Optimization of a finite element model for a lightweight structure

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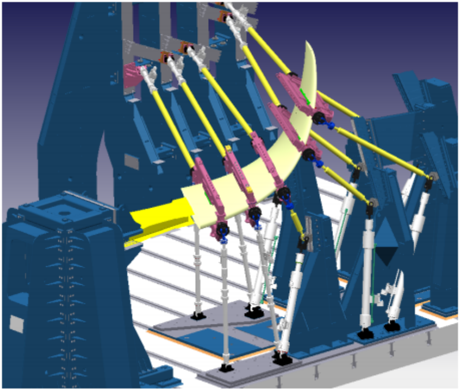
Content of the presentation

- Full scale test
- Finite element model
- Parameter calibration
- Nelder-Mead algorithm
- Calibration of friction parameters
- Comparison of strain values
- Results and conclusions

Overview

- A full scale test was carried out to simulate the forces occurring on a winglet during the flight.
- Based on this test a finite element model was developed by INTALES.
- The predictions of the finite element model were compared to the full scale test.
- When the desired level of consensus could not be reached, the experimental data was used to upgrade the model.
- The following presentation originated from my master thesis, written under the supervision of Univ-Prof. Dr. Michael Oberguggenberger at the University of Innsbruck.

Full scale test



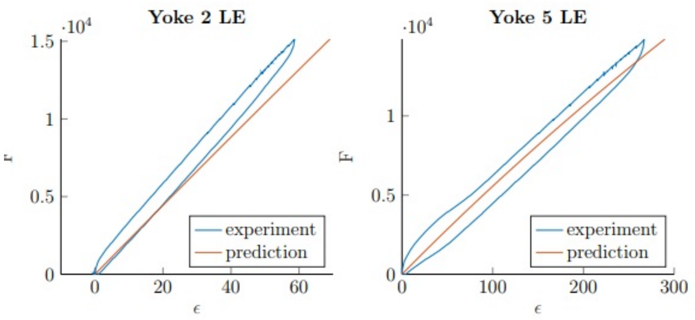
- The developed structure was tested in an experiment.
- The winglet was fixed in a strong frame.
- Loading was introduced via 15 actuators.
- Load cells and strain gauges measured the behavior of the winglet.

Finite element model

- Developed by INTALES GmbH Engineering solutions.
- Nonlinear simulation of the entire test in Abaqus.
- More than 3 million degrees of freedom.

- Generally there was a good consensus between prediction and measurements.
- Experimental deformations show a hysteresis behavior, which was not the case for the original prediction.

Comparison of experiment and prediction



- x-axis: Displacement in 10^{-3}m.
- y-axis: Force in N.

Model modifications

- Several approaches have been tried to improve the model predictions.
- L.Engelhardt developed a mechanical model to reproduce the hysteresis behavior of the actuator displacements.
- This model included 15 damping and spring stiffness parameters.
- A simpler model was constructed to reduce the complexity and therefore the calculation time of the model.
- Moreover a substructure was created. Substructures are collections of elements of which the internal degrees of freedom are removed.
- Friction parameters were included to model friction inside the joints of the fasteners.

Parameter calibration

- Experimental data is used to upgrade the model.
- Requires the solution of the optimization problem:

$$\min_{X \in S} Y = f(X)$$

where $f(X)$ is the objective function, X is the vector of input parameters and S is the admissible region.

The Nelder-Mead algorithm

- The Nelder-Mead algorithm is a numerical method to find the minimum of an objective function.
- The method uses the concept of a simplex, which is a special polytope of $n+1$ vertices in n dimensions.
- Nelder-Mead maintains a set of $n+1$ test points. It extrapolates the behavior of the function measured at each test point, in order to find new test points.
- Since the algorithm can converge to non-stationary points several improvements have been developed.

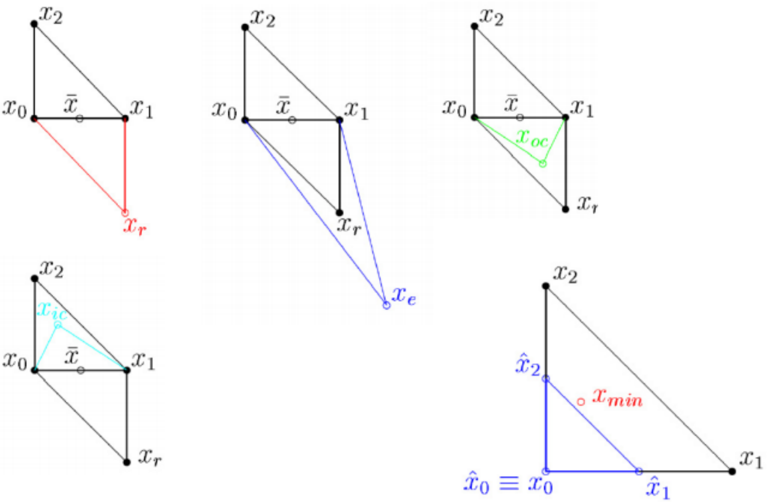
The Nelder-Mead algorithm

We minimize the function $f(x)$. We start with the initial simplex $x_0, x_1, \ldots, x_{n+1}$.

In each iteration step some of the following operations are performed:

1. We order the vertices such that $f(x_1) \leq f(x_2), \ldots \leq f(x_n)$
2. Calculate the centroid x_0 of $x_2, \ldots x_n$.
3. Reflection: $x_r = x_0 + \alpha(x_0 - x_{n+1})$.
4. Expansion: $x_e = x_0 + \gamma(x_r - x_0)$
5. Contraction: $x_c = x_0 + \rho(x_{n+1} - x_0)$
6. Shrink: $x_i = x_1 + \sigma(x_i - x_1)$ for $i \geq 2$

The Nelder-Mead algorithm



Parameter calibration on the full model

1. Calculate $e_i(\mu_0)$ and $e_i(\mu_1)$ for reasonable starting values.
2. Define:
$$\tilde{e}_i(x) := e_i(c_0) + \frac{x - c_0}{c_1 - c_0}(e_i(c_0) - e_i(c_1))$$
3. Plug e_i into the objective function obtaining:
$$\tilde{f}(x) := \sum_{i=1}^{15} \frac{(d_i - \tilde{e}_i(x))^2}{d_i^2}$$
4. Calculate the minimum $\bar{x}$ of f and set $c_0 := c_1$ and $c_1 := \bar{x}$

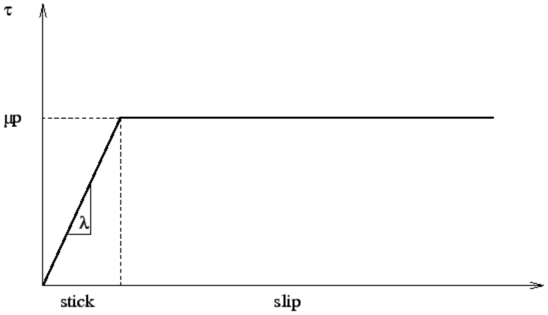
Parameter calibration

Objective function:

$$\sum_i \sum_t \left| \frac{e_i(t) - u_i(t, D, C, \mu)}{\max_t e_i(t)} \right|$$

$e_i \dots$ measured displacement of the $i-$th actuator.
$u_i \dots$ predicted displacement of the $i-$th actuator.
$D \dots$ vector of damping parameters.
$C \dots$ vector of spring stiffness parameters.
$\mu \dots$ friction coefficient.

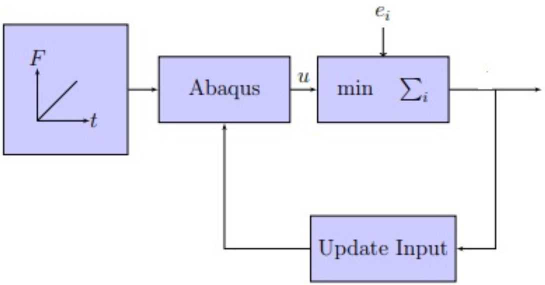
Friction behavior



Friction is characterized by a piecewise linear function with slope λ and a horizontal upper bound μp.

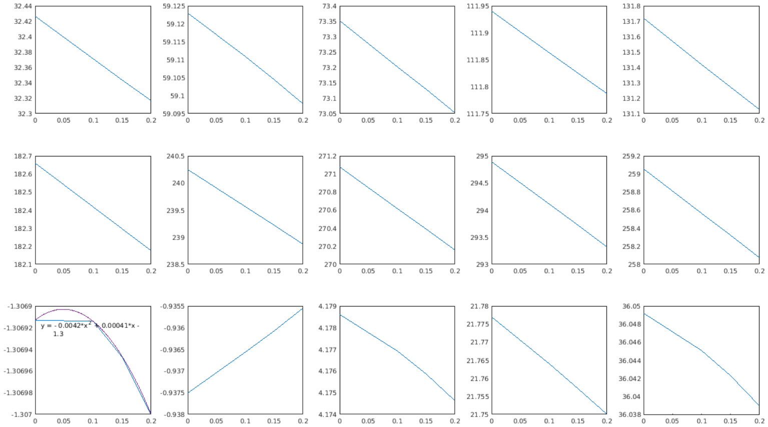
- μ: friction coefficient
- λ: slope in Nm^3.

Technical implementation



- Once the processing is performed displacements and strains are stored in an odb file.
- The desired data is extracted into an SQLite database.
- Coordinate transformation and optimization is performed in MATLAB.

Parameter study: Friction coefficient vs. maximum displacement



Strain comparison

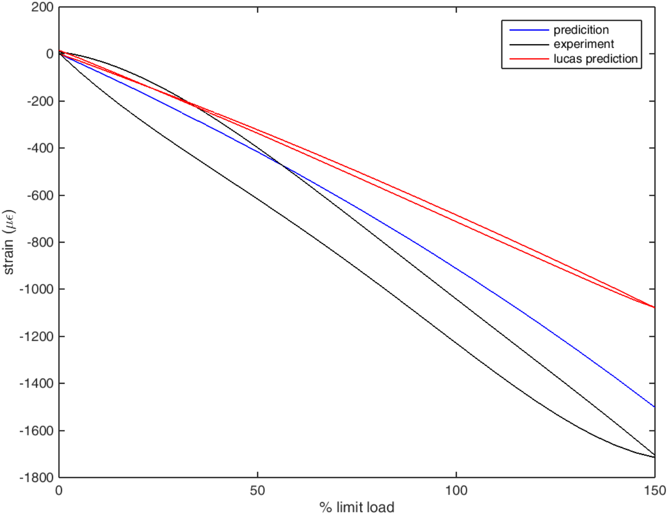
Strain measurement:

- 1168 strain gauges were distributed over the winglet.
- As the area where the strain gauge is attached starts to be deformed the electric resistance of the strain gauge changes.
- This resistance change is related to the quantity of strain.

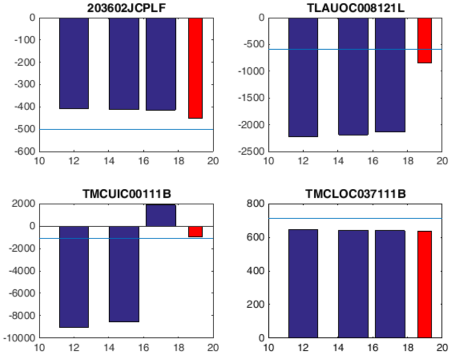
Strain curves:

- The percentage of the limit load is displayed on the $x-$axis.
- On the $y-$axis we see the strain value multiplied by 10^6.

Example of a strain curve (Element LMCUOC017121L)



Influence of friction on strains



- The prediction including friction is depicted in red.

Parameter study

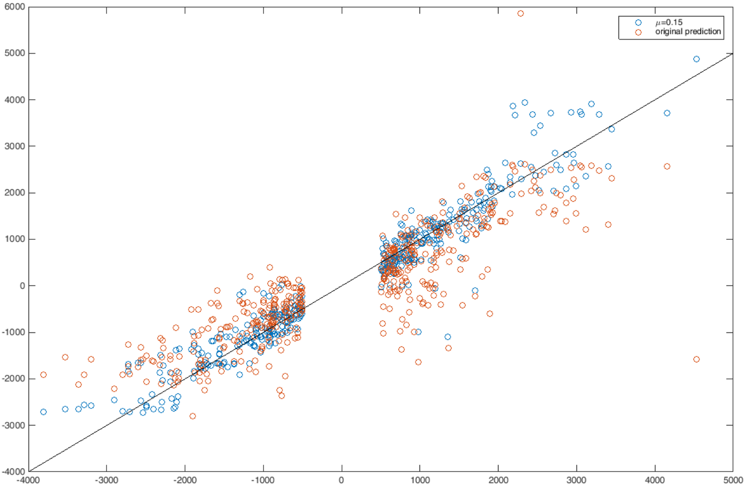
Table 6: Parameter study: Comparison of agreement with measurements

input parameter	$\alpha = 0.1$	$\alpha = 0.2$	$\alpha = 0.5$	absolute error	relative error
12000	367	297	148	$4.02 \cdot 10^4$	33.58
14882.78	**364**	293	146	$3.94 \cdot 10^4$	31.75
17000	367	**288**	**142**	$\mathbf{3.59} \cdot 10^4$	**29.52**

Table 8: Parameter study with friction

input parameter	$\alpha = 0.1$	$\alpha = 0.2$	$\alpha = 0.5$	absolute error	relative error
12000	333	211	57	$1.05 \cdot 10^4$	10.01
14882.78	**296**	**209**	**37**	$\mathbf{8.47} \cdot 10^3$	**6.82**
17000	327	218	58	$1.12 \cdot 10^4$	8.9

Strains overview: measurement vs. predictions.



Strains overview: measurement vs. predictions.