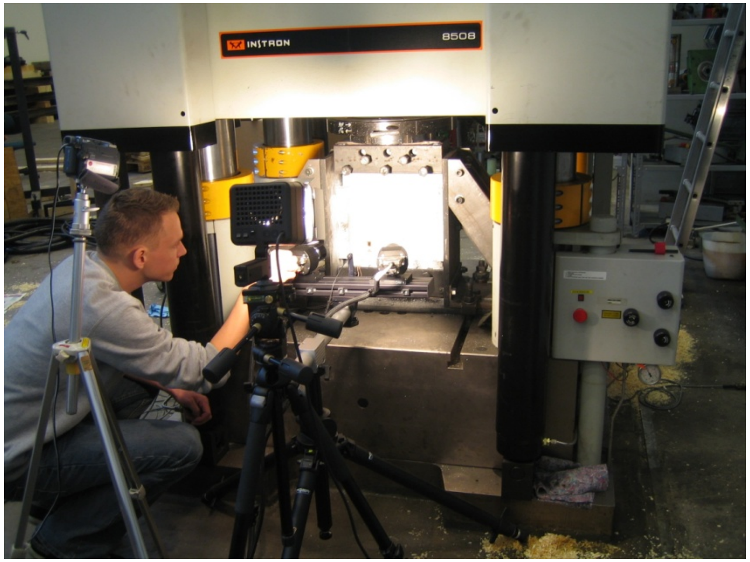
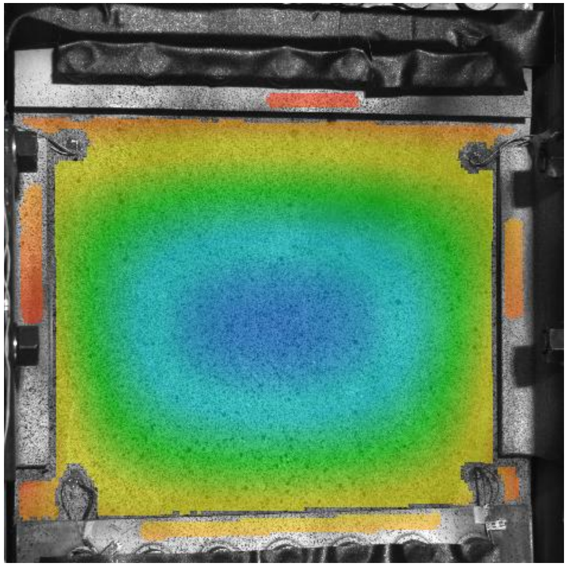
CompTest 2008
Air Force Research Laboratory and University of Dayton, USA,
October 20-22, 2008

BUCKLING STRENGTH OF THICK COMPOSITE PANELS IN WIND TURBINE BLADES – PART I: EFFECT OF GEOMETRICAL IMPERFECTIONS





Christian Berggreen, Associate Professor, PhD
Composite Lightweight Structures Group
Department of Mechanical Engineering
Technical University of Denmark

A big thanks to my fellow authors:

Nicholas Tsouvalis

Associate Professor, PhD

School of Naval Architecture and Marine Engineering,
Shipbuilding Technology Laboratory

National Technical University of Athens, Greece

Brian Hayman

Professor, PhD

Department of Structural Integrity and Laboratories and
Department of Mathematics

Det Norske Veritas AS and University of Oslo, Norway

Kim Branner

Senior Scientist, PhD

Wind Energy Department

Risø National Laboratory for Sustainable Energy

Technical University of Denmark

Contents

- Introduction
- Presentation of test setup and equipment
- Plate specimens and instrumentation
- Plate test results
- Round-Robin material characterization
- FE-modelling – Initial FPF validation and parametrical analysis
- FE-modelling in progress (if time)
- Conclusions

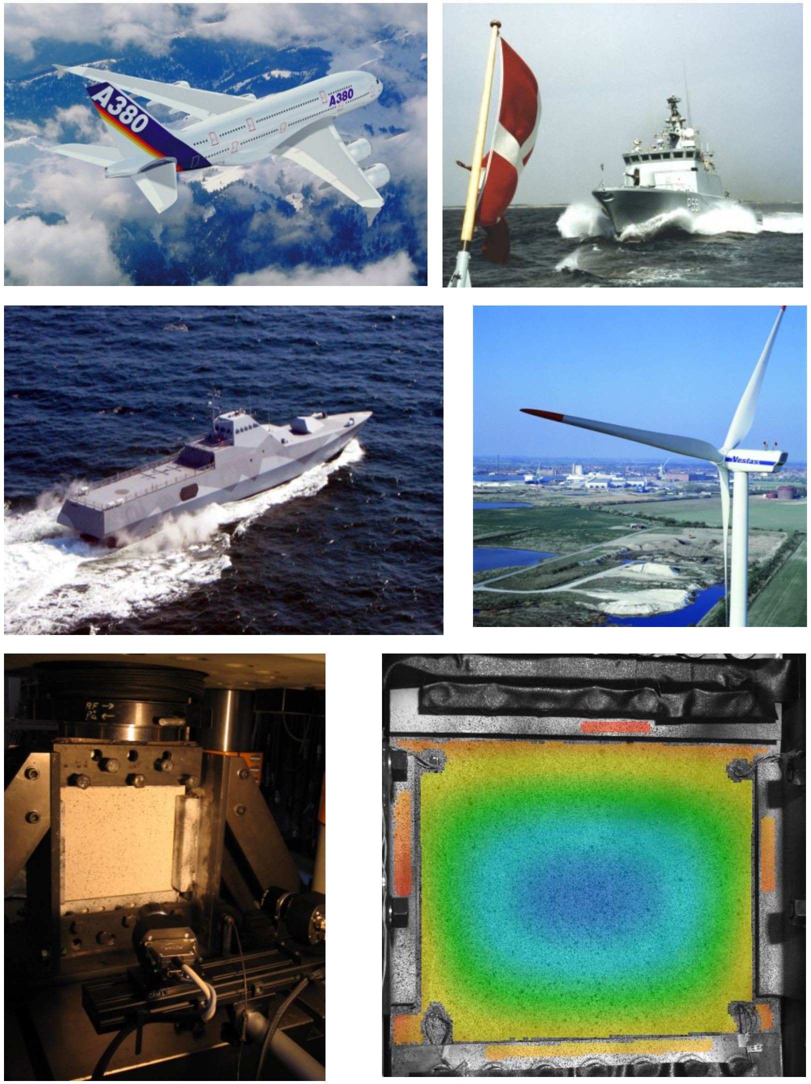
Introduction

Background

- Practical *design codes* covering FRP structures in compression:
    - Almost invariably treated in terms of the elastic critical load of the ideal structure
    - At best modified by a knock-down factor based on rather limited test data
    - A separate check for local compressive material failure is performed
    - Often neither considering *interaction* with buckling nor accounting for *imperfections* in a systematic way
- Relatively few test results are available for buckling of full-size FRP structures/compon.
- There is little published information on manufacturing imperfections

Objective

- To obtain an understanding of the buckling behavior of FRP components and structures in the presence of typical imperfections
- Develop rational procedures for estimating their strength for design purposes/codes

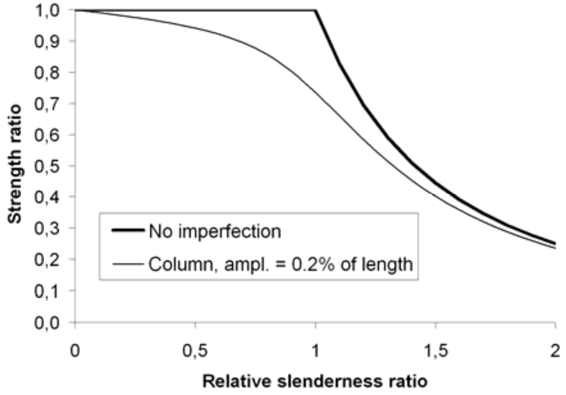


Introduction

Research agenda

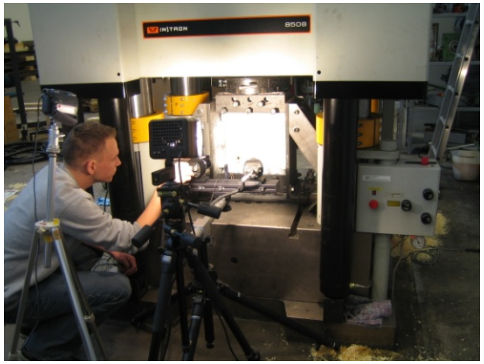
General

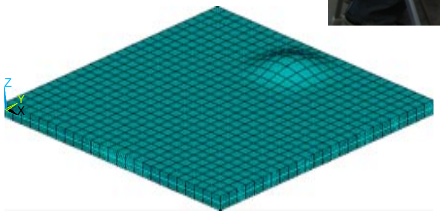
- Design curves are needed for compression strength as a function of imperfection magnitude/shape/location
- How well can we generate such curves based on numerical calculations?
- Can we use these curves to generate simple design tools?

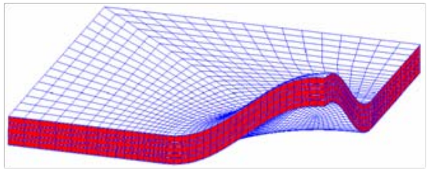


Test and analysis

- Experimental investigation (Plate compression tests + Round-Robin material characterization)
- Validation/benchmarking of numerical approaches to determine compression strength
- Parameter studies to map influence of *geometrical imperfections*
    - Magnitude
    - Shape
    - Size
    - Location







Introduction

Participating partners

EU FP6 Network of Excellence (MARSTRUCT):

- **DTU**
  - Experimental
  - Numerical
- **National Techn. Univ. Of Athens**
  - Experimental
  - Numerical
- **UoS + UGS + UNEW**
  - Numerical
- **DNV**
  - Coordination and design guidelines

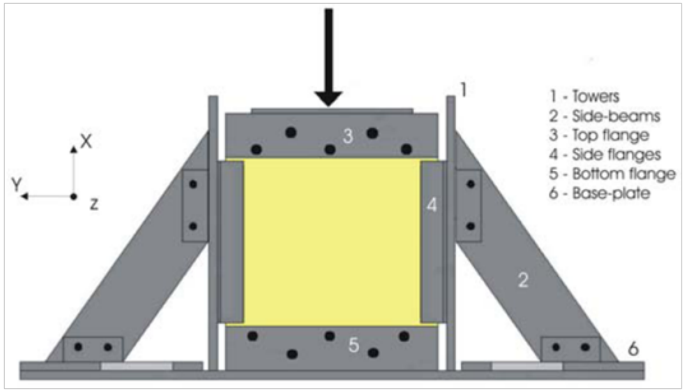
- *Industry support:*
  - SSP Technology (Denmark)
  - Vestas Wind Systems (Denmark)

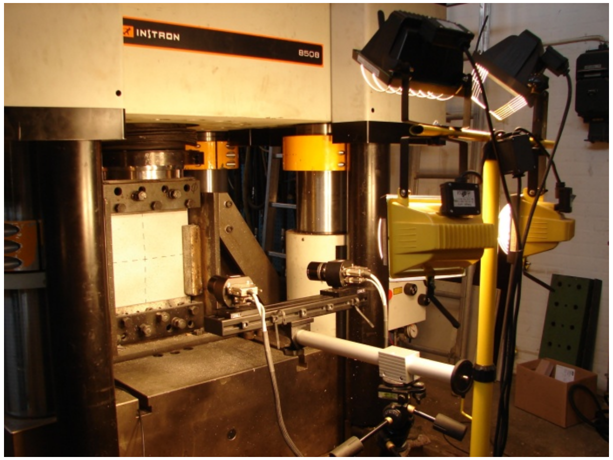
MARSTRUCT
Network of Excellence on Marine Structures

Test equipment

Test rig and measuring equipment

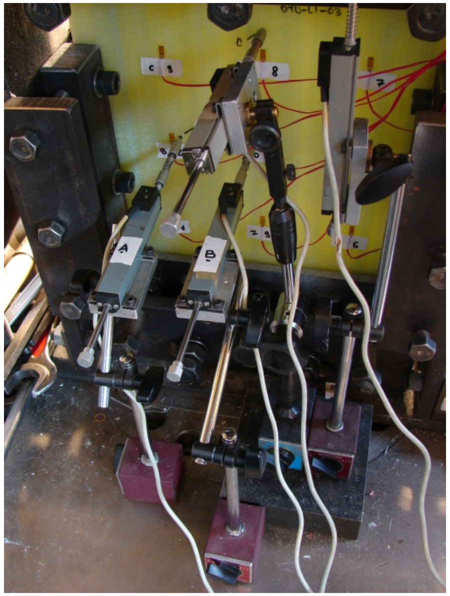
- Test rig
  - Panel is fixed between two towers
  - Top edges ”fully” clamped over 40 mm
  - 30 mm of the side edges able to slide in-plane within clamping guides
- 5 MN Instron 8508 servo-hydraulic test machine
- Test is carried out in displacement control
- Digital Image Correlation (DIC) measurements are carried out to measure *full panel displacement/strain field*
- Cross-checked with strain gauge and LVDT results





DIC system (ARAMIS 2M & 4M)

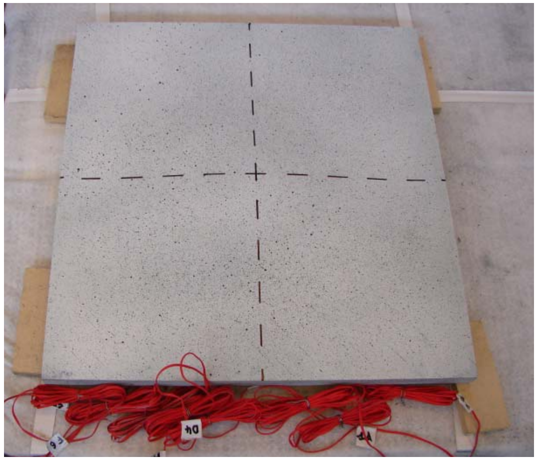
5MN Instron 8508



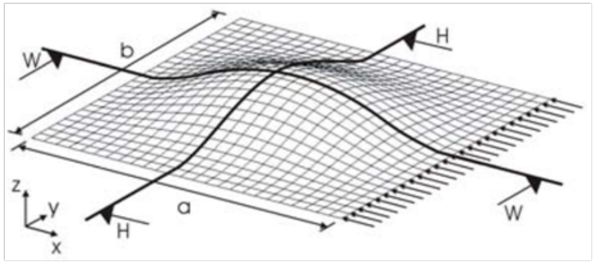
LVDT & strain gages

DTU plate specimens (1/3)

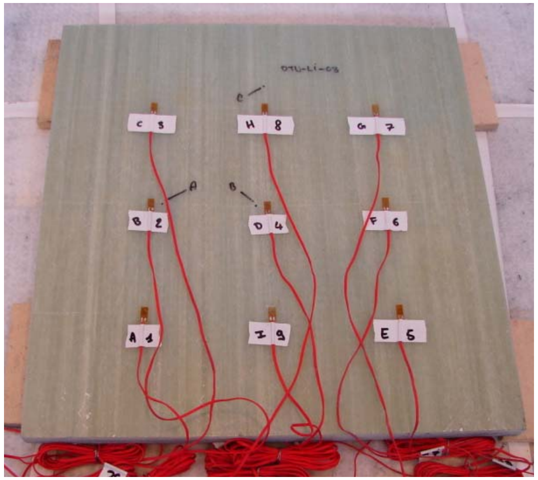
- Typical panels from the load carrying spar of a wind turbine blade have been chosen
- 9 panels supplied by Vestas (+ 18 from NTUA)
  - 3 without imperfection **(NI)**
  - 3 with a **3,2 mm** imperfection **(SI)** (1% of active plate width)
  - 3 with a **9,6 mm** imperfection **(LI)** (3% of active plate width)
- Vacuum assisted pre-preg curing (Vestas/DTU panels)
- Approx. 85% UD, 15% Biax, E-glass/epoxy
- Approx. 19,6 mm thickness (9 & 16 mm for NTUA)
- a*b= 380x400 mm
- 320x320 mm active buckling panel area
- $\lambda_r \approx 1 \Rightarrow$ highly imperfection sensitive (DTU-panels)
- 9 strain gauges/panel



DIC speckle pattern (front side)



Imperfection shape – 1st buckling mode for 300x300 CL

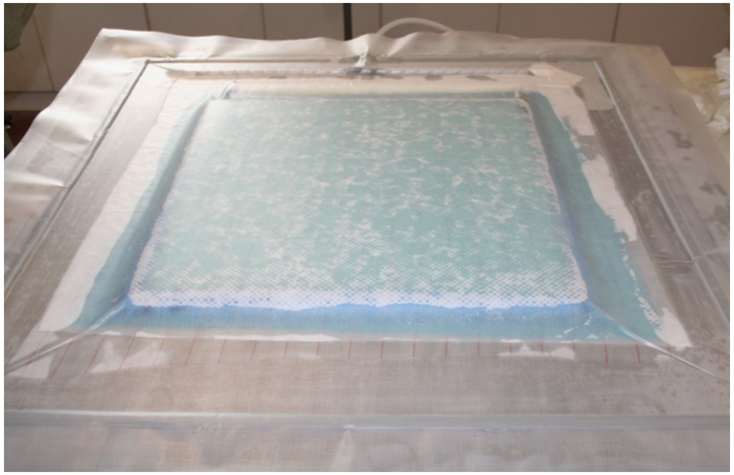


Strain gages location (back side)

DTU plate specimens (2/3)

***DTU specimens*: Pre-pregs and vacuum assisted curing using an engaged *double sided* mould**

***NTUA specimens*: Hand lamination and vacuum assisted curing in single sided mould**



DTU plate specimens (3/3)

Measured data

- Test machine
    - Load
    - Piston movement
- DIC (ARAMIS 2M or 4M)
    - Full-field in-plane and out-of-plane displacements and strains
    - → Buckling pattern
    - Section displacements at all load stages
- Conventional devices
    - LVDT: Out-of-plane displacements
    - Strain gages: Strains on concave face in the load direction

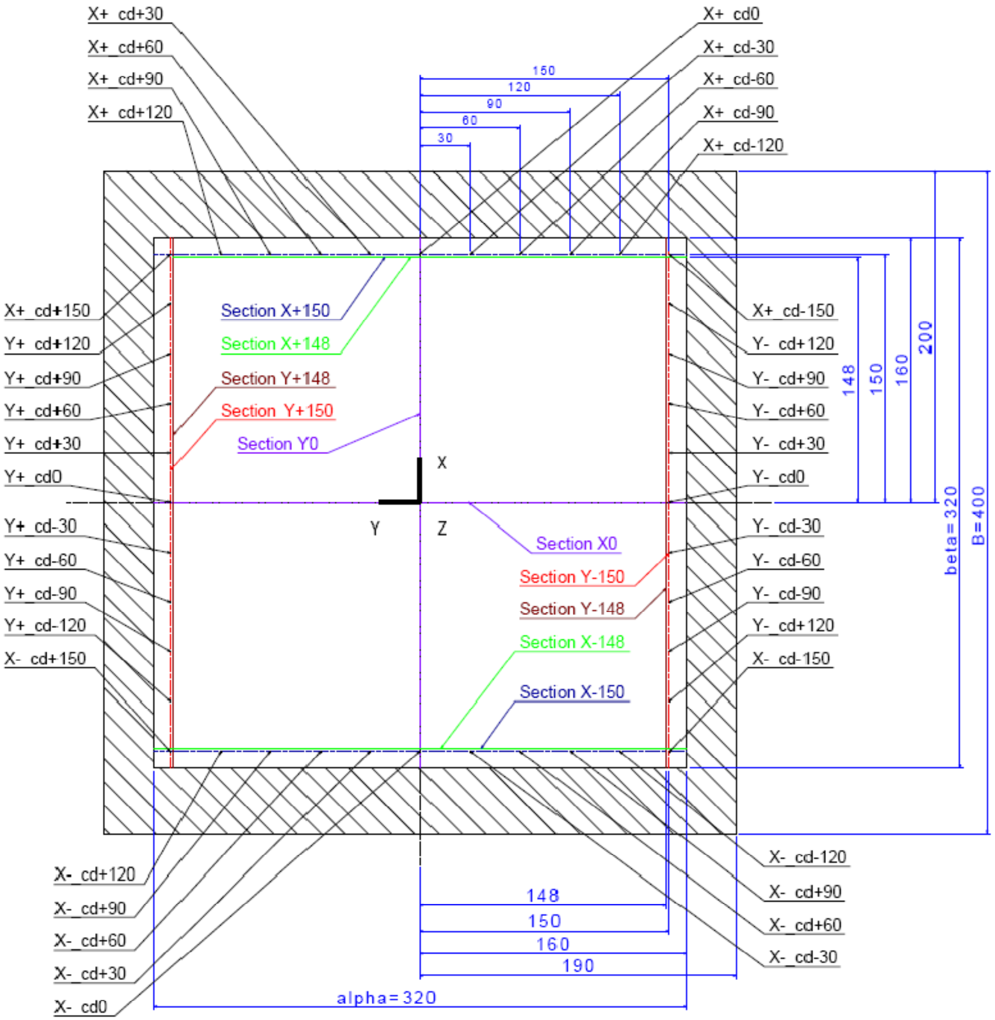
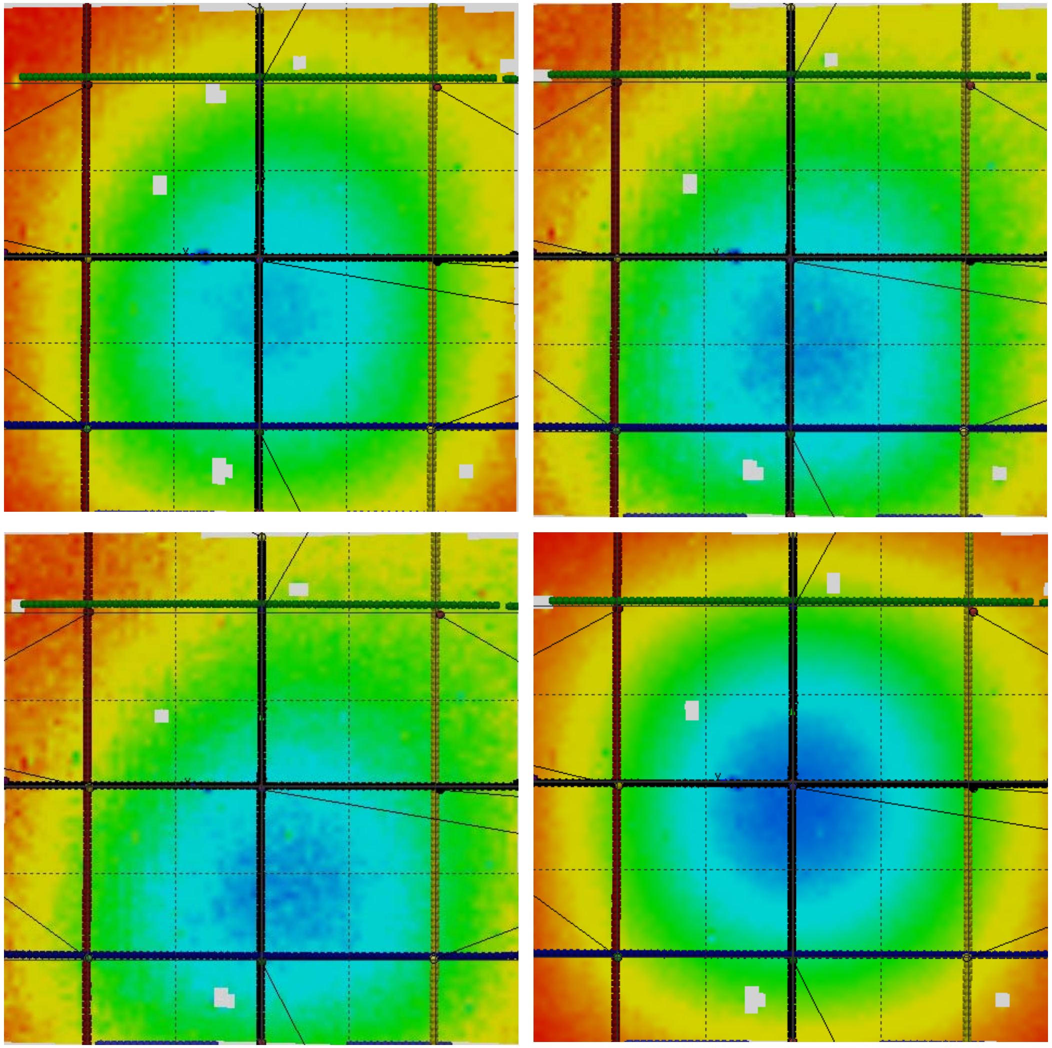


Plate dimensions & measuring locations (convex side)

Plate test results

DIC full-field displacement results

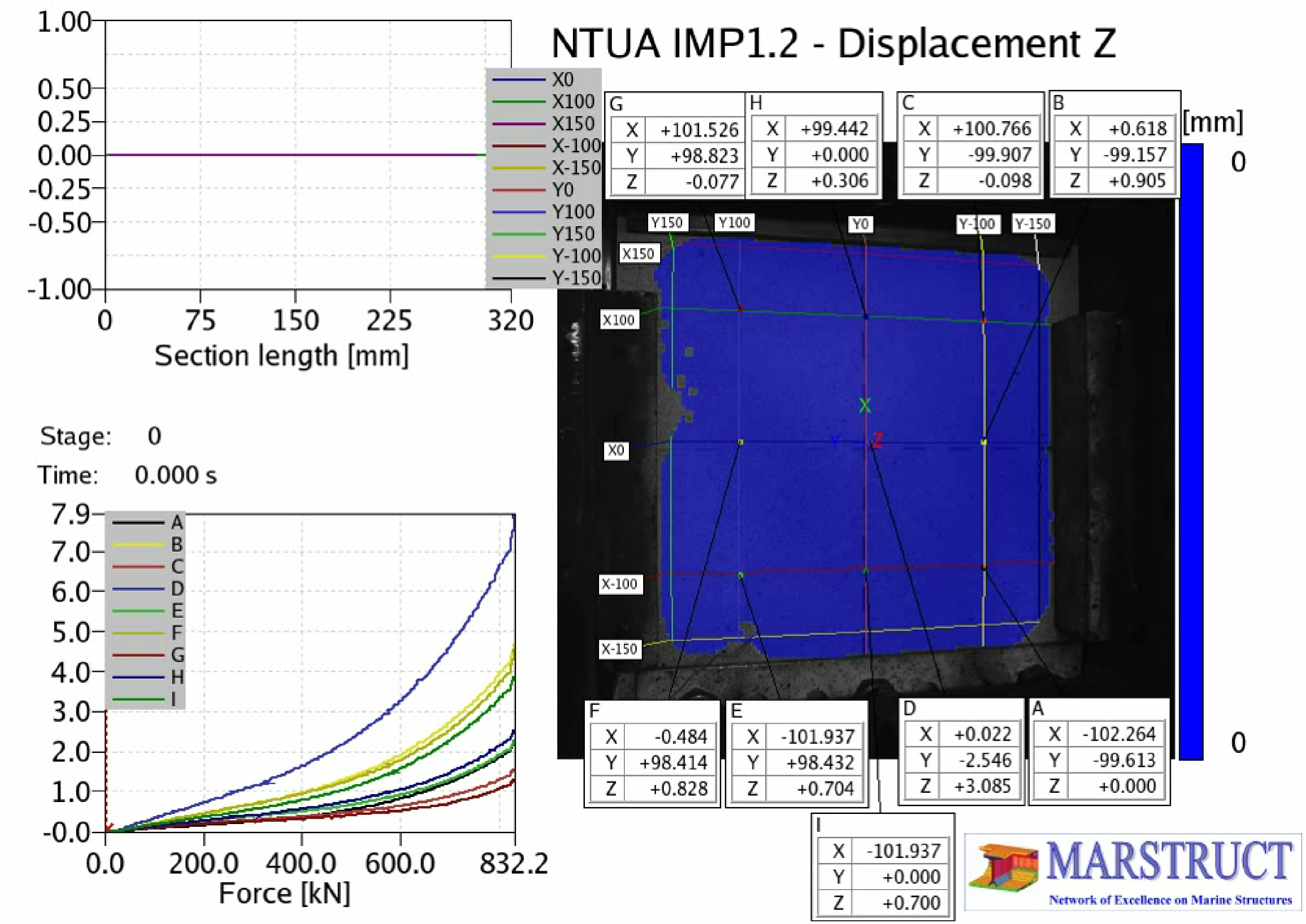


Propagation of the out-of-plane displacement

(S3-0-3: Thick & intact)

Plate test results

DIC results (S2-32-02: NTUA 15 mm specimen with small imperfection)



G	
X	+101.526
Y	+98.823
Z	-0.077

H	
X	+99.442
Y	+0.000
Z	+0.306

C	
X	+100.766
Y	-99.907
Z	-0.098

B	
X	+0.618
Y	-99.157
Z	+0.905

F	
X	-0.484
Y	+98.414
Z	+0.828

E	
X	-101.937
Y	+98.432
Z	+0.704

D	
X	+0.022
Y	-2.546
Z	+3.085

A	
X	-102.264
Y	-99.613
Z	+0.000

I	
X	-101.937
Y	+0.000
Z	+0.700

Panel tests results

Ultimate failure loads (DTU & NTUA panels)

	DTU Thick	Failure load [kN]	NTUA Mid-thick	Failure load [kN]	NTUA Thin	Failure load [kN]
Perfect Panels	*S3-0-1*	2250	*S2-0-1*	1218	*S1-0-1*	N/A
	S3-0-2	2070	*S2-0-2*	1092	*S1-0-2*	415
	S3-0-3	Not received	*S2-0-3*	1170	*S1-0-3*	390
Panels with small imperfect°	*S3-32-1*	2380	*S2-32-1*	906	*S1-32-1*	294
	S3-32-2	2303	*S2-32-2*	882	*S1-32-2*	213
	S3-32-3	2327	*S2-32-3*	930	*S1-32-3*	309
Panels with large imperfect°	*S3-96-1*	1543	*S2-96-1*	750	*S1-96-1*	294
	S3-96-2	1934	*S2-96-2*	780	*S1-96-2*	320
	S3-96-3	1892	*S2-96-3*	792	*S1-96-3*	Broken before test
Ave. Imp 0	2160,0		1160,0		402,5	
Ave. Imp 32	2336,7		906,0		301,5	
Ave. Imp 96	1789,7		774,0		307,0	

- General trend: Decreasing compressive strength for increasing imperfection size
- **HOWEVER**: Active BC's during the test seems to act as additional imperfections!!

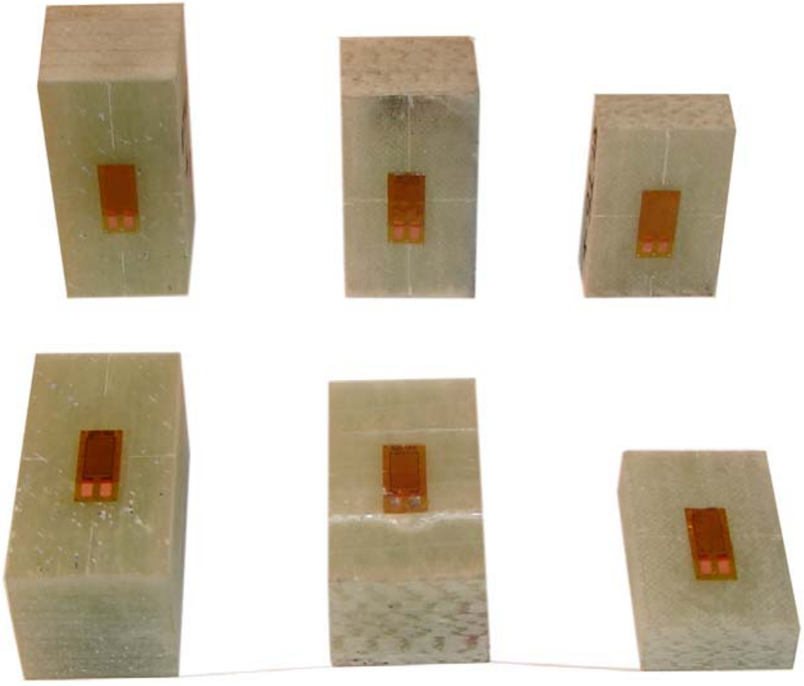
Laminate Compression Tests

Purpose: **Investigate the compressive strength of the material layups used for NTUA & DTU specimens**

- Specimens cut from "un-damaged" areas in already tested DTU & NTUA panels
- 6 specimens for Serie 1: **32mm*20mm*9mm**
- 6 specimens for Serie 2: **35mm*20mm*16mm**
- 9 specimens for Serie 3: **40mm*20mm*19,6mm**
- 2 strain gages to check an eventual buckling of the specimens

Results:

- Average maximum stresses:
  - ***Series 1: 288 MPa*** *(NTUA: thin)*
  - ***Series 2: 251 MPa*** *(NTUA: mid-thick)*
  - ***Series 3: 529 MPa*** *(DTU: thick)*
- *Expected* approx. maximum intact panel failure loads: (assuming **pure** compr.)
  - ***Series 1: 985 kN*** *(NTUA: thin)*
  - ***Series 2: 1526 kN*** *(NTUA: mid-thick)*
  - ***Series 3: 3940 kN*** *(DTU: thick)*
- **Again:** **Active BC's in tests are important!!**

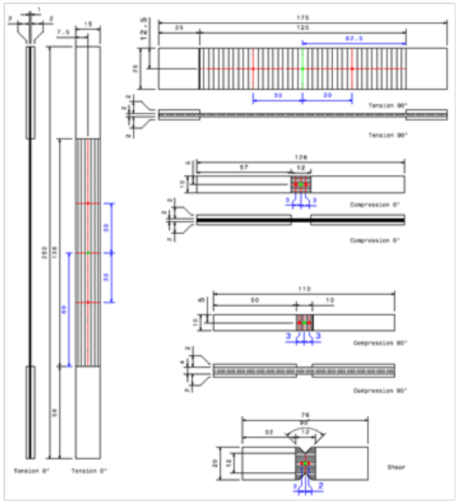


From left to right: Serie 3-DTU-thick, Serie 2- NTUA mid-thick, and Serie 1-NTUA-thin

Measured ave. intact panel failure loads	**Series 1**	**Series 2**	**Series 3**
	402,5	**1160,0**	**2160,0**

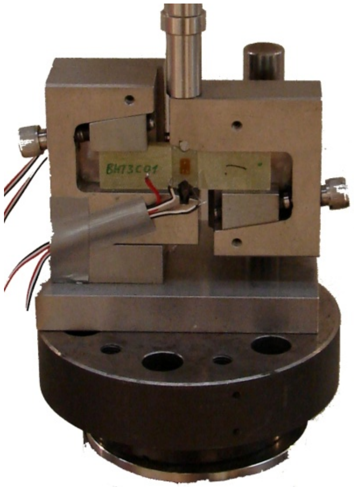
Round-Robin material characterization

Overview



<u>Purpose:</u> Determine tensile, compressive and shear properties for UD material applied in the DTU and NTUA plate specimens.

- Standards used:
  - ASTM D3039M
    - Tension at 0°
      - Tensile modulus in the fibre direction E_{1t}
      - Poisson's ratio ν_{12}
      - Maximum tensile stress in the fibre direction X_t
    - Tension at 90°
      - Tensile modulus in the transverse direction E_{2t}
      - Maximum tensile stress in the transverse direction Y_t
  - ISO 14126
    - Compression at 0°
      - Compressive modulus in the fibre direction E_{1c}
      - Maximum compressive stress in the fibre direction X_c
    - Compression at 90°
      - Compressive modulus in the transverse direction E_{2c}
      - Maximum compressive stress in the transverse direction Y_c
  - ASTM D5379
    - Iosipescu Shear
      - Shear modulus G_{12}
      - Maximum shear stress S



Iosipescu shear fixture

Material tests

Obtained results

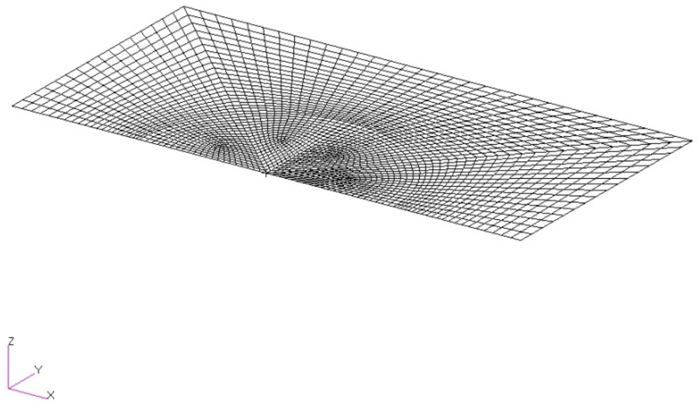
	NTUA specimens		DTU specimens	
	Test @ NTUA	Test @ DTU	Test @ NTUA	Test @ DTU
E1-tension	**29658**	**33170**	**48634**	**56235**
E1-compression	**38671**	**37238**	**50619**	**56209**
E2-tension	**6563**	**9338**	**18535**	**20422**
E2-compression	**8501**	**9536**	**12325**	**15729**
G12	**2034**	**2169**	**4800**	**4264**
v12	**0.29**	**0,268**	**0,27**	**0,284**
Xt	**559**	**698**	**968**	**1141**
Xc	**253**	**191**	**915**	**952**
Yt	**60**	**43**	**24**	**22**
Yc	**59**	**69**	**118**	**127**
S	**31**	**30**	**65**	**64**

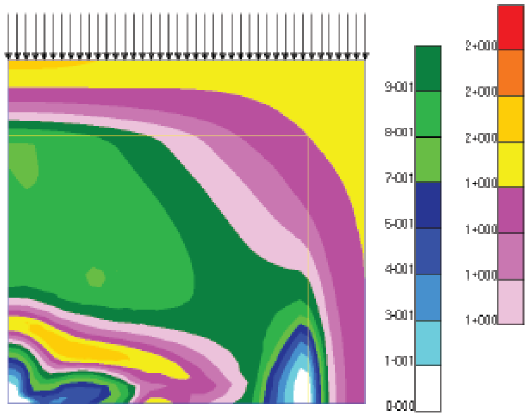
- DTU specimen properties higher than NTUA properties – pre-preg vs. vacuum ass. hand-layup
- Some discrepancy for matrix dir. in tension for the NTUA material
- However, relatively fair correlation between results, given the different testing conditions and experience in the involved laboratories.

FE modeling

Initial FPF models

- MSC.Patran Laminate Modeller has been used to generate the model
- Series of PCL (Patran Command Language) routines to define and control:
    - Desired geometry
    - Imperfections
    - Mesh
    - Boundary conditions
    - Load cases
    - Solution
- Thick shell element including transverse shear deformation (quad4)
- Geometrically non-linear analyses including FPF material failure have been carried out using:
    - MSC.Marc code with Newton-Raphson and Arc-length solvers
    - Tsai-Wu failure criterion



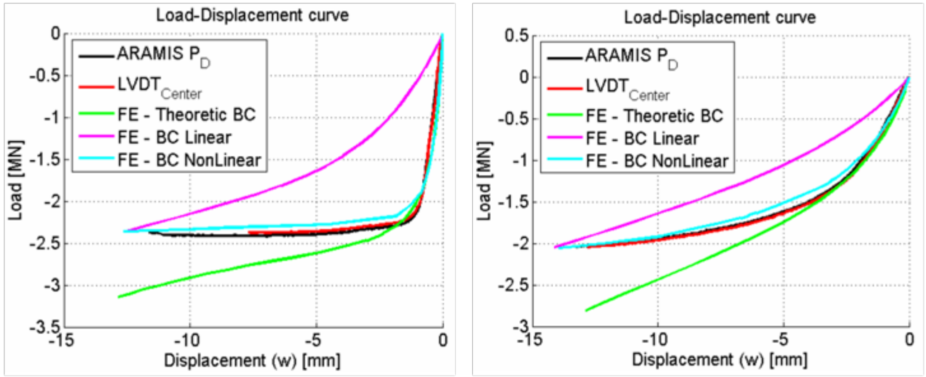


FE modeling

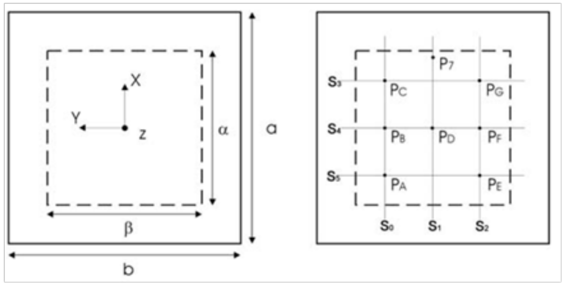
Initial FPF models

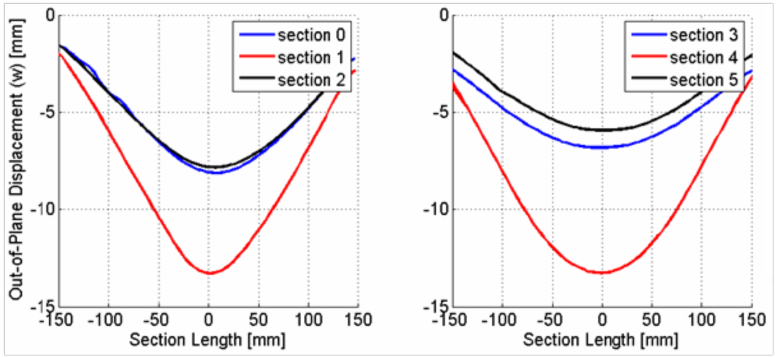
Validation of numerical model

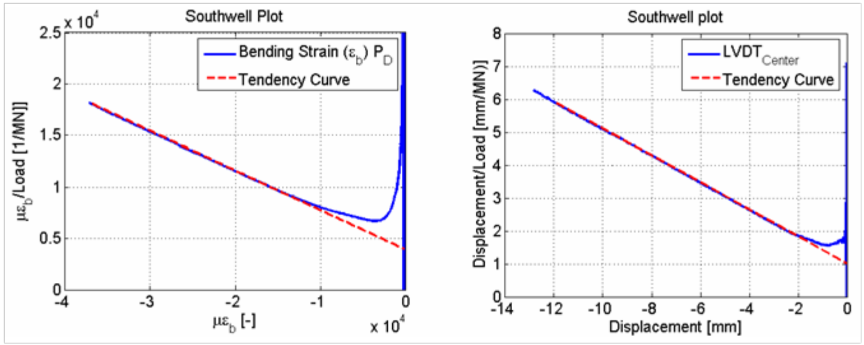
- Three thick specimens chosen for the validation
- Influence of edge rotations have been investigated
- Using the DIC measurements, edge rotations are used as BC’s in FEA
- Critical instability loads are successfully compared using Southwell plots



Panel	Ultimate [MN]	Southwell [MN] ε_b	Southwell [MN] LVDT	Southwell [MN] FE NL-BC
1	2.37	2.35	2.42	2.38
2	2.10	2.48	2.36	2.46
3	2.04	2.60	2.44	2.49

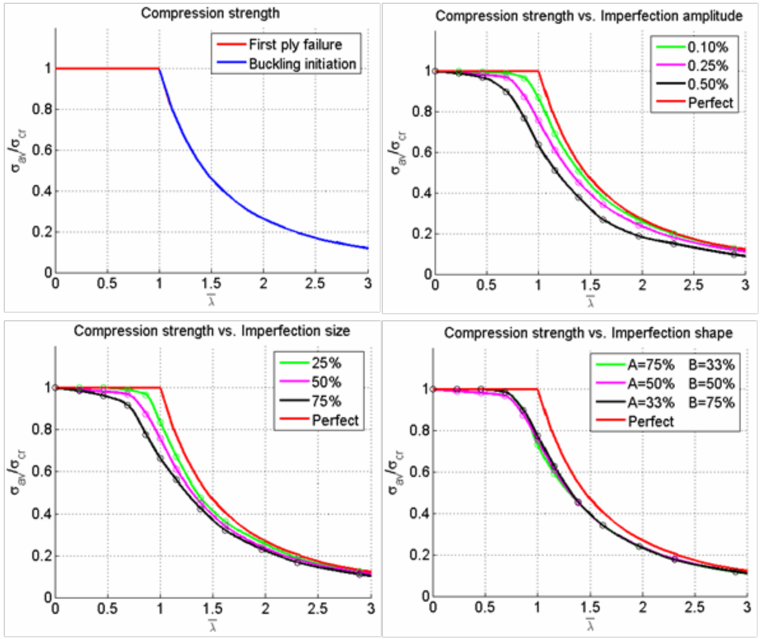






Initial Numerical Parameter Studies

- An initial extensive parameter study has been carried out with the FPF models using:
  - First ply failure (Tsai-Wu)
  - Typical material data from the literature
- Parameters studied: (SS BC's)
  - Relative slenderness ratio
  - Imperfection amplitude
  - Imperfection size
  - Imperfection shape
- Conclusion: Compression strength is sensitive to imperfection amplitude and size !!



E_1	E_2 [GPa]	E_3	ν_{12}	ν_{23} [-]	ν_{31}	G_{12}	G_{23} [GPa]	G_{31}
46.0	13.0	13.0	0.30	0.42	0.30	5.0	4.6	5.0
X_T	X_C	Y_T	Y_C	Z_T [MPa]	Z_C	S_{XY}	S_{YZ}	S_{ZX}
1000	680	30	140	30	140	60	40	40

Typical UD glass/epoxy material data

Next 6 months:

Round-Robin analyses between several European partners using/comparing progressive failure models.

1. Multi-axial wind turbine layup (like tests)
2. Quadri-axial marine layup
3. Woven marine layup

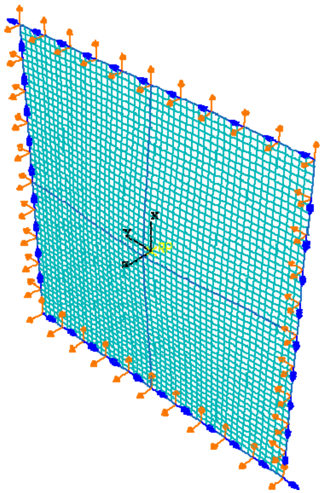
FE modeling in progress

LPF / Progressive failure models

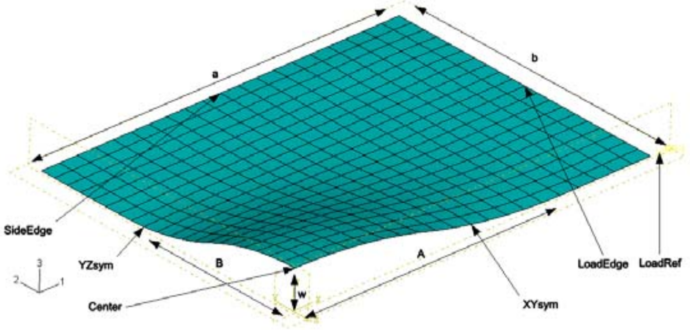
<u>Aims:</u>

1. **Generate models able to predict failure loads**
2. **Validate numerical models against experimental results through non-linear BC's**
3. **Generate model to be used for parametric analyses**

- 2 ABAQUS FE models generated:
  - <u>Model #1:</u> (mainly for validation analyses)
    - Non-linear BC's from DIC measurements
    - Full active area / kinematic linking to active BC's
    - Buckling shape as first buckling mode
    - FPF or LPF/progressive failure material models
  - <u>Model #2:</u> (mainly for parametric analyses)
    - Simply supported BC's
    - ¼ panel
    - Possibility to define imperfection arbitrary as a trigonometric shape
    - FPF or LPF/progressive failure material model



Non-linear BC FE model



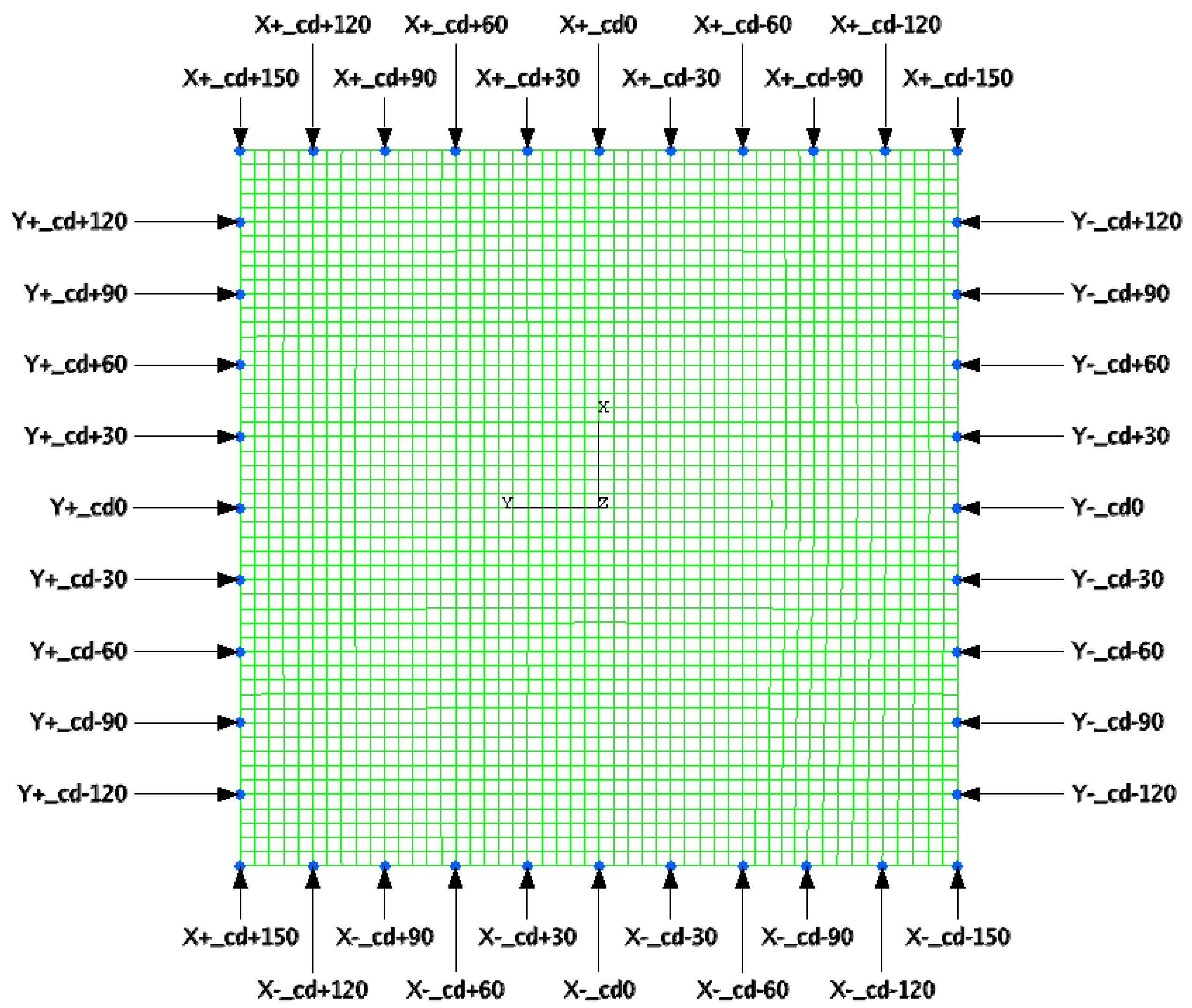
Parametric study FE model

FE modeling in progress

LPF / Progressive failure models - Model #1

- Section points

  ➔ master nodes
- Kinematic coupling constraints between master and slave nodes
- Updated at every load step
- Only updated discretely in initial models



FE modeling in progress

Material properties – Adaptation to failure model

Model #1 (non-lin BC) :

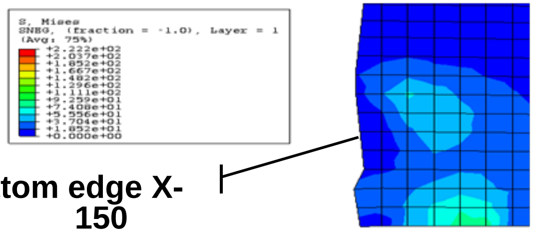
- Hashin failure model
- Initially due to BC-problems:
  No progressive fail. ➔ Only response

Model #2 (Simply sup. BC):

- Hashin failure model
- Progressive failure analysis

  Model # 2 tested with:
- Adapted energy for each material

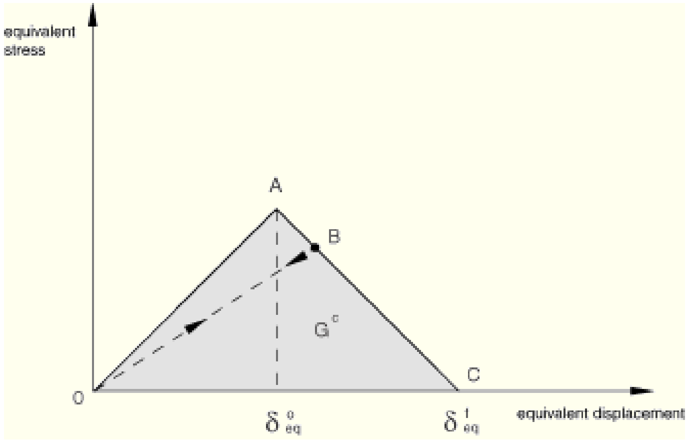
		Average max stress	Average max strain	Adapted Energy (Gc)
DTU	Xt	1141	0,01845	21,05
	Xc	952	0,01504	14,32
	Yt	22	0,001	0,02
	Yc	127	0,01302	1,65
NTUA	Xt	698	0,0249	17,38
	Xc	191	0,00547	1,04
	Yt	43	0,013	0,56
	Yc	69	0,0054	0,37



Bottom edge X-150

Mesh problem with model #1 & progressive failure

Failure energies (Model 2)



Built-in failure model:

- **Based on energy dissipation**
- **Assumes a linear degradation**

δ^0_{eq} **: maximum strain of the material**

δ^f_{eq} **: strain for totally damaged material**

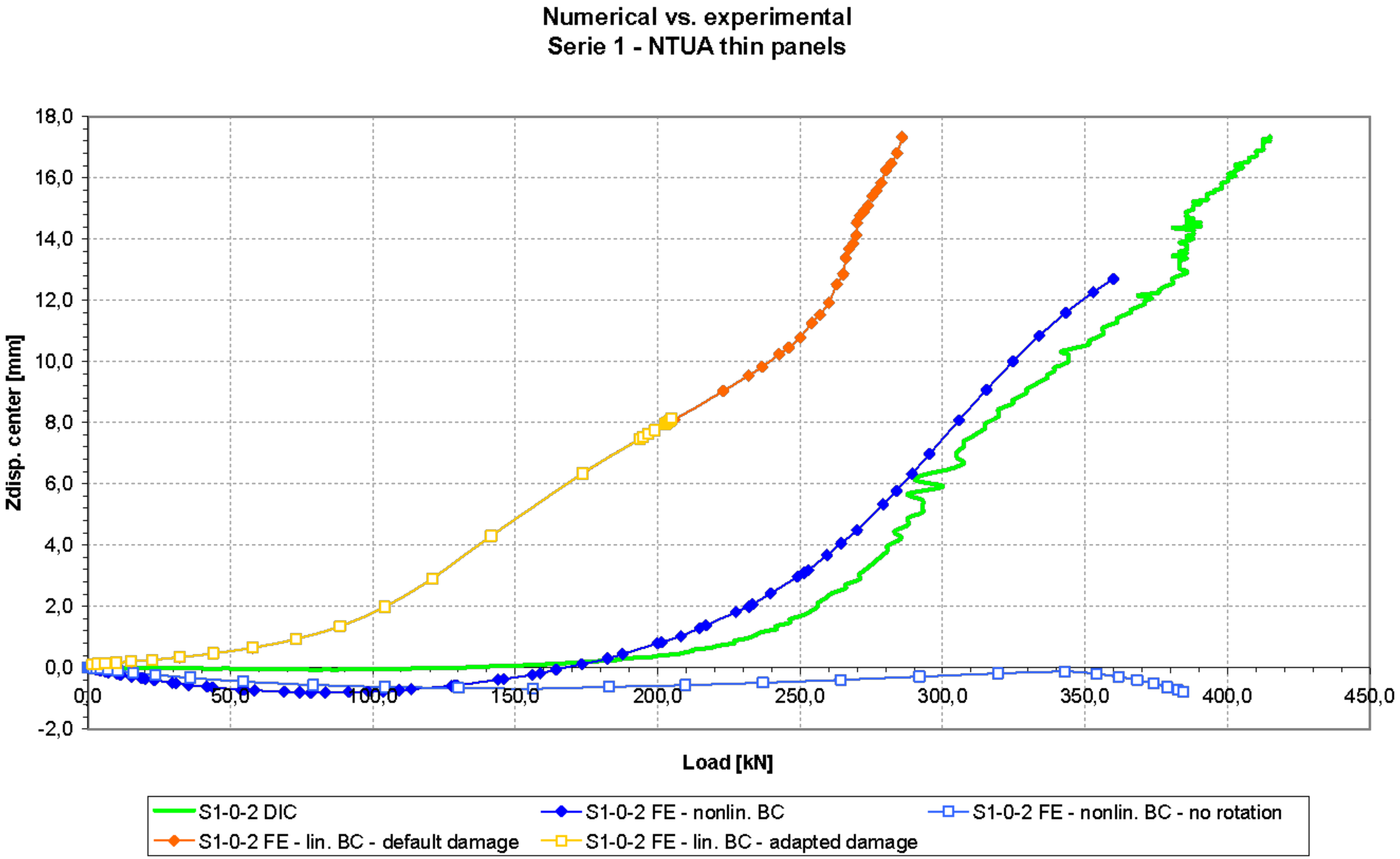
G^c **: dissipated energy**

Energies calculated from the material test results assuming that:

$$\delta^f_{eq} = k^* \delta^0_{eq}$$

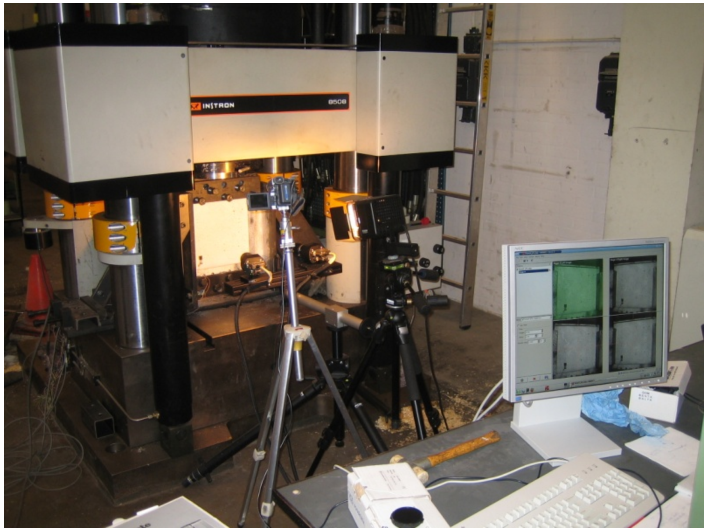
FE modelling in progress

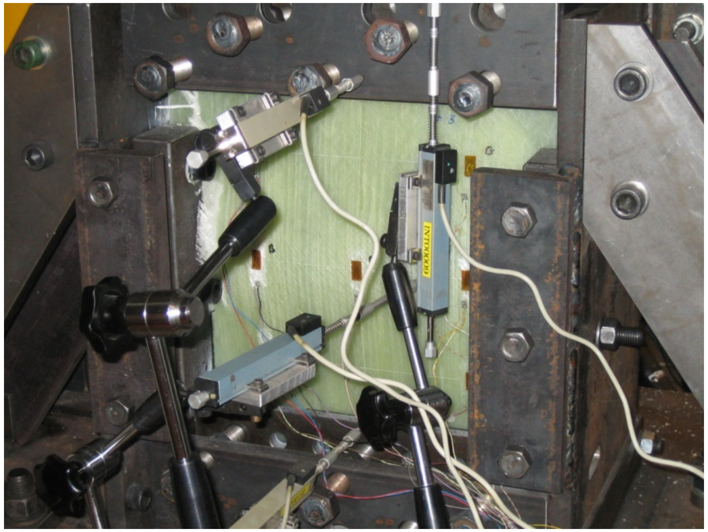
Results S1-0-2: Intact & thin



Conclusions

- Large-scale DIC monitored panel compr. tests
- From initial numerical modeling:
  1. *Non-linear BC's* provided by the test-rig have a *dominating influence* on the panel behavior
  2. Demonstrated the *sensitivity* of the *buckling loads* to the boundary conditions of the panels
  3. *Good agreement* - when both rotations and translation of the *panel boundaries* were *re-used* in the FE model
- Initial parameter study:
  - Investigated UD lay-up is *sensitive* to imperfection *amplitude and size*
  - *Not sensitive* to *imperfection shape*
- <u>On-going work</u> with progressive failure models:
  - Initiation and progression of failure is highly sensitive to introduction of BC's at panel edges – improvements needed
  - Estimation of damage parameters must be validated against simple compression material tests to improve accuracy





THE END

Discussion!!

Acknowledgements:

This work has been performed within the Network of Excellence on Marine Structures (MARSTRUCT) and has been partially funded by the European Union through the Growth Program under contract TNE3-CT-2003-506141. Furthermore, the sponsoring of test specimens by Vestas Wind Systems A/S and SSP Technology A/S is highly appreciated.