Studies on the Aeroelastic Behavior of Wing Structures in Postbuckling Regime

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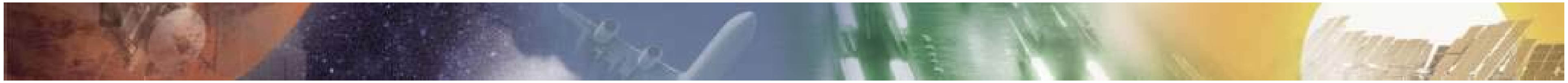
Summary

- Short CV
- Objective and Motivations
- State of the Art: Composite Structures in Postbuckling
- State of the Art: Nonlinear Aeroelasticity
- Methodology
- Case Study
- Conclusions and Next Steps

Short CV

- **Mechanical Engineering (Bachelor and Master) – Universidade Federal do Rio de Janeiro (UFRJ) - Brazil**
- **EMBRAER - Loads and Aeroelasticity Department (5 years)**
  - Dynamic loads analyses using finite element models
  - Tuned and continuous gust loads calculation
  - Projects EMBRAER 170, 190 and 195
- **EMBRAER - CAE/CAD Technologies Department (5 years)**
  - Technical support for engineering analyses and software tools
  - Development of customized applications for engineering
  - MDO Project
- **DLR Braunschweig – Institute of Composite Structures and Adaptive Systems - PhD Studies**

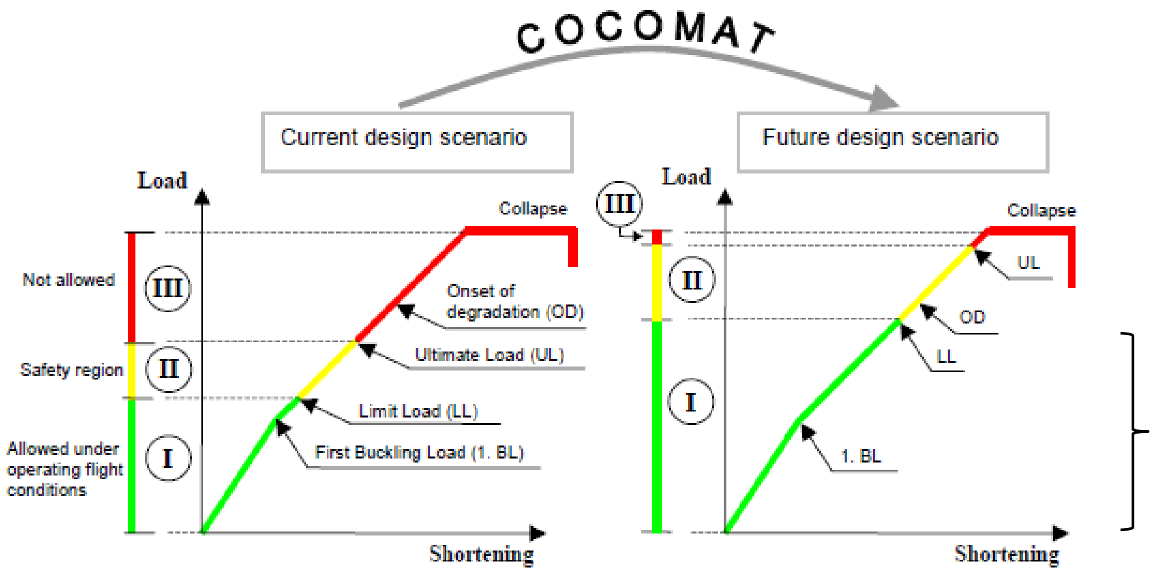


PhD Thesis

Aeroelastic Behavior of Wing Structures in Postbuckling Regime

Objective

- Develop a method to analyze the aeroelastic response and stability of an aircraft wing structure operating in postbuckling regime.



Aeroelastic Analysis
- Stability
- Transient response
- Postbuckling effects

Fig.1 – Current and future design scenarios for composite structures design [1]

Motivations

- Contribute to recent efforts to achieve weight and cost reductions in composite wing structures allowing them to work in postbuckling regime when subjected to limit loads.
- Investigate the effect of stiffness changes caused by postbuckling on the aeroelastic response and stability of composite wings.
- Provide additional guidelines for the design in postbuckling regime of new light-weight composite wing structures taking into account the aeroelastic behavior.

State of the Art: Composite Structures in Postbuckling

- The exploitation of strength reserves of composite stiffened structures during postbuckling is the main interest [1-3]
- Attention shall be focused on the fact that the stiffness of the structure is reduced in the postbuckling regime
- Analytical models for collapse prediction considering material degradation have been developed
- Recent studies have shown that stiffened composite panels can work changing between pre and postbuckling regimes during a big amount of cycles without failure.

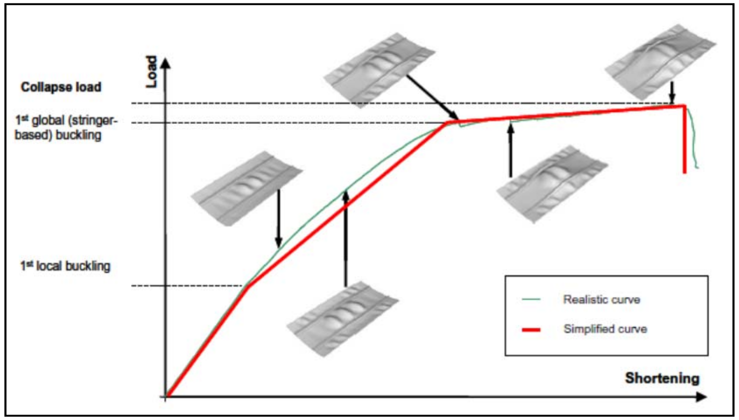


Fig.2 – Load x displacement curve for composite stiffened panel in postbuckling regime [2]

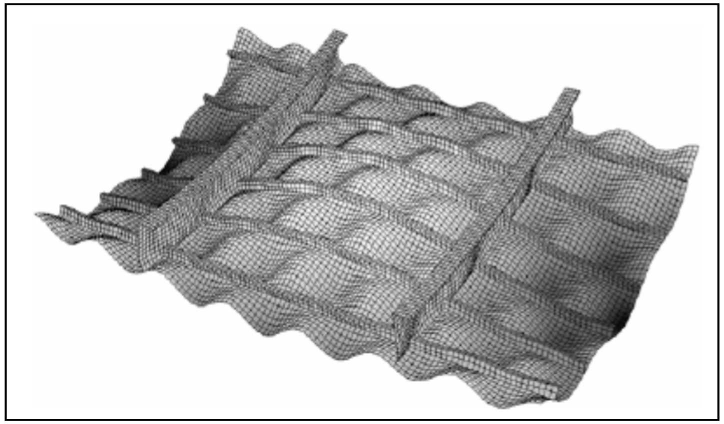


Fig.3 – Postbuckling shape obtained by the iBUCK tool [2]

State of the Art: Composite Structures in Postbuckling

- Postbuckling simulation requires the solution of a set of nonlinear differential equations

- Several computational tools based on FEM and semi-analytical methods have been developed to simulate the structural behavior in postbuckling regime [4-6].

- Recent strategies for structural optimization have been developed to consider that the structure may operate in postbuckling regime [7].

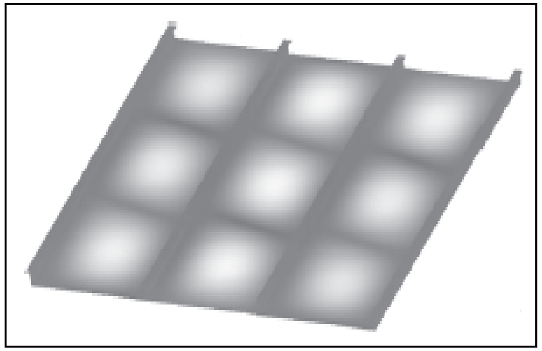


Fig.4 – Deformed shape in postbuckling calculated by semi-analytical tool [6]

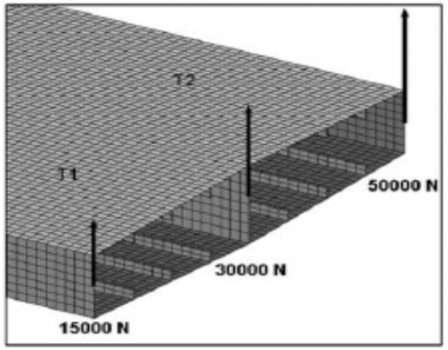


Fig.5 – Finite element model used in postbuckling optimization [7]

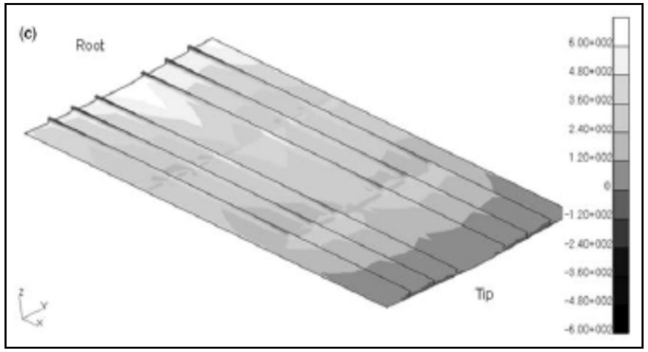


Fig.6 – Stress distribution after optimization with postbuckling effects [7]

State of the Art: Nonlinear Aeroelasticity

- High aspect-ratio wings may have large displacements and rotations during flight. This condition may cause two types of nonlinearity:
  - structural nonlinearity, making the stiffness of the wing to be a function of the displacements.
  - aerodynamic nonlinearity, due to redistribution of the aerodynamic loads and stall effects.
- The natural frequencies and consequently the flutter speed vary with the angle of attack and flight condition.

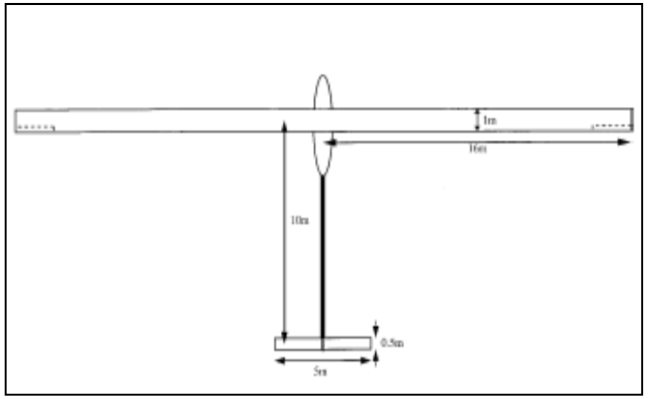


Fig.7 – Example of high-aspect-ratio-long-endurance aircraft [8]

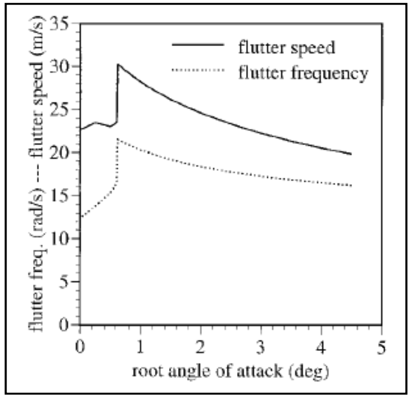


Fig.8 – Variation of the flutter speed with root angle of attack [8]

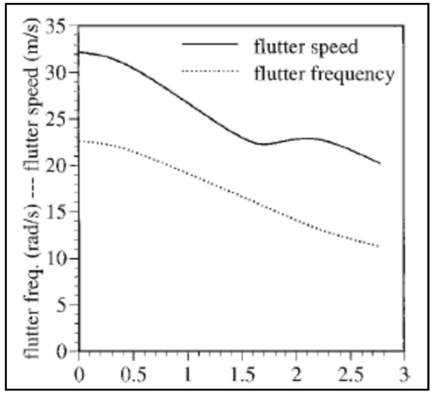


Fig.9 – Variation of the flutter speed with wing tip displacement [8]

State of the Art: Nonlinear Aeroelasticity

- The frequency of the 1st flexible mode can be low enough to be close to the frequency of the rigid-body mode.
- In this case the rigid-body mode can cause an instability of the aircraft if it couples with the flexible modes.
- Structural response may be stable or unstable depending on the amplitude of the excitation.

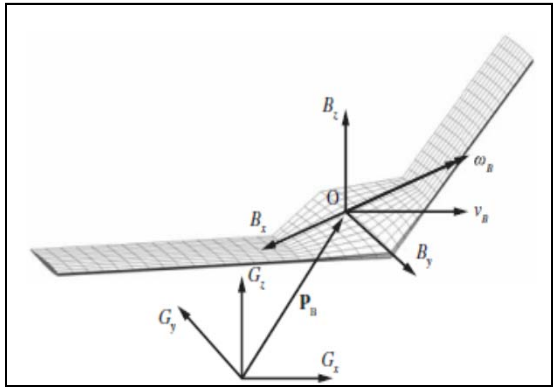


Fig.10 – Blended-wing-body aircraft model [9]

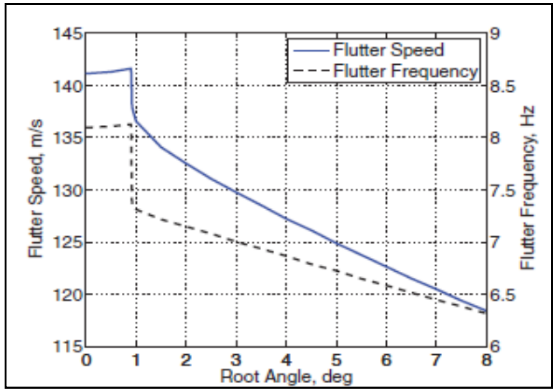


Fig.11 – Variation of the flutter speed and frequency with root angle of attack [9]

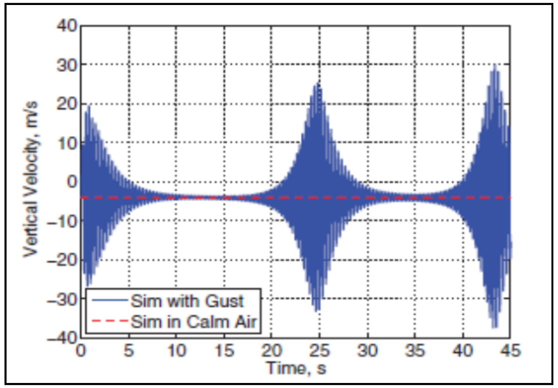


Fig.12 – Vertical velocity response due to a discrete gust [9]

Panel Flutter

- External panels of aerospace vehicles may experience flutter when exposed to high velocity airflow and high temperatures.
- The vibrations grow with time until they are restrained by in-plane strains generated by geometric nonlinearities, and can cause fatigue of the panel, failure of attached equipment or excessive noise levels.
- Such conditions may also include buckling of the composite panel, which makes necessary to analyse the problem regarding both static and dynamic stability.
- Most of the studies about panel flutter used linear aerodynamic models for supersonic flow and nonlinear structural models to consider large displacements of the structure.

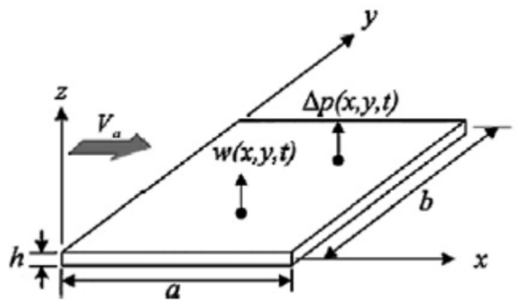


Fig.13 – Schematic description of panel flutter [10]

Panel Flutter – Flat Composite Panels

- Nonlinear transient aeroelastic analyses of flat composite plates were realized.
- The response was calculated for different fiber angles, aspect ratios, mass ratios and composite lay-ups.
- The effects of pressure differential, in-plane loads and dynamic pressure on the transient response were investigated.
- The combination of these effects may cause significant changes in the response, which can vary from a stable configuration to a limit cycle oscillation or even a chaotic motion.

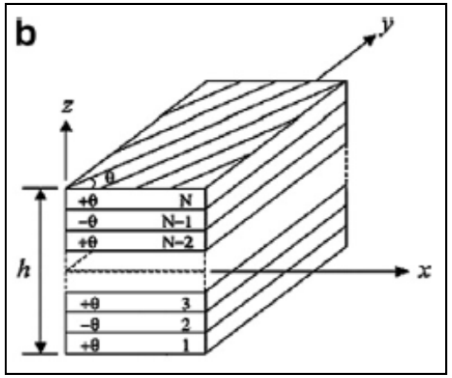


Fig.14 – Fiber orientation used in the composite plate [10]

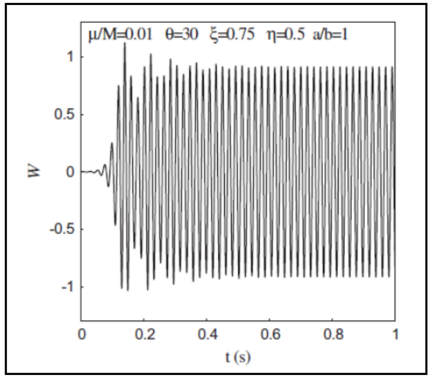


Fig.15 – Displacement of a point of the plate versus time, showing the limit cycle oscillation [10]

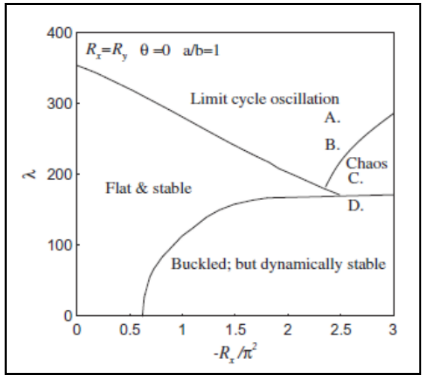


Fig.16 – Influence of in-plane loads Rx and dynamic pressure λ [10]

Panel Flutter – Cylindrical composite panels

- Linear flutter analyses were performed on conditions of large deflections.
- Modal frequencies and damping factors were calculated as a function of dynamic pressure.
- Variations were applied in the following parameters: cylinder radius, aspect ratio, shallowness angle, fiber angle.
- Results show that geometric parameters have important influence on flutter modes.

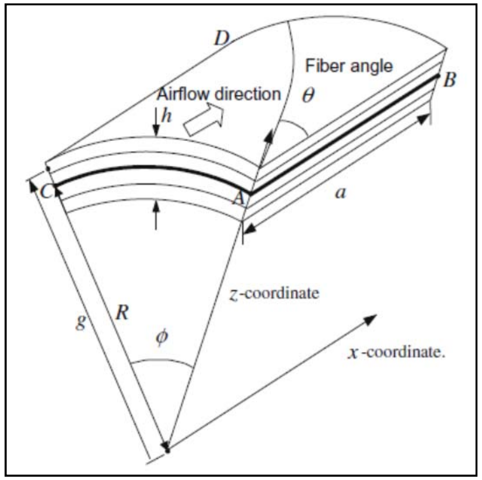


Fig.17 – Geometric parameters of cylindrical composite panels [11]

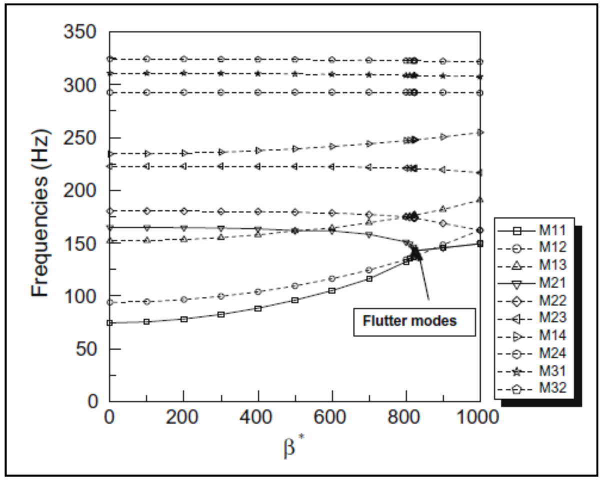


Fig.18 – Natural frequencies as a function of nondimensional dynamic pressure, Φ = 1° [11]

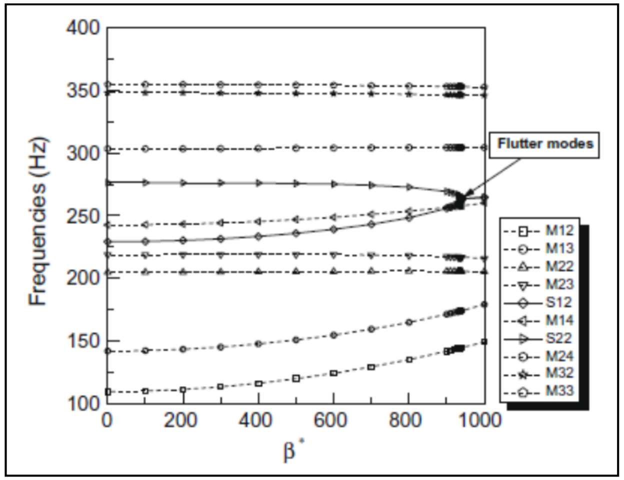


Fig.19 – Natural frequencies as a function of nondimensional dynamic pressure, Φ = 5° [11]

Aerothermoelasticity of Composite Structures

- High temperature distributions caused by supersonic and hypersonic viscous flow, propulsive heat and radiation can influence the dynamic responses, aeroelastic stabilities and fatigue life of composite structures as well as thermoelastic buckling and large deflections.
- Thermal stresses due to high temperature environments may induce buckling and flutter.
- Various studies have been made about the influence of thermal loads on the aeroelastic behavior of composite panels, considering variations on geometry, laminate parameters and temperature differential.
- The use of nonlinear structural models is mandatory, to account for the large postbuckling displacements due to thermal loads.

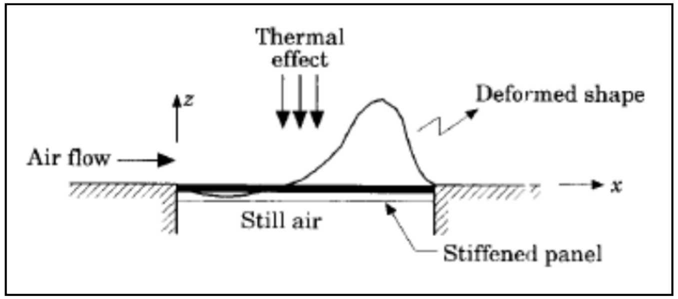


Fig.20 – Schematic view of aerothermally loaded panel [12]

Aerothermoelasticity of Composite Structures

- Flat stiffened composite panels with thermal loads were investigated.
- Linear flutter and nonlinear transient aeroelastic analyses were performed on conditions of large aero-thermal deflections.
- Variations on the following parameters were studied:
  - Number of stiffeners
  - Geometry of stiffeners (height and thickness)
  - Temperature difference

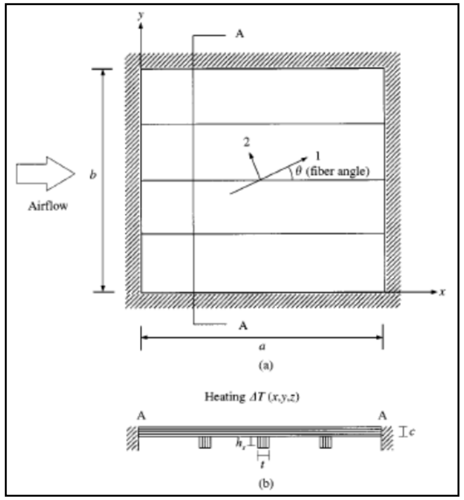


Fig.21 – Geometry of the stiffened plate [12]

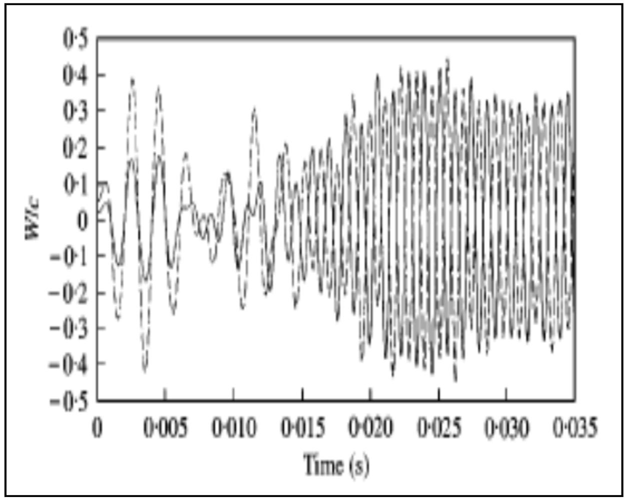


Fig.22 – Transient response of two points on the composite panel [12]

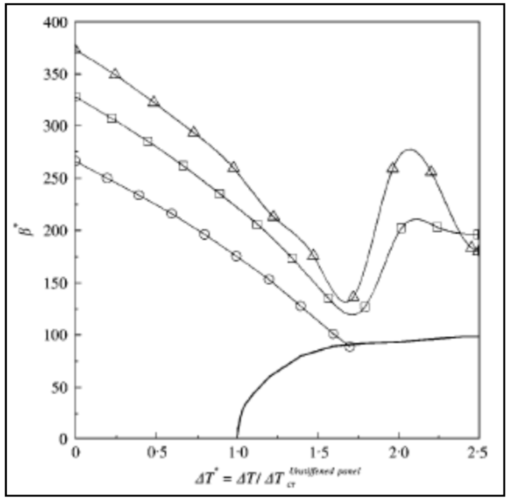


Fig.23 – Critical dynamic pressure as function of temperature differential [12]

Fluid Structure Interaction: Transonic Panel Flutter

- A nonlinear structural model is used to model large displacements.
- A CFD model with moving mesh algorithm is used to cope with panel deformations.
- The transient response is calculated, and depending on the Mach number, stable response or limit cycle oscillation is observed.
- The CFD model indicates that shock waves move along the panel, and their effects result in periodic but non-harmonic motions of the panel.

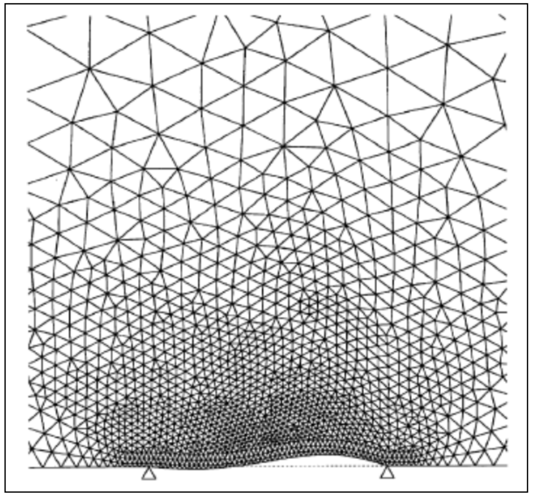


Fig. 24 – CFD moving mesh surrounding the panel in a deformed state [13]

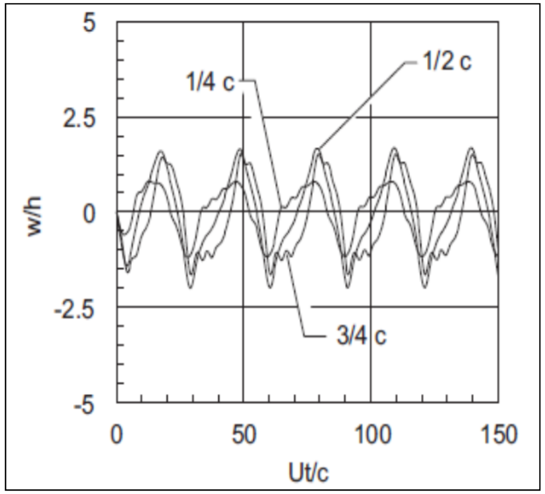


Fig. 25 – Transient response of the transverse displacement, mid span and along the chord [13]

FSI: Transonic Flutter of High Aspect Ratio Wings

- The transient response of a composite wing was calculated with the solution of the coupled fluid-structure equations in time domain.
- Aerodynamic and structural (geometric) nonlinearities are considered.
- Coupling between structural and aerodynamic nonlinearities is observed.
- Limit cycle oscillation could be predicted with good correlation with experimental results.

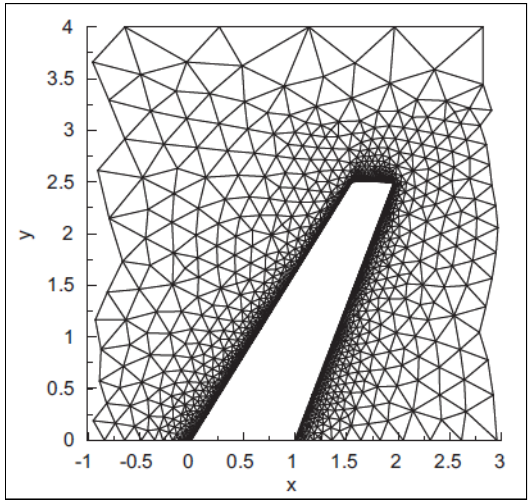


Fig. 26 – CFD moving mesh surrounding the wing [13]

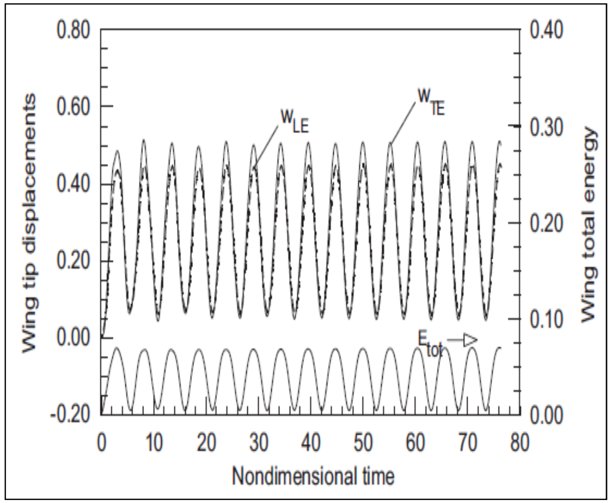


Fig.27 – Transient response of the wing showing the limit cycle oscillation [13]

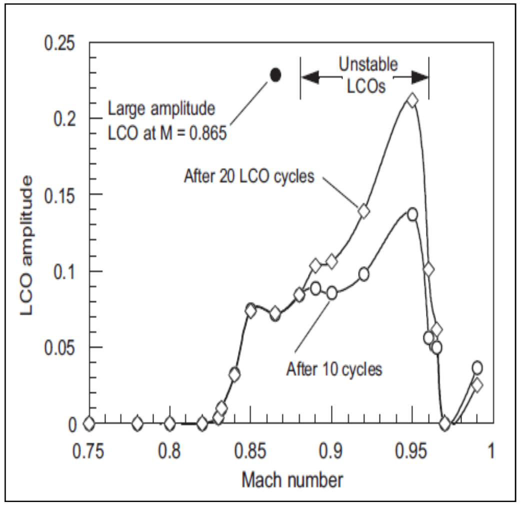
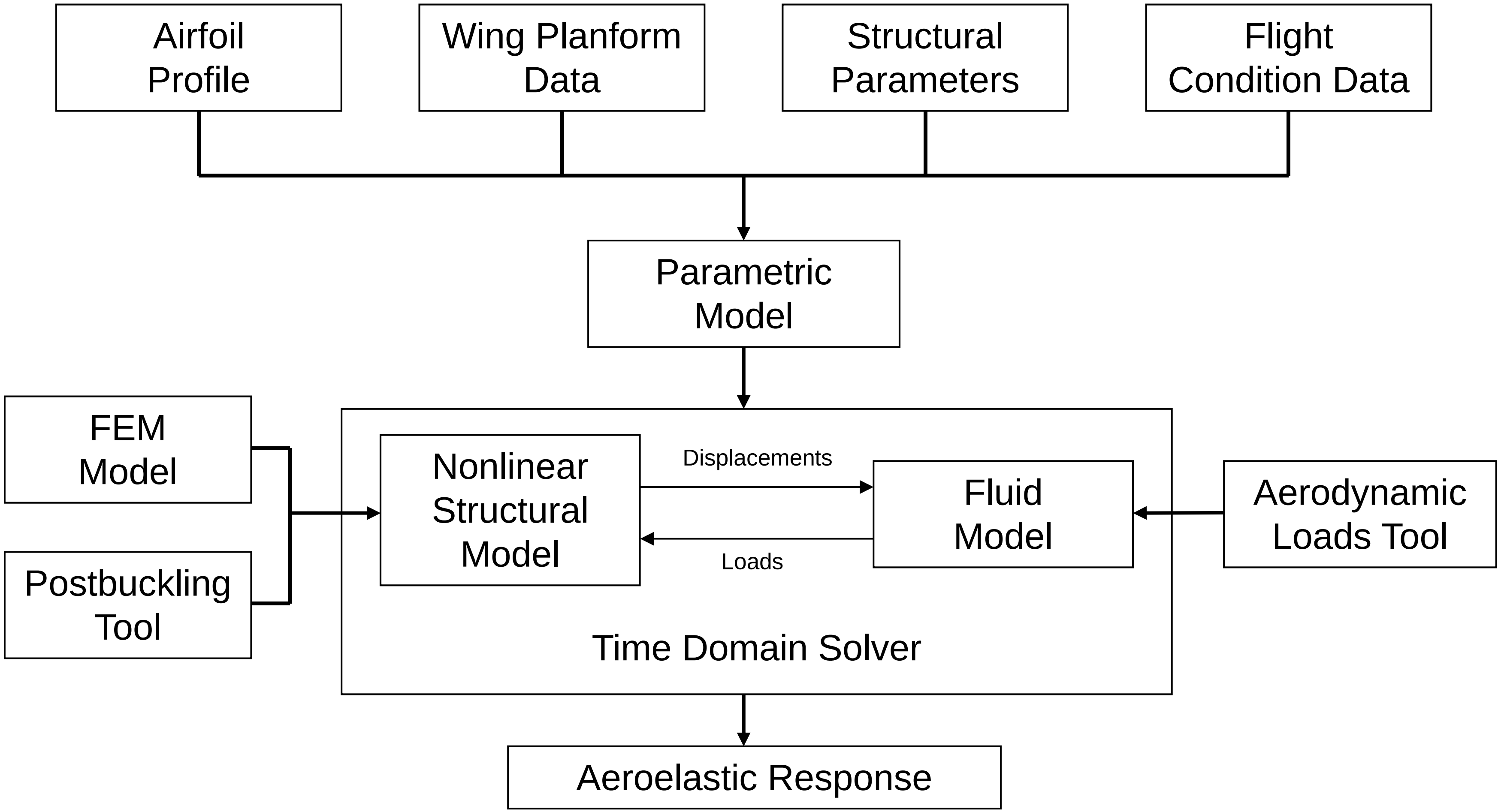


Fig.28 – Variation of the amplitude of LCO vibrations with Mach number [13]

Methodology - Overview



Equations of Motion – Nonlinear Aeroelastic System

- The stiffness matrix is a function of the displacement.
- Aerodynamic forces can be nonlinear functions of the displacement vector and its derivatives.
- The natural frequencies and normal modes of the structure may change depending on the load distribution.

$$[M]\{\ddot{u}\}+[B]\{\dot{u}\}+[K(u)]\{u\}=\{F_{aero}(u,t)\}+\{F_{ext}\}$$

- M : mass matrix
- B : damping matrix
- K(u) : stiffness matrix
- u: displacement vector
- F_{aero} : aerodynamic force vector
- F_{ext} : external force vector (for flutter analysis, F_{ext}=0)

Open Questions

- Postbuckling design may be used to decrease weight and increase the load-carrying capacity, but what are the effects on aeroelasticity ?
- If a wing or fuselage structure changes its condition between prebuckling and postbuckling during a gust excitation, what is the influence on the aeroelastic response ?
- What is the best way to design composite wing and fuselage structures working in postbuckling regime and having the best compromise with aeroelastic response and stability ?

Case Study - Wing Box Model in Postbuckling Regime

- Analyse the variation of the natural frequencies of a wing box structure working in postbuckling regime.
- Span 14 m, sweep angle 15.0 degrees, root chord 3.5 m, taper ratio 0.6, weight 1200 kg, aluminum
- Ribs, spars and panels are modeled using shell elements
- Caps, attachments and stringers are modeled using beam elements
- A vertical load was applied on the tip of the wing, on the point of 25% of the root chord.

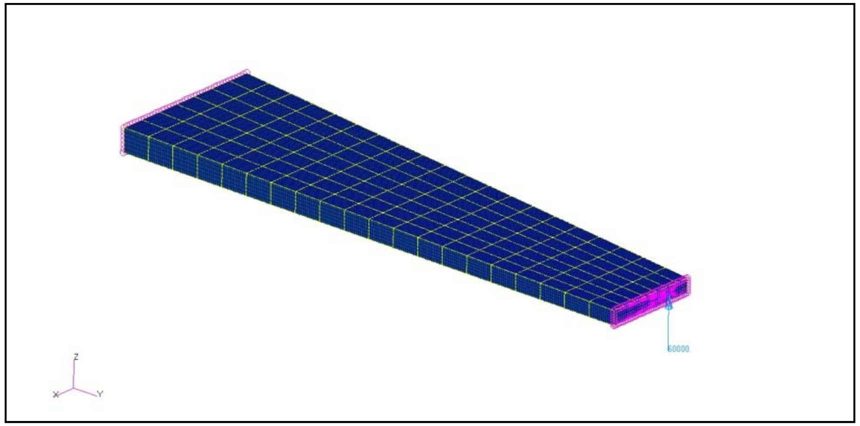


Fig.29 – Perspective view of the wing box model

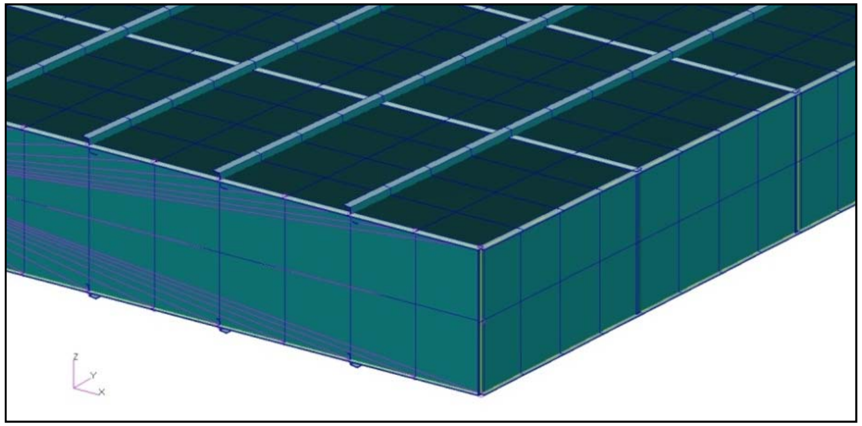


Fig.30 – Detailed view of the wing box model – stringers, caps and attachments

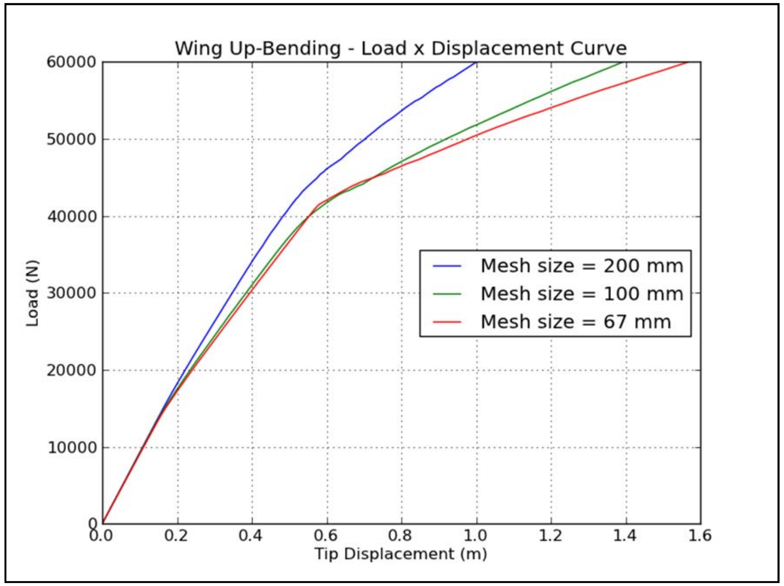
Postbuckling Analysis – Tip Load

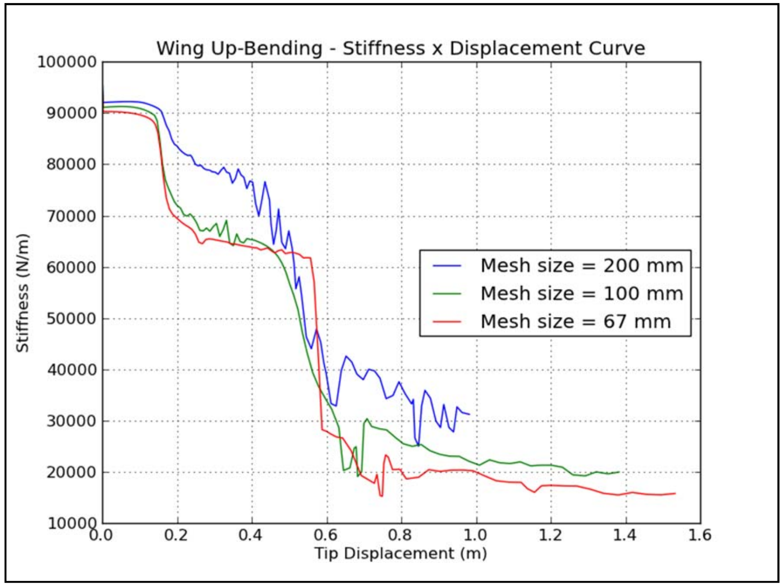
- The following table shows the first 10 buckling loads obtained with a linear buckling analysis, for each mesh size:

Average element size (mm)	200	100	67
Number of DOF	17202	72042	164658
Buckling mode	Eigenvalues (kN)		
1	14.02	10.55	10.43
2	16.60	12.26	11.94
3	17.47	12.43	12.21
4	18.06	12.97	12.58
5	18.36	13.50	13.06
6	18.94	13.62	13.31
7	19.47	13.96	13.53
8	19.49	14.04	13.64
9	19.98	14.27	13.78
10	20.04	14.27	13.89

Postbuckling Analysis – Mesh Convergence

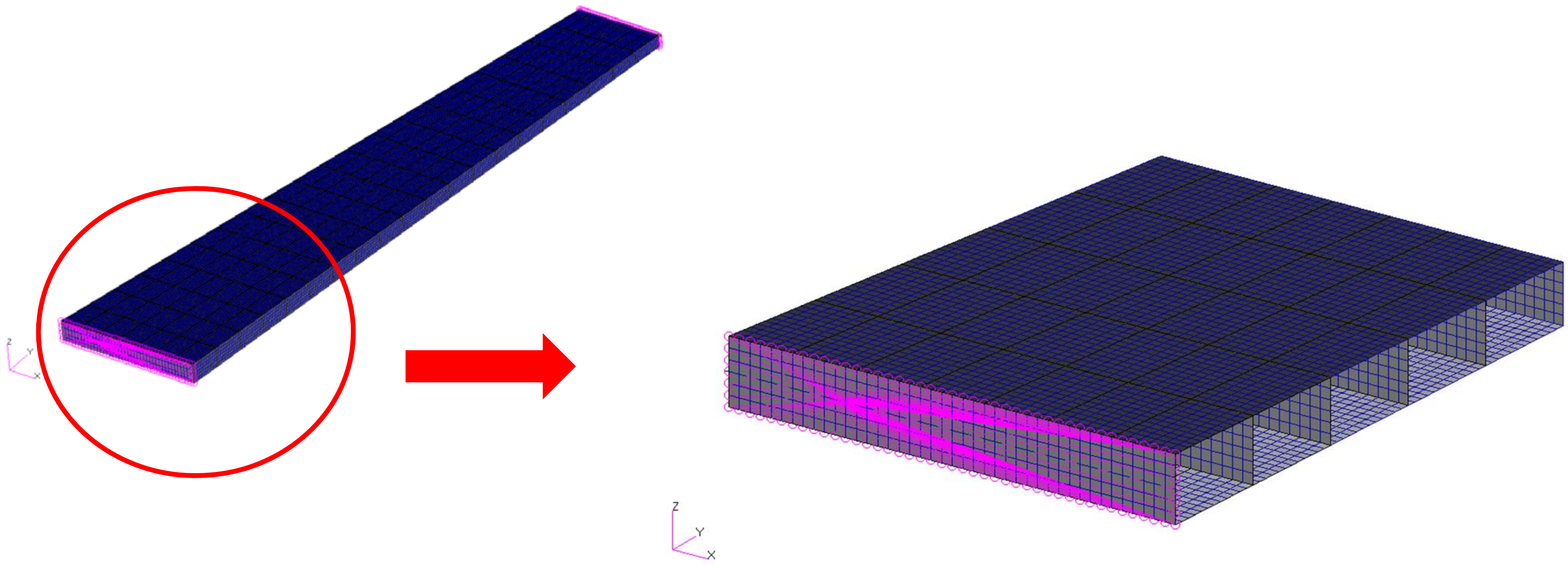
- A nonlinear static analysis was conducted using SOL 400 from MSC Nastran
- The applied load and the stiffness are showed as a function of the wing tip displacement.
- The values of the local and global buckling loads were identified approximately as 16 kN and 41 kN.

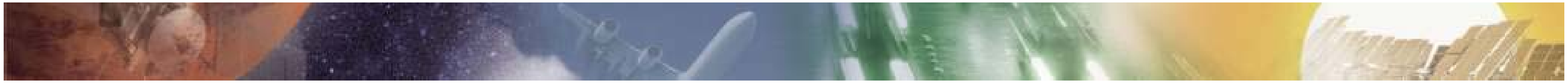




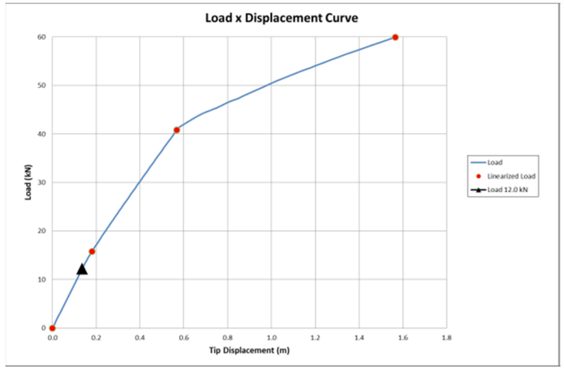
Postbuckling Analysis – Deformed Shape

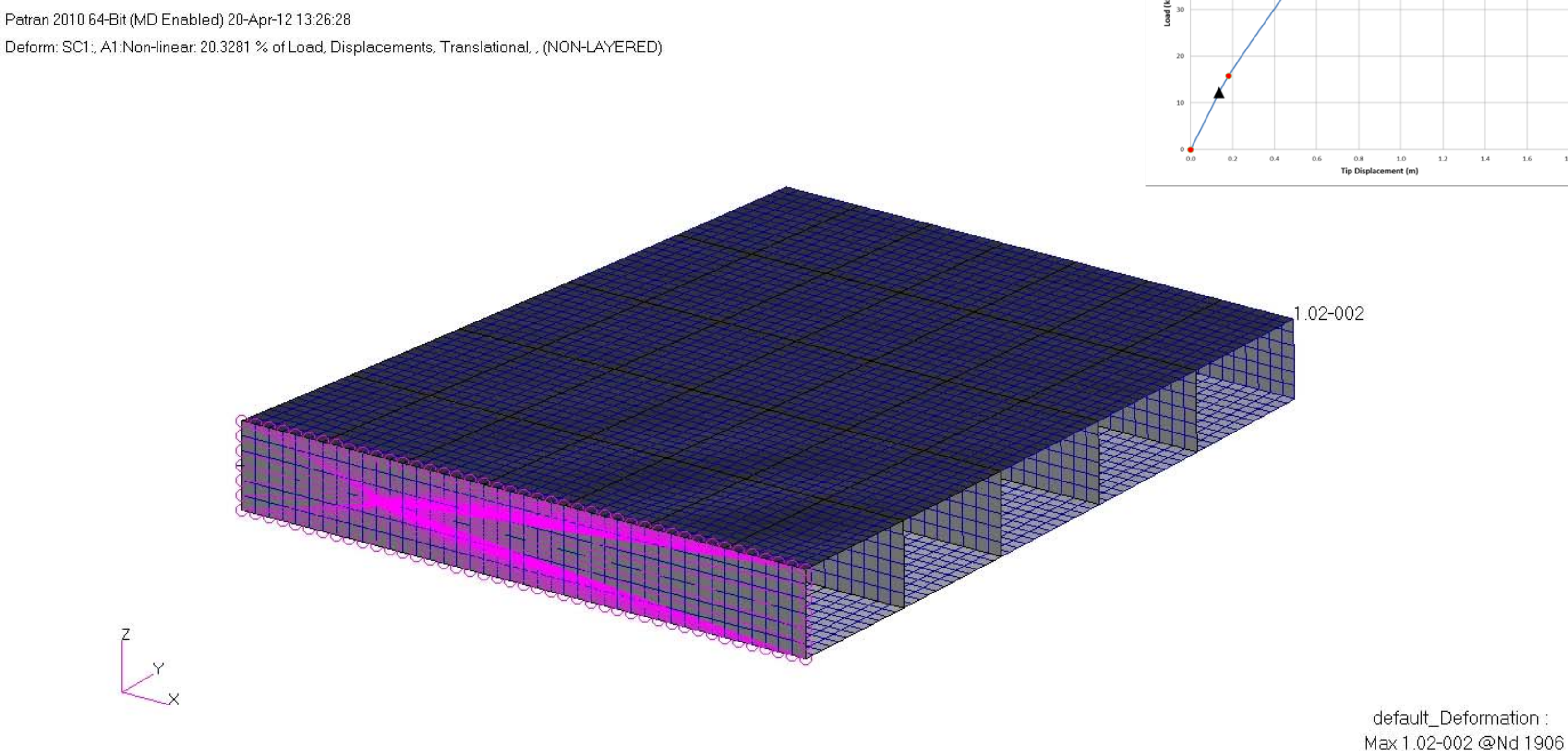
- The next pictures show the deformation of the structure as a function of the applied load.
- The displacements are multiplied by a factor of 5.
- The deformation is shown in the region of the first five bays near the root, and the spars were removed for better visualization.





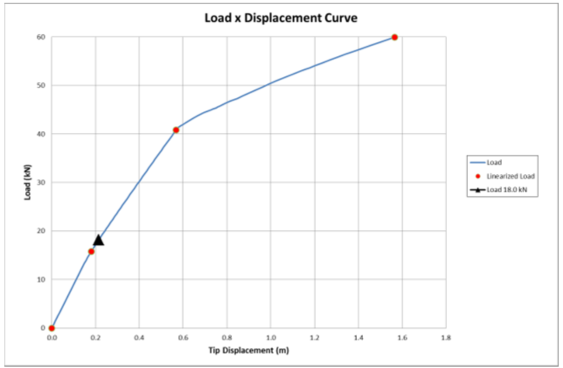
Postbuckling Analysis – Deformed Shape

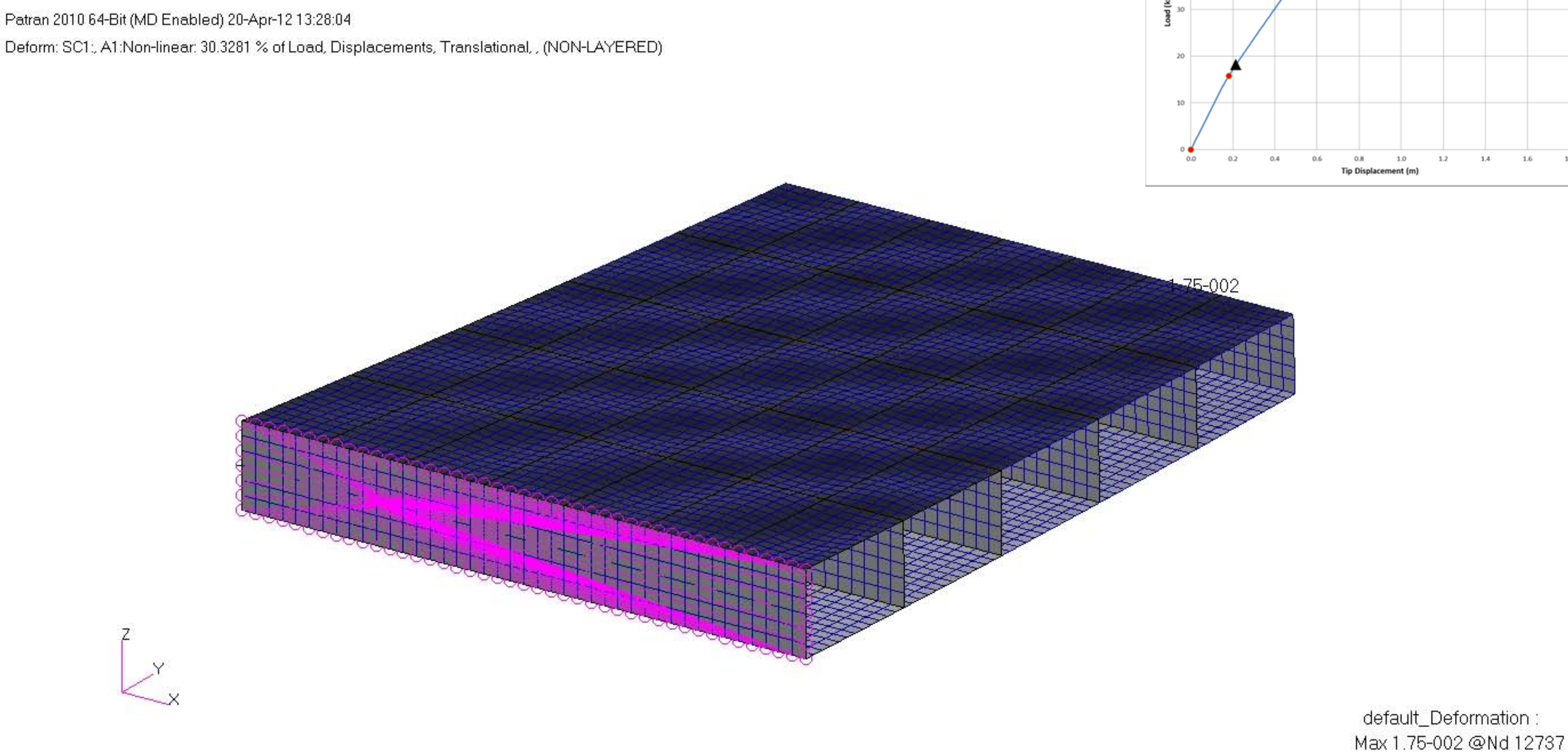




Deformed shape on 5 ribbays near the root – load 12.0 kN (75% of 1st local buckling load)

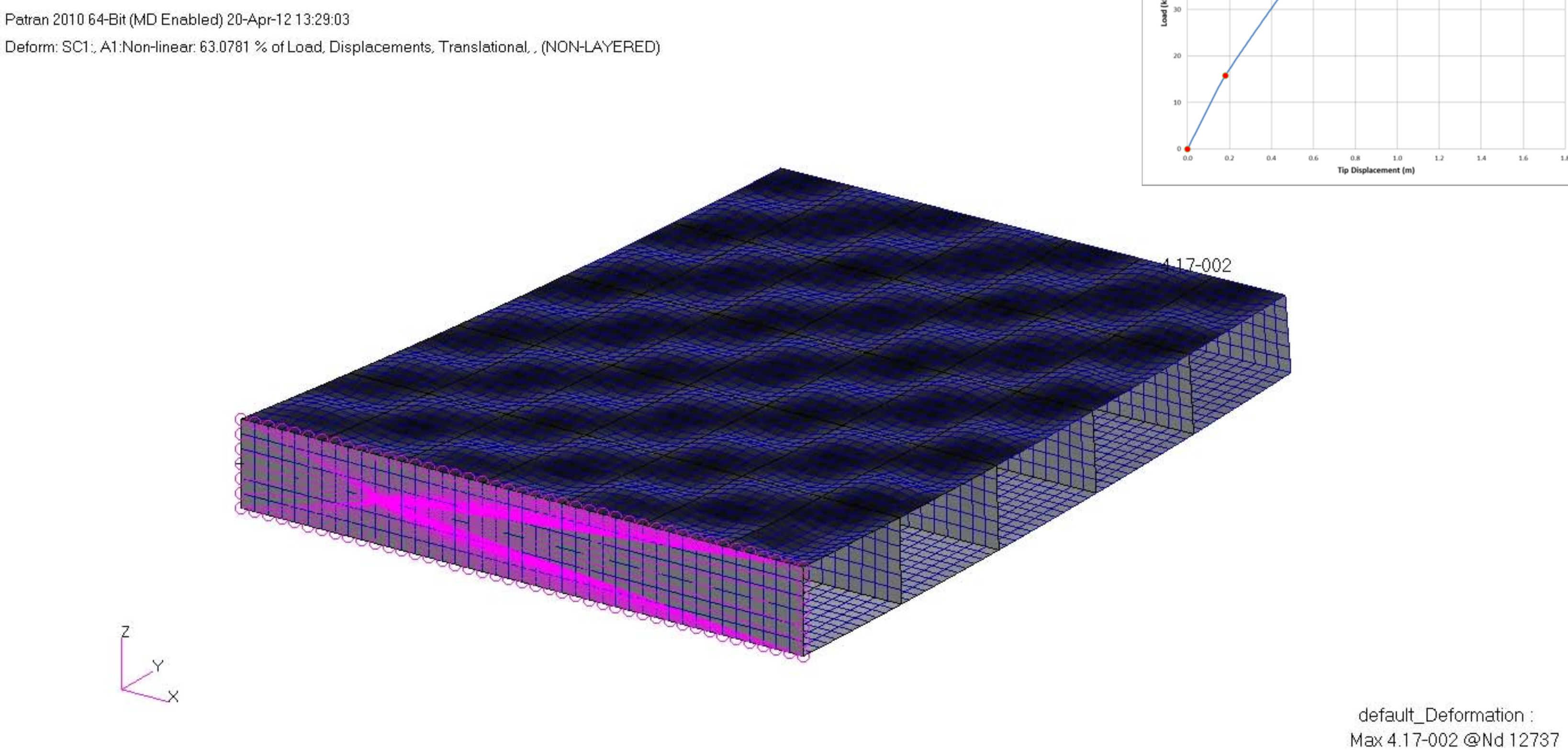
Postbuckling Analysis – Deformed Shape

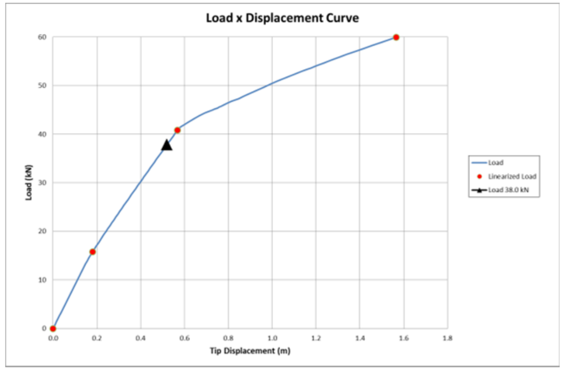




Deformed shape on 5 ribbays near the root – load 18.0 kN (113% of 1st local buckling load)

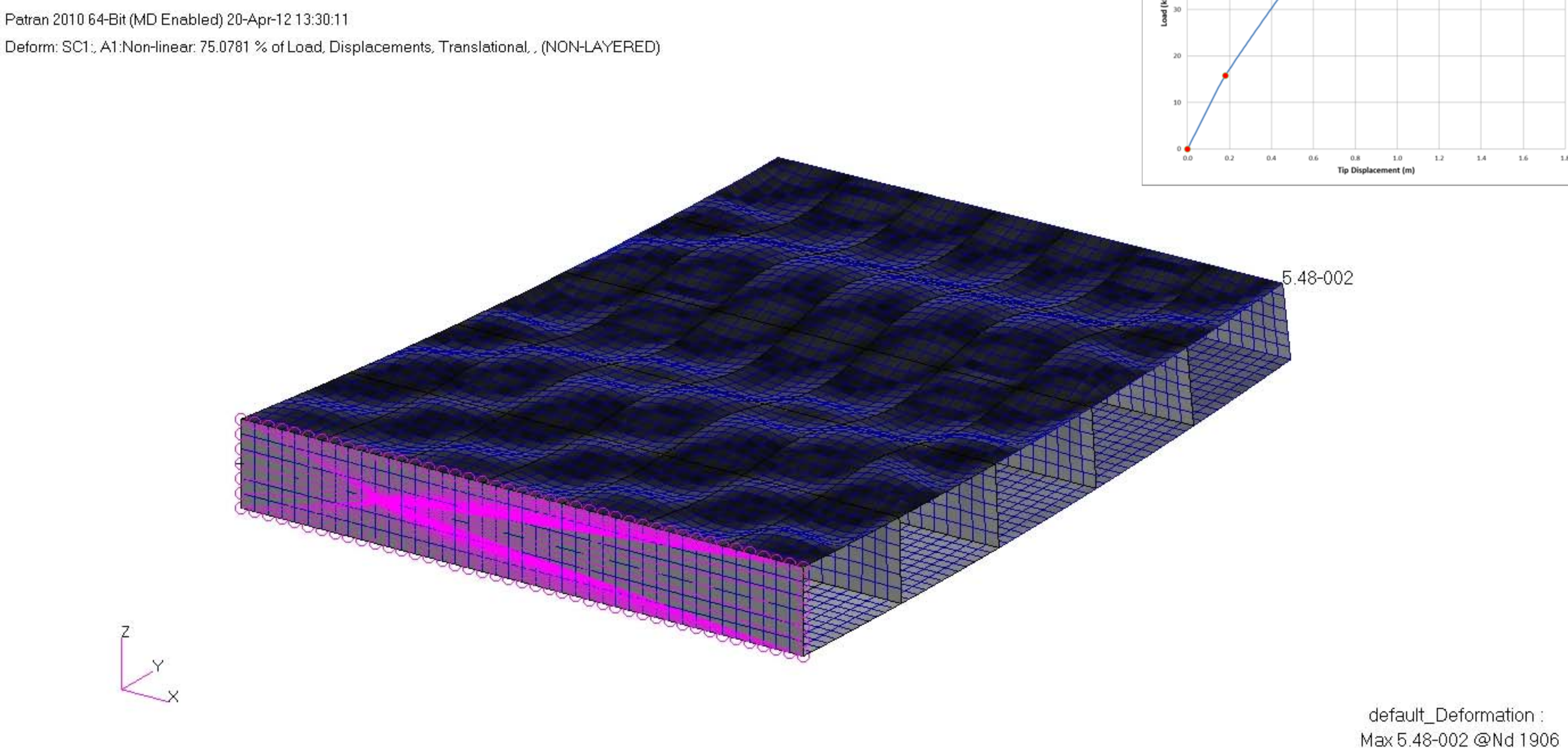
Postbuckling Analysis – Deformed Shape

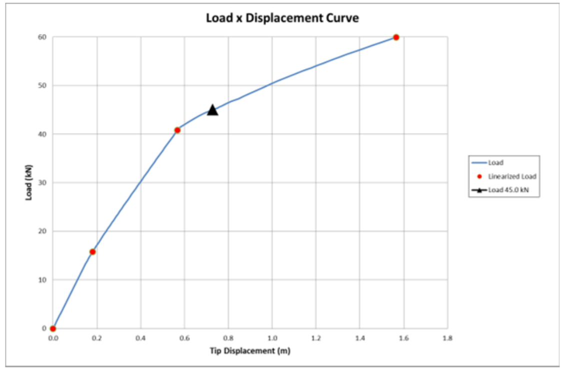




Deformed shape on 5 ribbays near the root – load 38.0 kN (238% of 1st local buckling load)

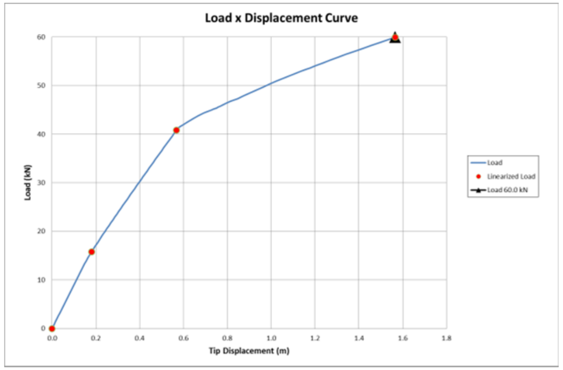
Postbuckling Analysis – Deformed Shape

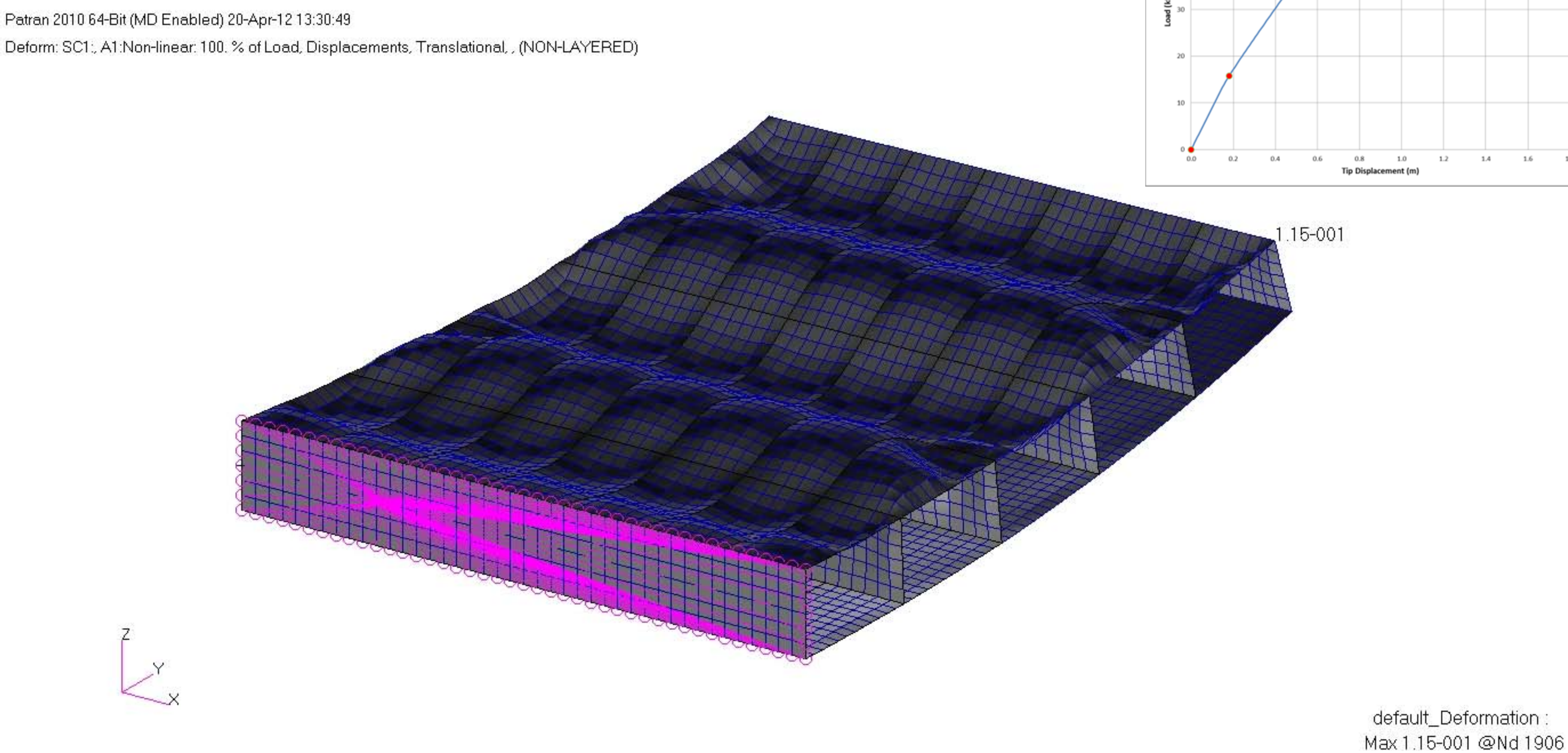




Deformed shape on 5 ribbays near the root – load 45.0 kN (281% of 1st local buckling load)

Postbuckling Analysis – Deformed Shape

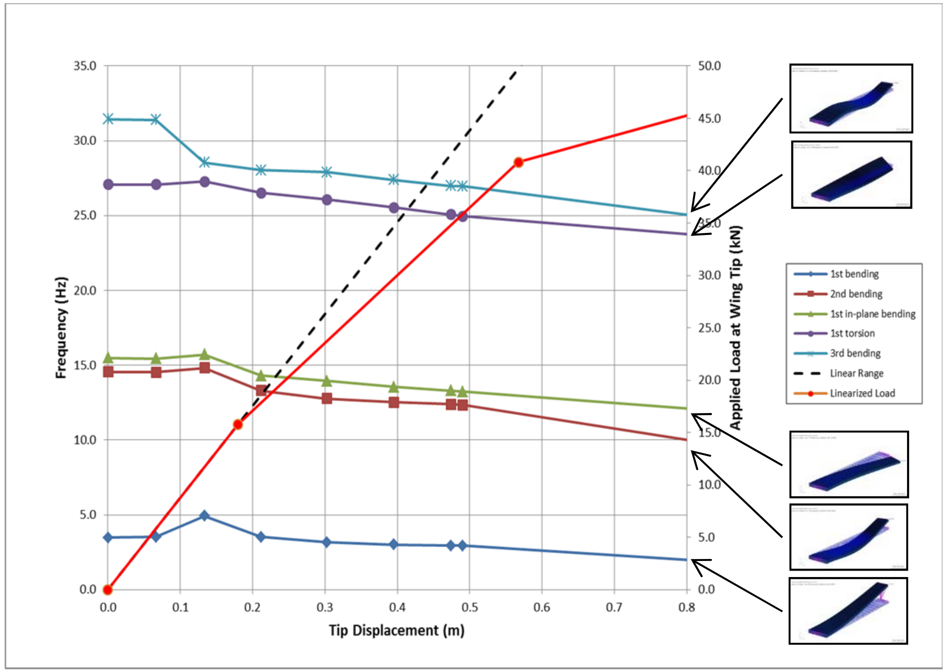




Deformed shape on 5 ribbays near the root – load 60.0 kN (375% of 1st local buckling load)

Variation of the Natural Frequencies in Postbuckling Regime

- A set of points in the load displacement curve was chosen for calculation of the natural frequencies on the deformed structure.
- It can be observed that, between the local and global buckling points, all the analyzed modes showed a decrease in their natural frequencies, varying from 7.8 % to 15.7 %.



Mode	Natural Frequency (Hz)		
	Unloaded structure	Before global buckling	Variaton (%)
1st bending	3.5	2.9	-15.7
2nd bending	14.6	12.3	-15.2
1st in-plane bending	15.5	13.2	-14.6
1st torsion	27.1	25.0	-7.8
3rd bending	31.4	27.0	-14.2

Conclusions

- Structural and aerodynamic nonlinearities may cause a significant change in the dynamic and aeroelastic behavior of a structure
- The natural frequencies of a wing structure may be significantly affected if the wing is operating in postbuckling regime

Next Steps

- Introduce composite parts on the wing model
- Increase the level of details of the wing structure
- Improve the mass distribution representation
- Apply a realistic aerodynamic load distribution on the structure
- Evaluate the effect of postbuckling on the flutter speed and transient response due to a gust
- Investigate the effect of different wing configurations, including engines and winglets

Questions ?

Thank you !

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