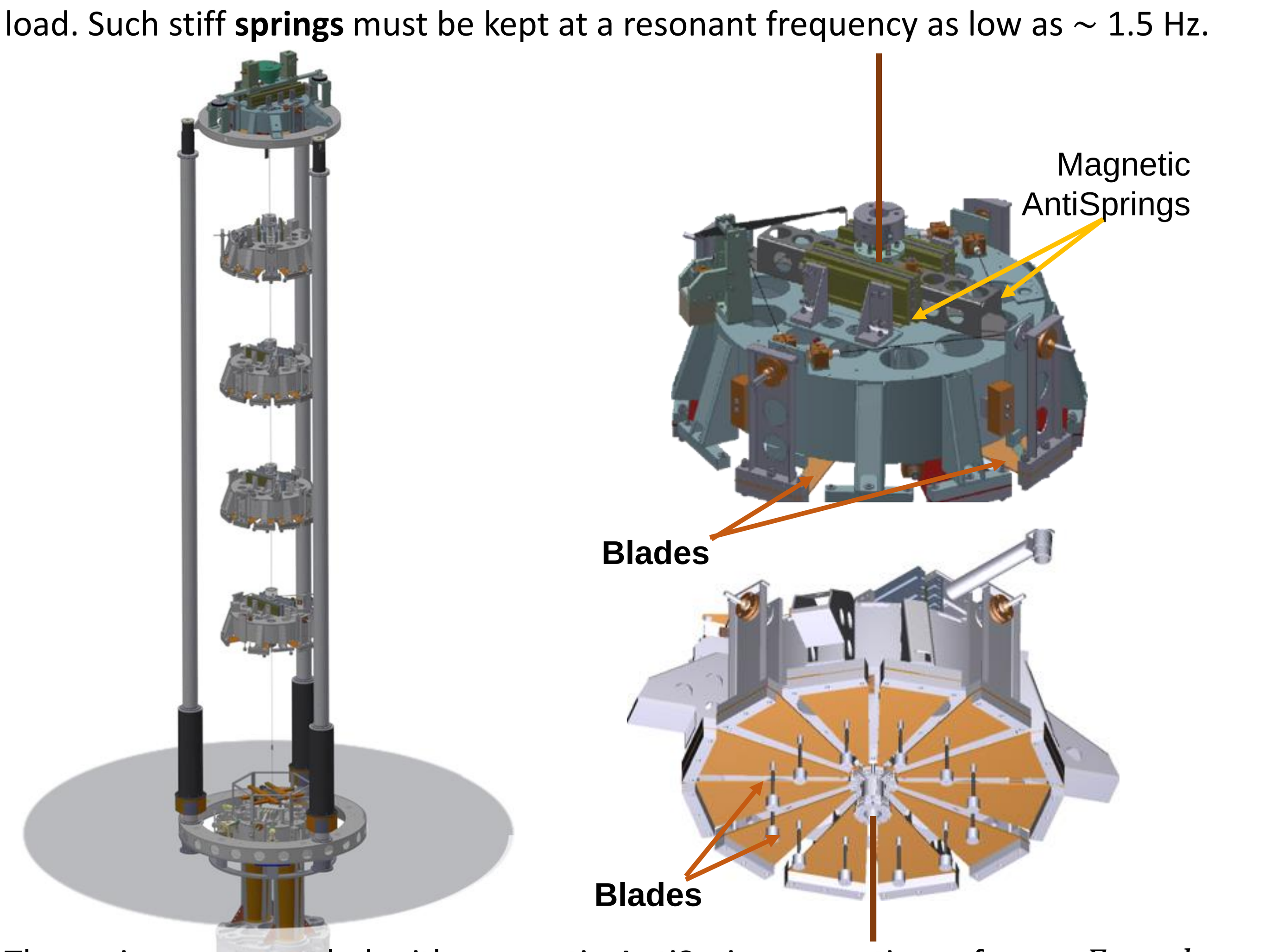
In 2027, the Advanced Virgo Plus (AdV+) gravitational-wave detector will enter Phase II, a thermal noise reduction upgrade involving the increase of the masses of the terminal payloads and the update of all the vertical oscillators in the terminal SuperAttenuators. These are based on thin elastic blades of maraging steel designed to carry the load of the chain of pendulums and oscillate at a pre-set frequency of 1.5 Hz. An appropriate curvature is given to the blades before installation, so that they get flatten by the load and oscillate around a plan configuration. The design of a blade includes appropriate choices of shape, thickness and curvature that provide correct frequency, stress and vertical alignment.

Triggered by the need for stiffer maraging blades, we present a study of the statics of these parts of the SuperAttenuator and of the ideal flattening loads. A simulation code allowing accurate previsions for realistically shaped blades is presented in comparison with the experimental tests. We show that the code can be used to characterize the material, by getting an experimental value of the elastic modulus. Furthermore, simulations are shown of real blades in real conditions.

The vertical oscillators in a SuperAttenuator

Each filter supports the weight of the subsequent chain of filters by means of pre-bended **elastic maraging blades**. The blades must be stiff enough to support the load. Such stiff **springs** must be kept at a resonant frequency as low as ~ 1.5 Hz.



The springs are coupled with magnetic AntiSprings, exerting a force $F = -k_{AS} \cdot y$ with a negative k_{AS}. The total elastic force $F = -(k_{\text{blades}} + k_{\text{AS}}) \cdot y$ can then be set to give a vertical frequency $f_v = 0.3$ Hz.

Maraging blades

NAIVE MODEL
For an ideal triangular blade pulled from the tip, with no tilt:

Flattening load: $F = E \dfrac{w_0 h^3}{12\, L\, R_C}$

Spring constant (flattened): $k = E \dfrac{w_0 h^3}{6 L^3}$

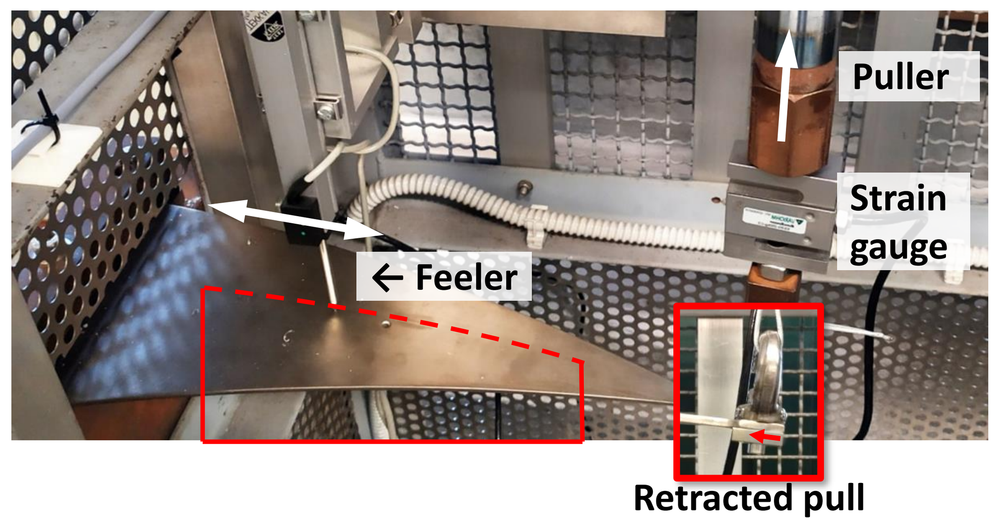
Stress (flattened): $\sigma = E \dfrac{h}{2\, R_C}$

DESIGN FIGURES
- Frequency ~ 1.5 Hz
- Stress < 0.5 UTS (~ 0.9 GPa)

Two-stage test

1) Profile detection

(Blades are pulled from a retracted point)



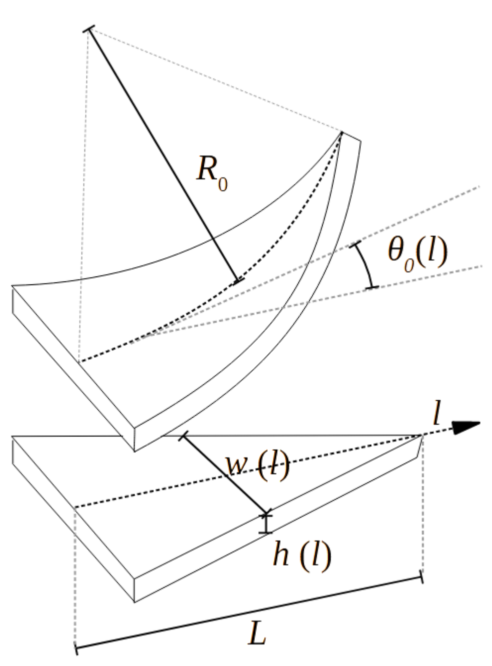
2) Flattening load, Spring constant

(Blades are pulled from the very tip)

A set of 26 blades (from 2 sheets of the same steel) has been cut, bent and aged with the same procedure. Two different thickness have been prepared (3.5 mm and 3.7 mm).
10 more blades have been tested coming from older stocks.

BladePuller

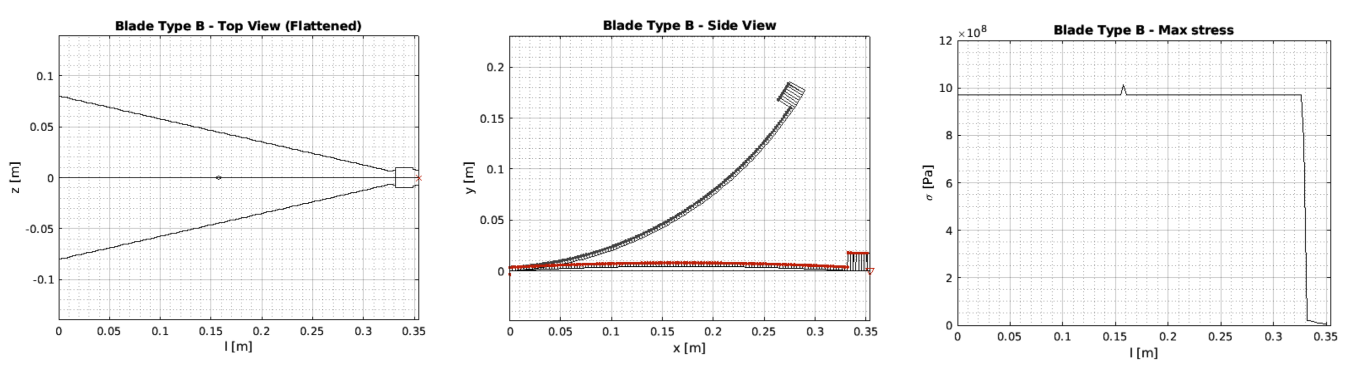
Based on the shaped width $w(l)$, the thickness $h(l)$ and the curvature radius of the unloaded blade, an equation for the mechanical potential energy can be written as follows:



$$U_{el} = \frac{1}{2}\int_0^L E\,\frac{w(l)\,h(l)^3}{12}\left(\frac{d\theta(l)}{dl} - \frac{1}{R_0}\right)^2 dl$$

$E \sim 180$ GPa is the Young modulus of the aged maraging.

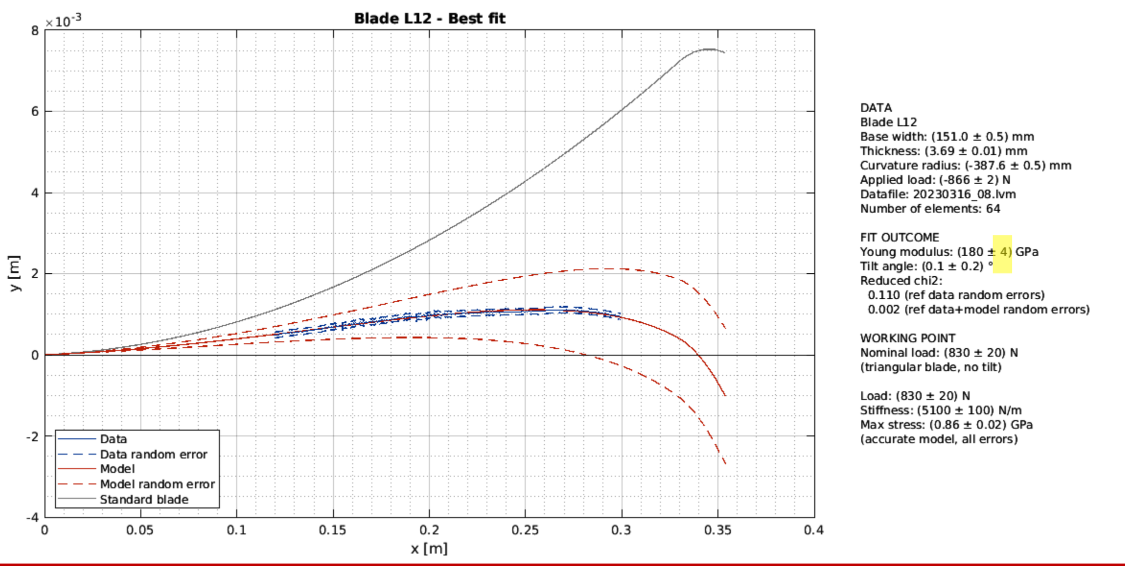
BladePuller is a numerical code that minimizes a discretized approximation of the above integral. Versions have been developed to explore a single blade, tune a filter, fit test data.

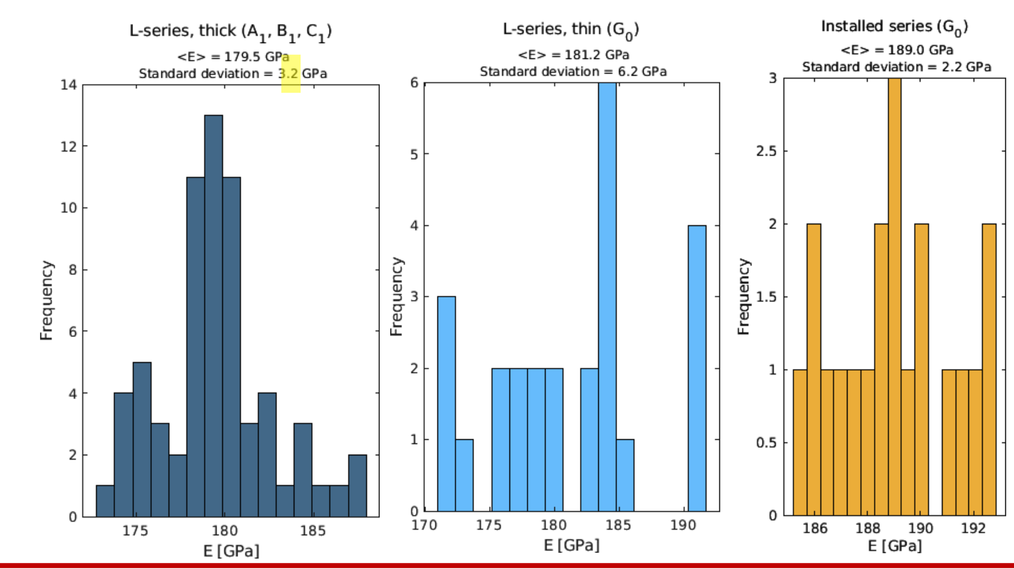


VARIABLE INPUTS		OUTCOMES	
Young Modulus	Curvature at rest	Profile	Tuned curvature
Shaped width	Tilt angle θ(0)	Flattening load	Filter performance
Shaped thickness	Pulling point	Spring constant	Movable blades
Load		Stress	

Test 1: Profile fits and parameter tuning

The loaded blade profile is scanned and measured with a precision feeler. Data are compared to simulations and two parameters are tuned for the best fit. For each blade, we get a value for the **Young modulus** and a value for the **tilt angle** θ(0).
In most cases experimental profile data and simulations coincide within the experimental profile uncertainty.
Blades are divided into three homogeneous samples. An **average Young modulus** is obtained for each sample. The standard deviation is fully compatible with the fit uncertainty (between 3 and 6 GPa, depending on blade).

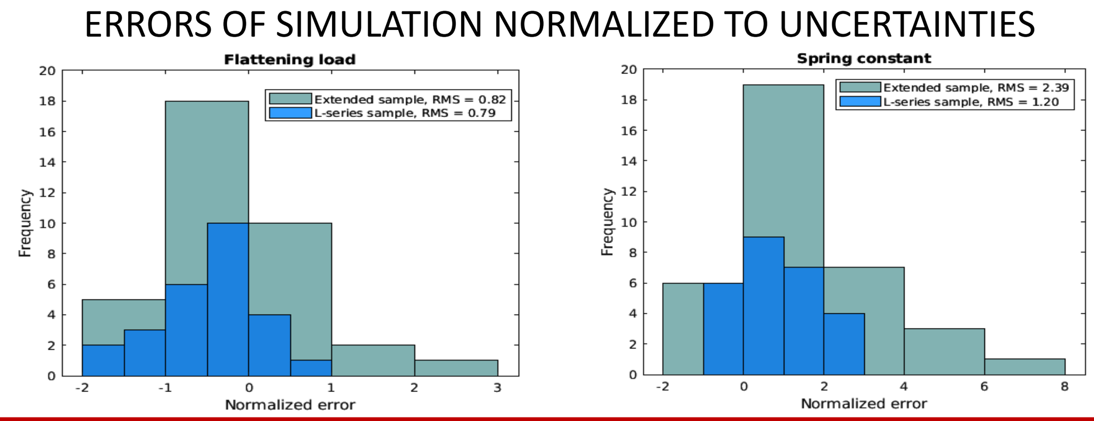




Test 2: Blade performance and simulation validation

Each blade is tested for **flattening load** and **spring constant** by pulling it from the tip (as in filters). New simulations are run in this configuration (with the appropriate average Young modulus) giving estimations of flattening load (± 3%) and spring constant (± 4%).
Simulated flattening load is validated within the uncertainties.
Simulated spring constant is in agreement with the data of the most accurately known blade sample.

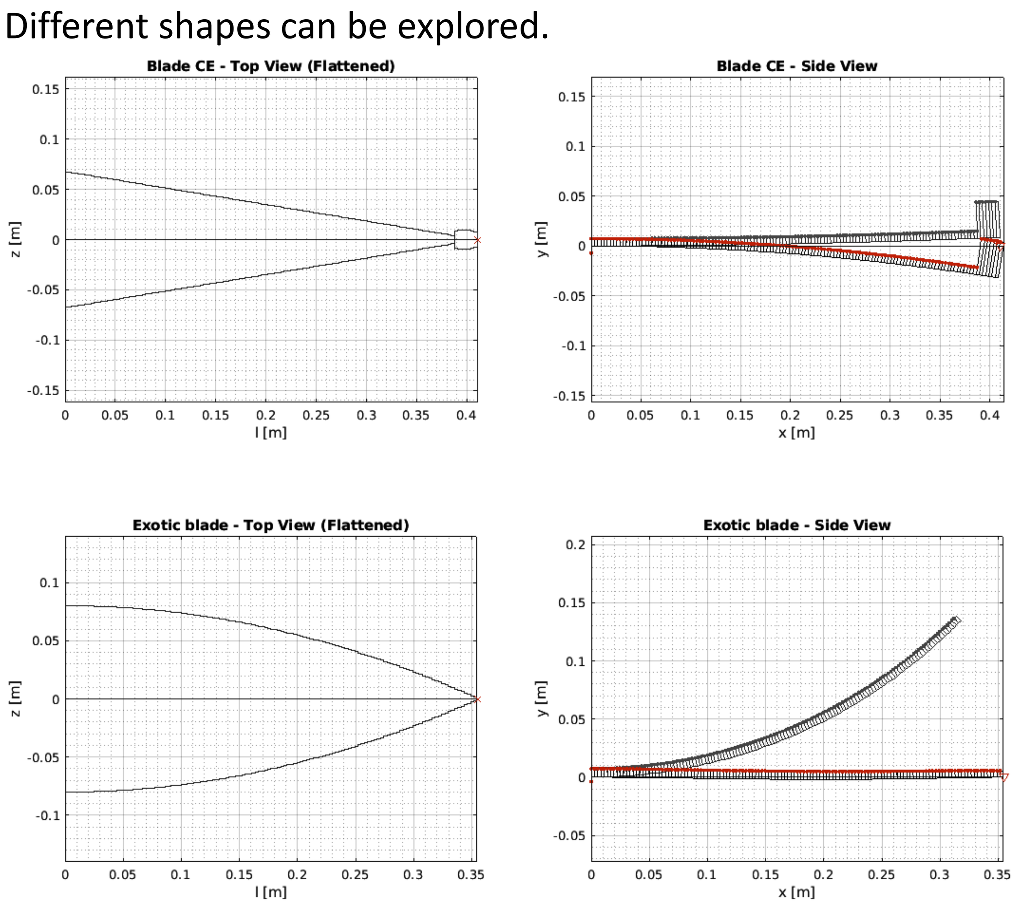
ERRORS OF SIMULATION NORMALIZED TO UNCERTAINTIES



SOME APPLICATIONS

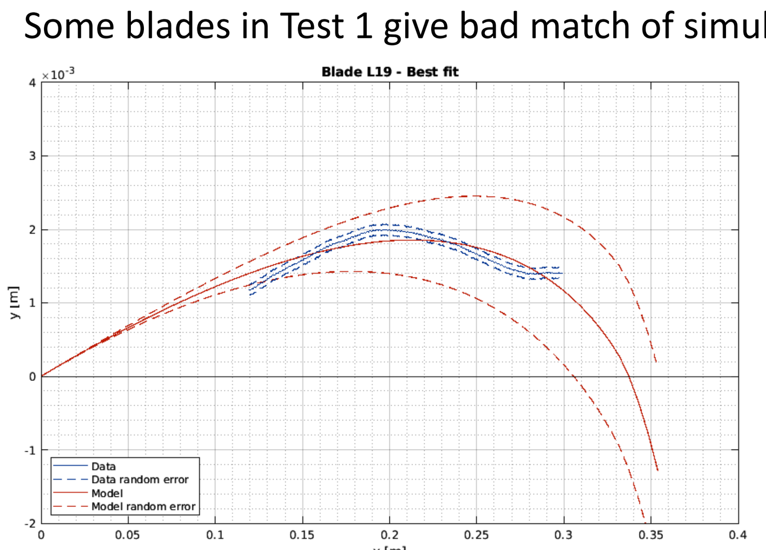
Blade design

Different shapes can be explored.

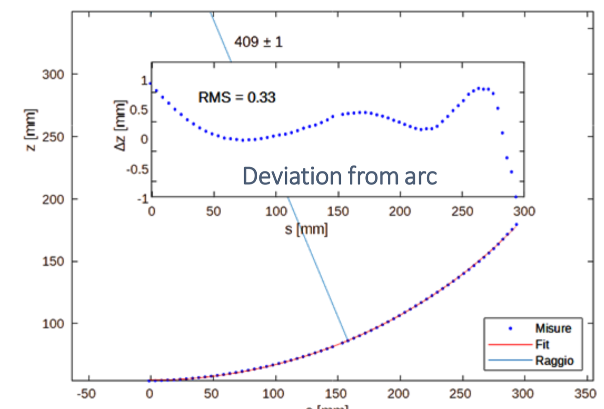


Residual curvature errors

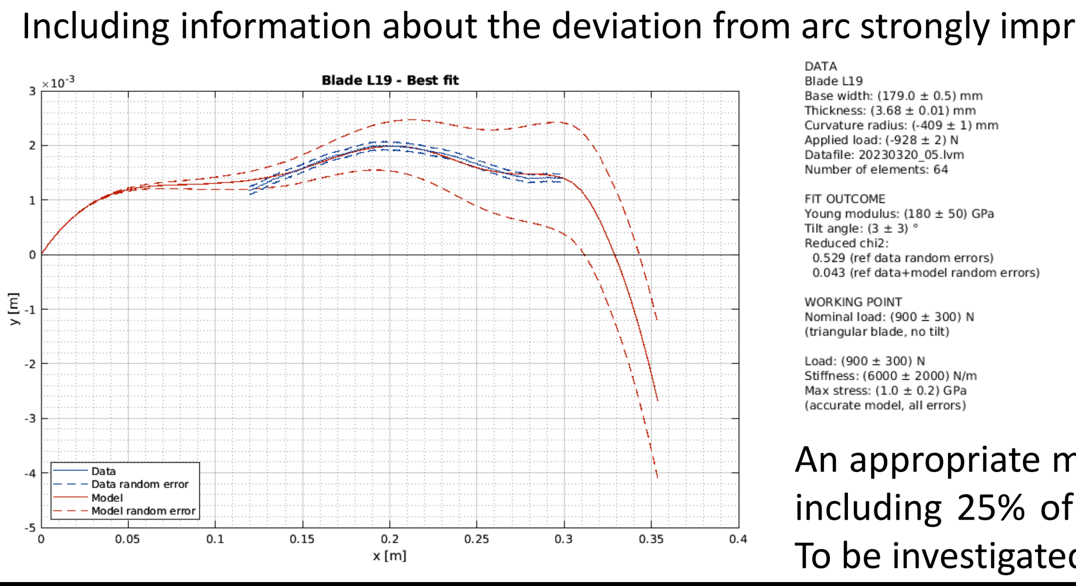
Some blades in Test 1 give bad match of simulated and experimental profiles.



At rest, some deviation of the blade profile from a perfect arc is visible.



Including information about the deviation from arc strongly improves fits.



An appropriate match is obtained by including 25% of the rest deviation.
To be investigated.

Filter tuning

Filters have movable blades designed to tune the device to the actual load. Movable blades are tilted upwards to accommodate an excess load (downwards for the opposite accommodation). Filter workpoint changes and, eventually, movable blade stress is increased.
BladePuller computes the total vertical performance of a given filter.