Cost reduction approaches for lightweight marine composite structures

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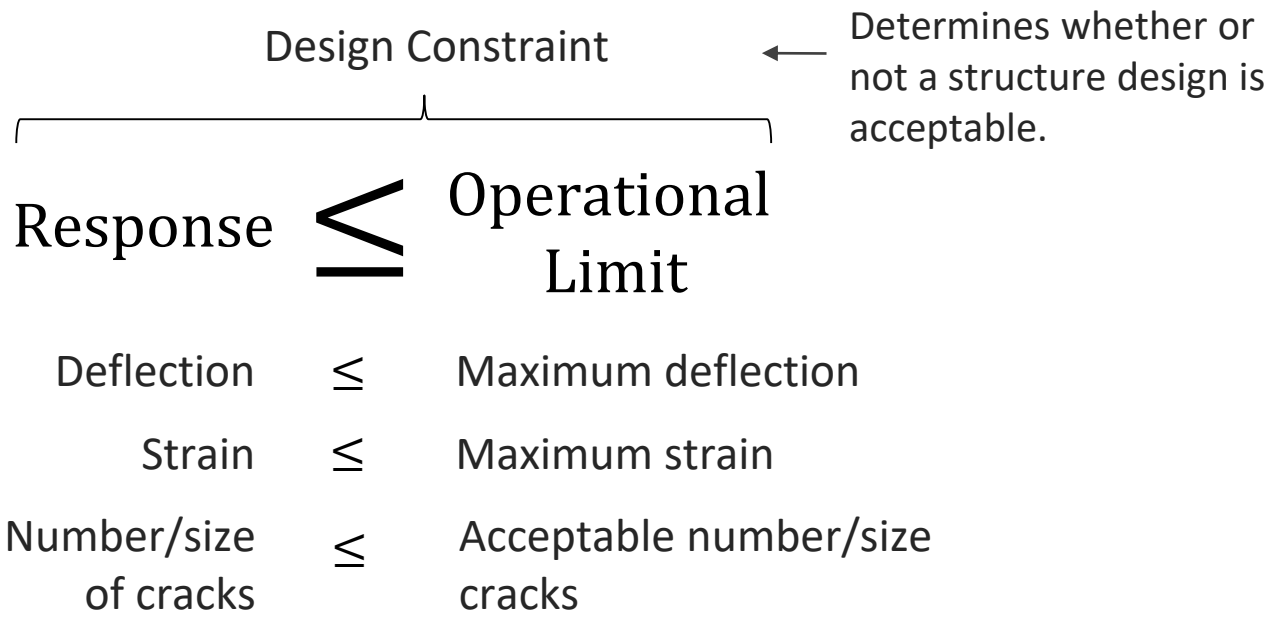
Researcher, RISE

Objective of my PhD work

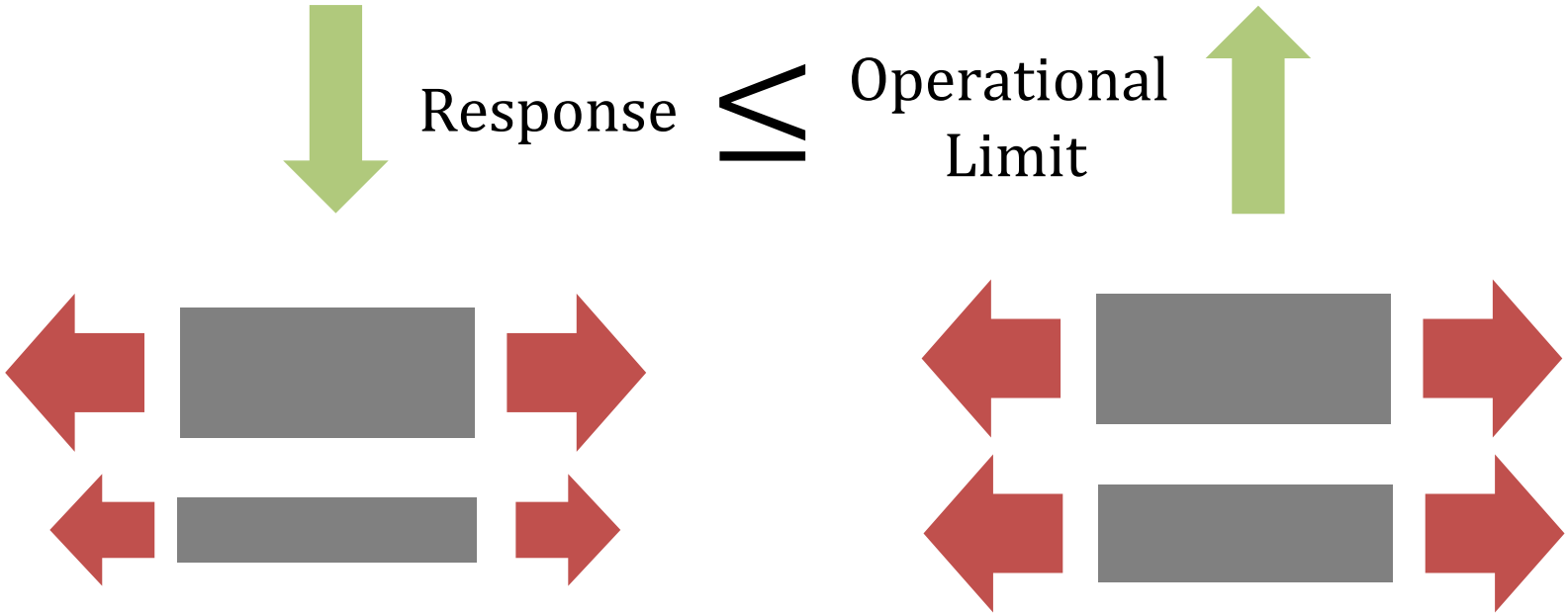
Carried out at Chalmers University of Technology

To reduce the weight of composite marine structures,
so as to make them more economically attractive.

Considered Cost Reduction Approaches



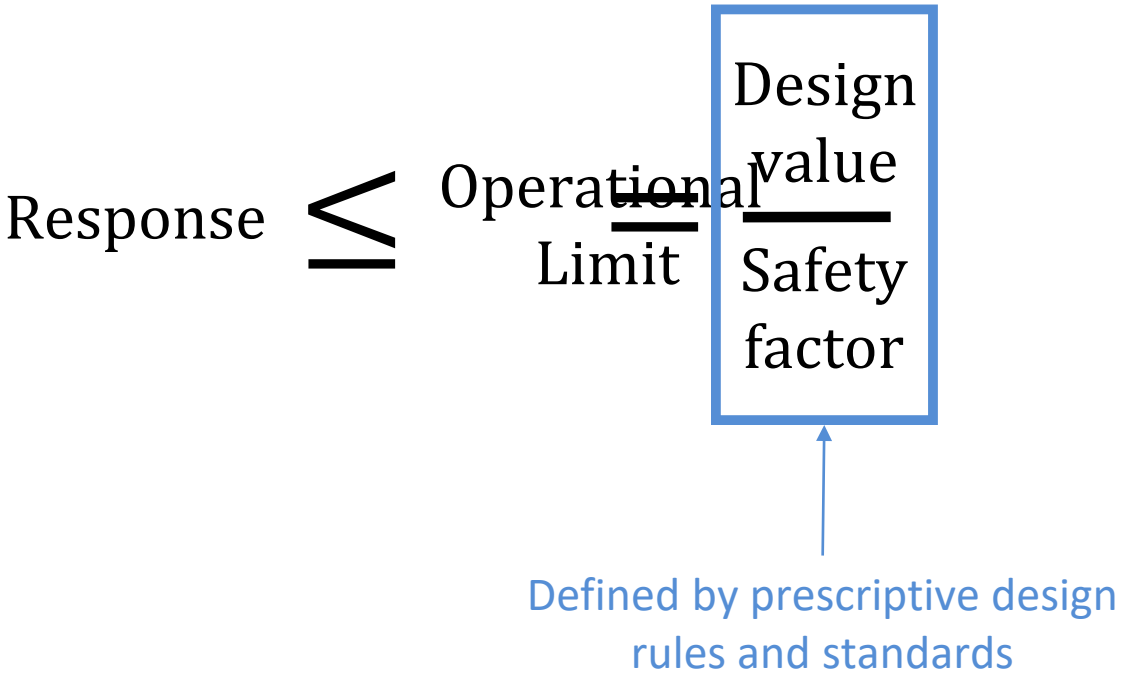
Considered Cost Reduction Approaches



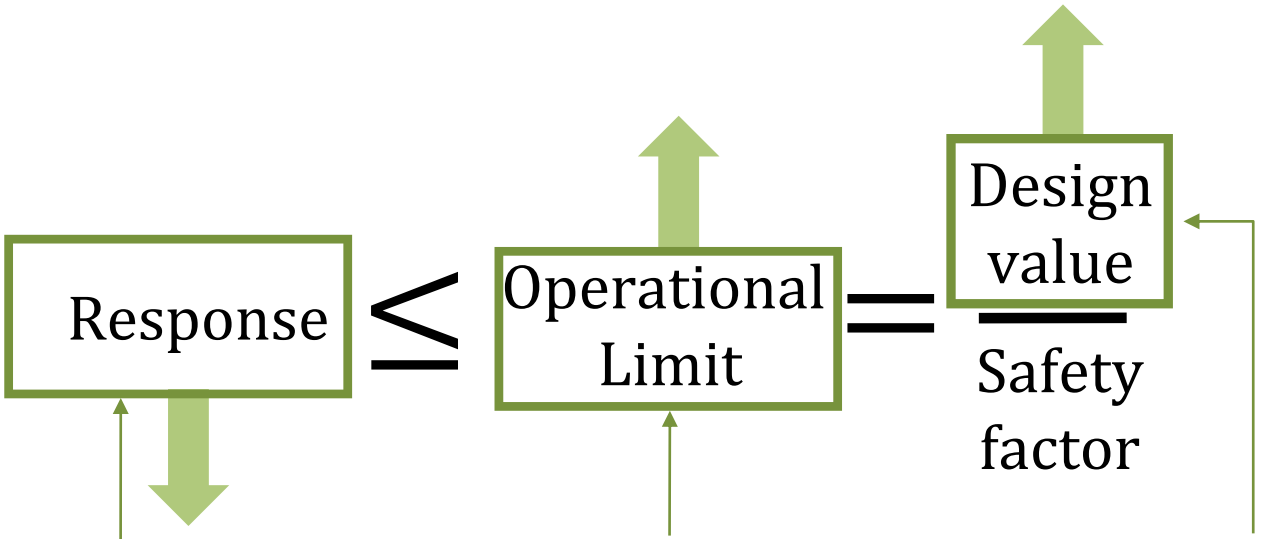
WEIGHT REDUCTION
by reducing the response

WEIGHT REDUCTION
by increasing the operational limit

Considered Cost Reduction Approaches



Considered Cost Reduction Approaches



Can it be increased?

Operational Limits

Can it be increased?

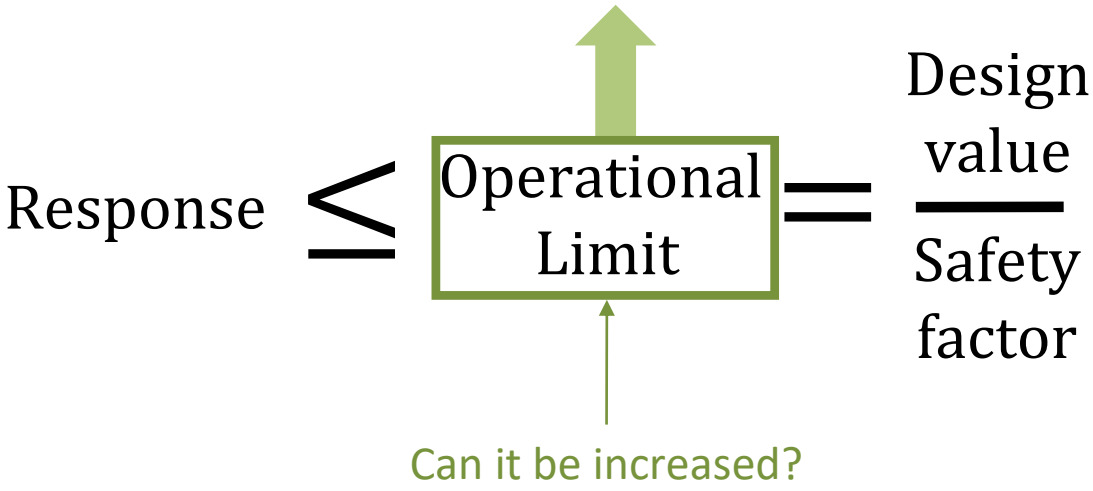
Material Characterization

It can be decreased, but how does it compare to the other two opportunities for weight reduction?

Structural Design Exploration

Operational Limits

Research Question



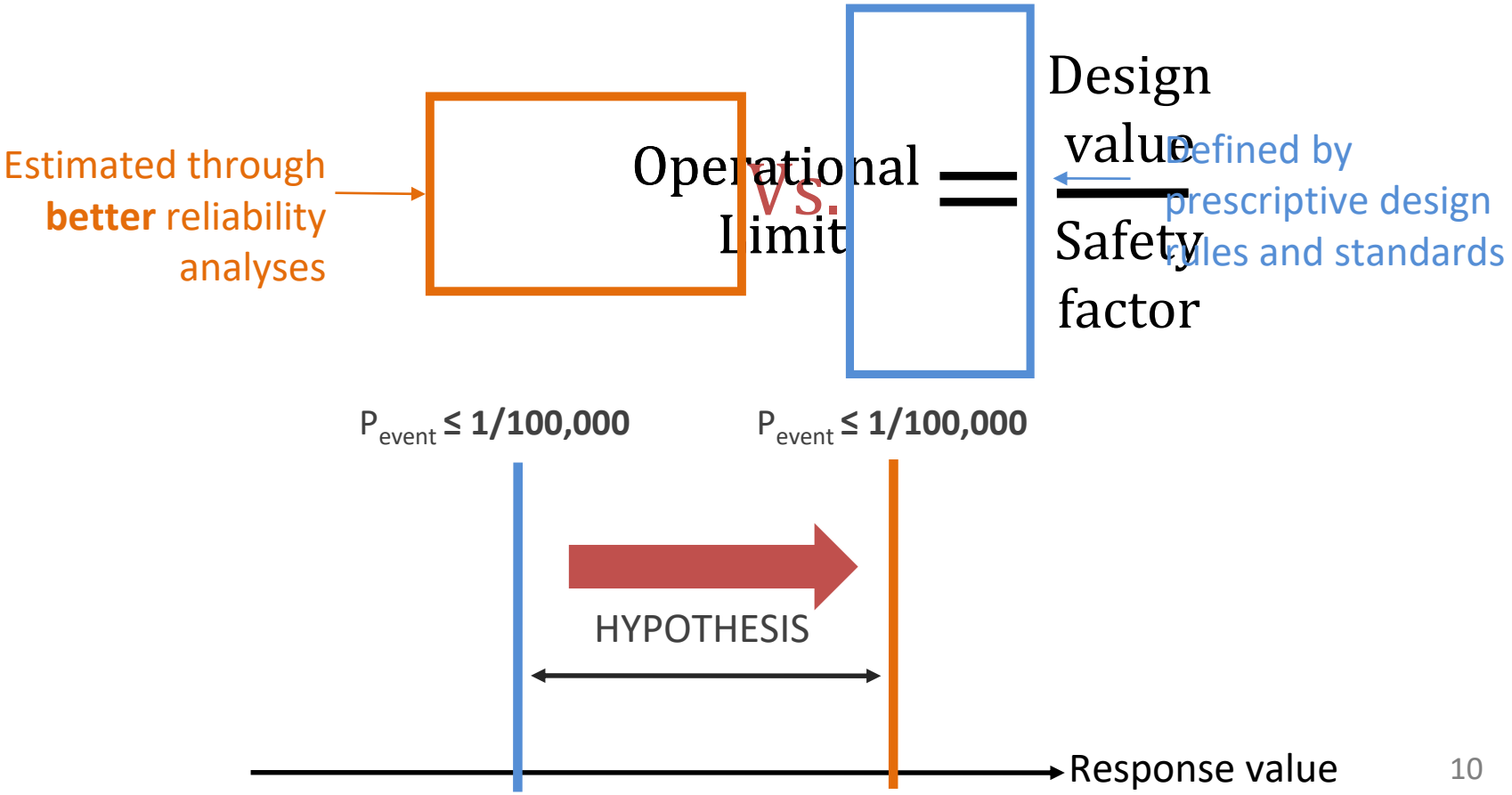
Methodology

$$\text{Response} \leq \text{Operational Limit} = \frac{\text{Design value}}{\text{Safety factor}}$$

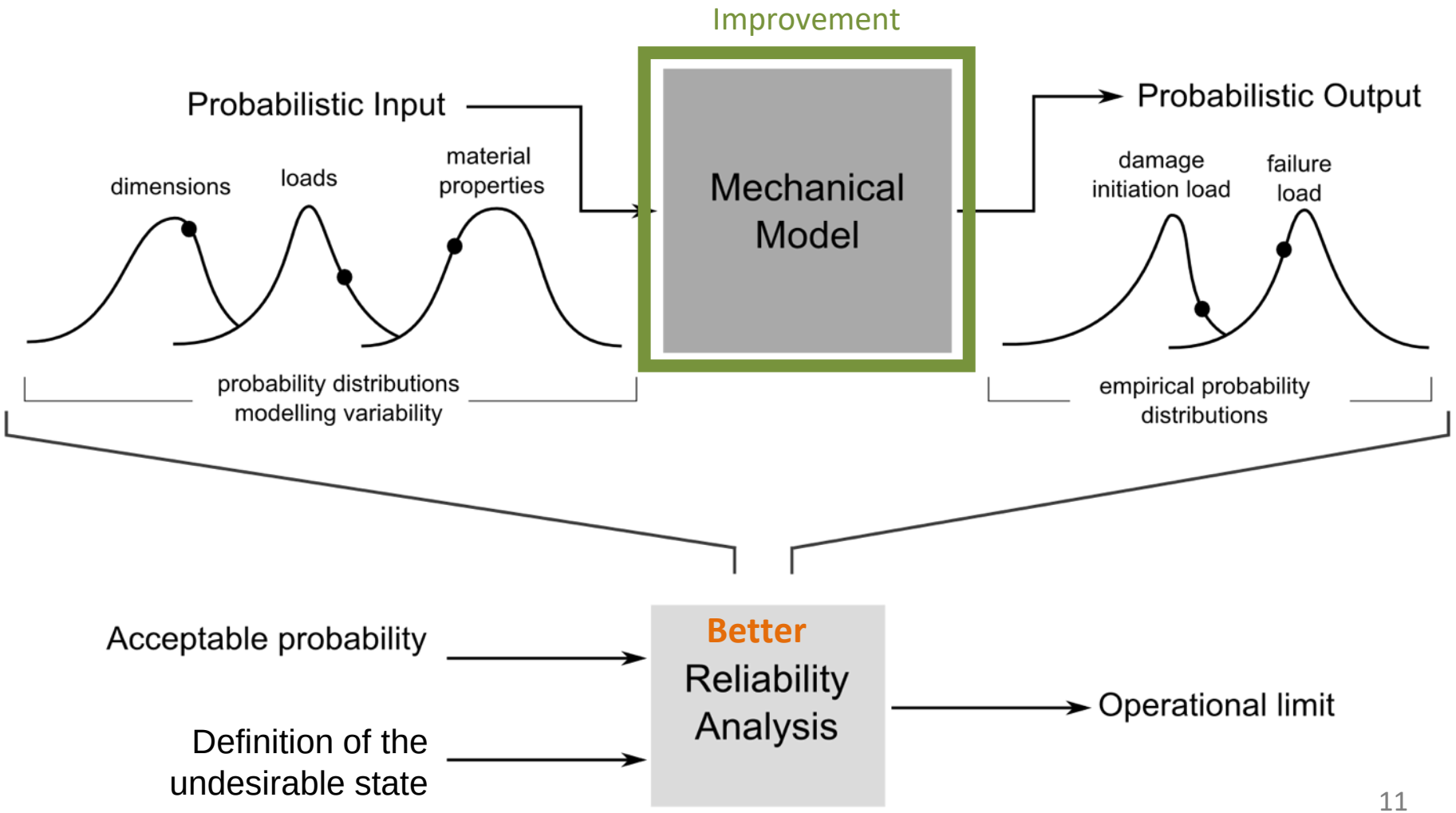
Hypothesis

The operational limits given by prescriptive rules are unnecessarily conservative

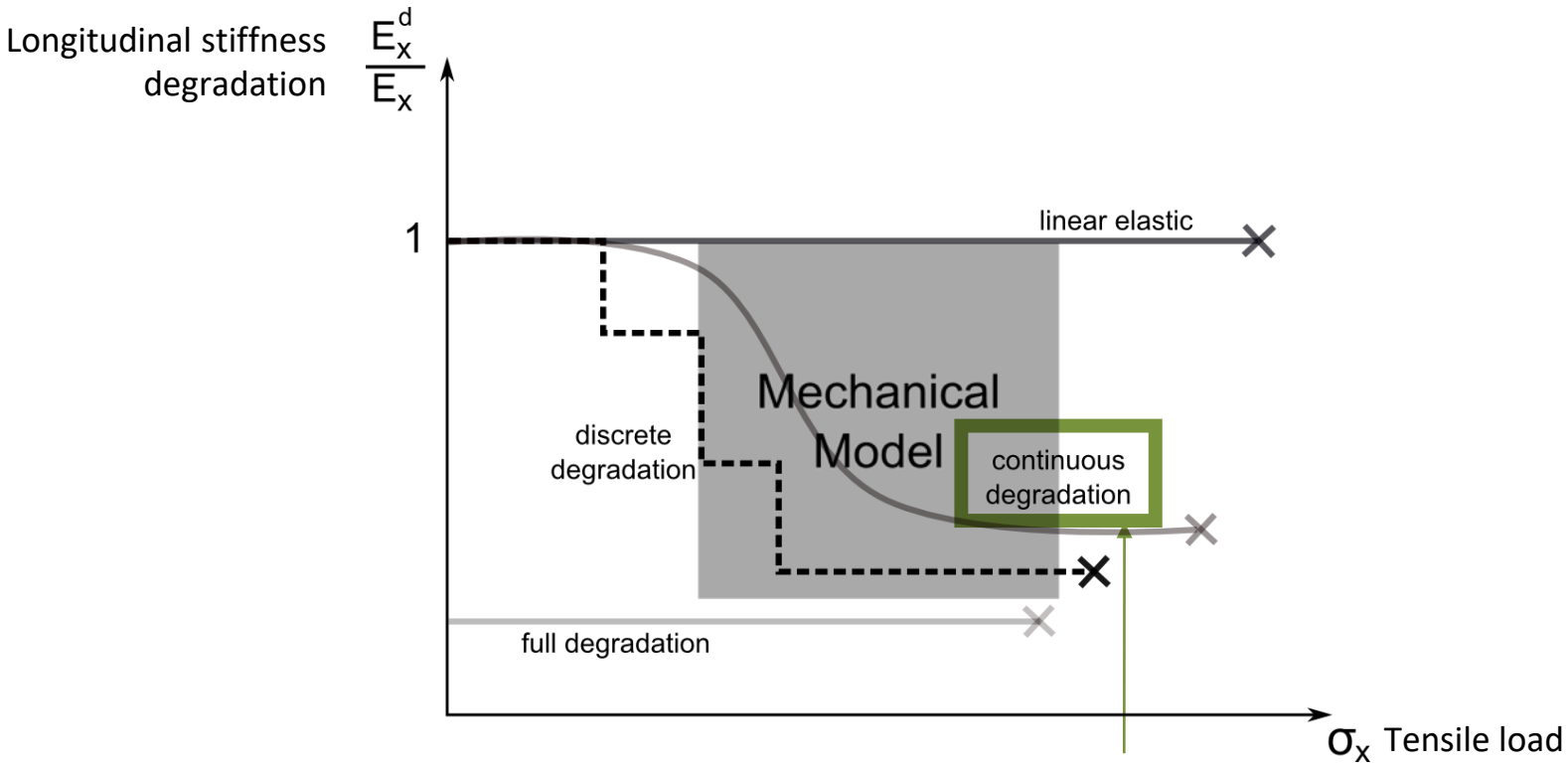
Methodology



Methodology



Methodology



First time used in reliability analyses of composite materials

Limitations

Material: carbon/epoxy and glass/epoxy prepregs.

Load case: unidirectional tensile monotonic loading.

Type of laminate: cross-ply.

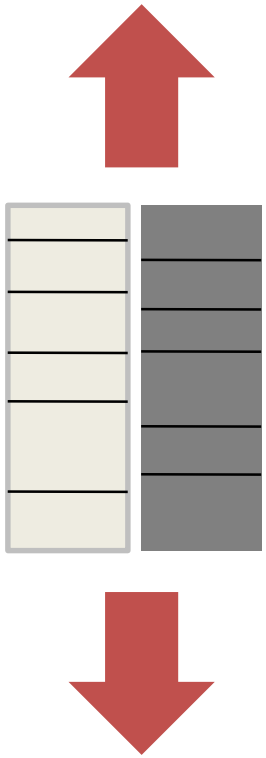
Mode of degradation: only matrix cracking.

Effect of degradation: only stiffness degradation.

Undesirable ultimate limit states:

Failure due to Fibre Fracture

Failure due to Fibre Fracture or Matrix Cracking



$[0_m/90_n]_S$

or

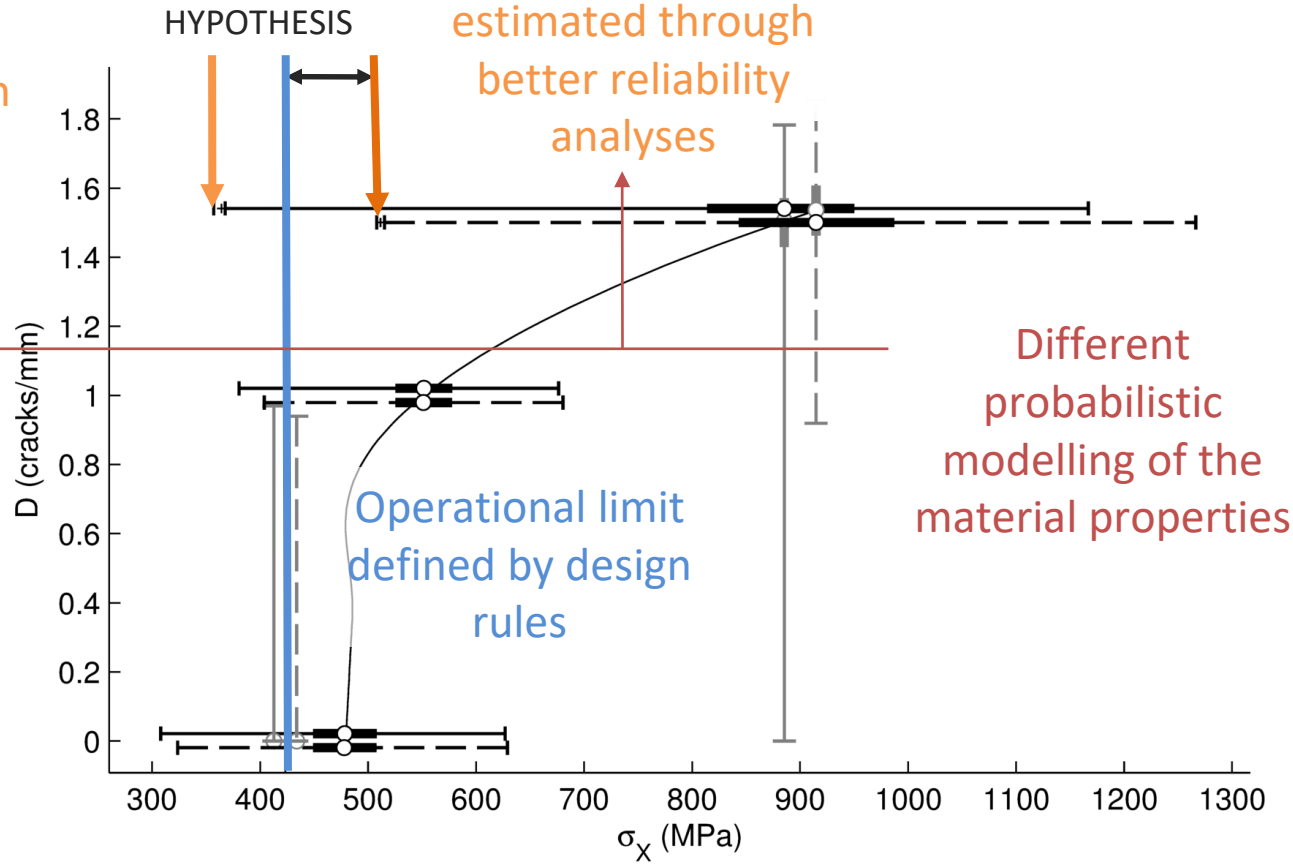
$[90_n/0_m]_S$

Operational Limit

Uniaxial tensile stress at which the probability of a ultimate limit state is equal or smaller than the value deemed as acceptable.

Results

Operational Limit estimated through better reliability analyses



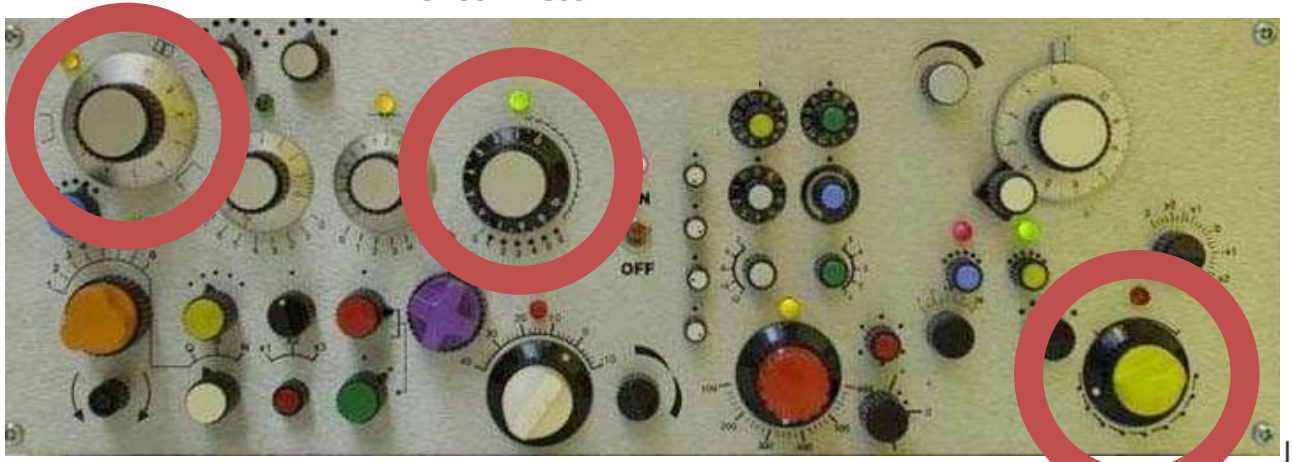
Crack density in a cross-ply laminate

Uniaxial tensile longitudinal stress to which it may be subjected

Results

Effects of matrix cracks other than loss of stiffness

Probabilistic modelling of material strength



Definition of failure due to matrix cracking

Acceptable probability for the ULS

Definition of ULS

Reliability Analysis

Operational limit

Highly sensitive to some settings" we are uncertain about!

Concluding Remarks

Can higher operational limits be motivated for composite marine structures through reliability analyses?

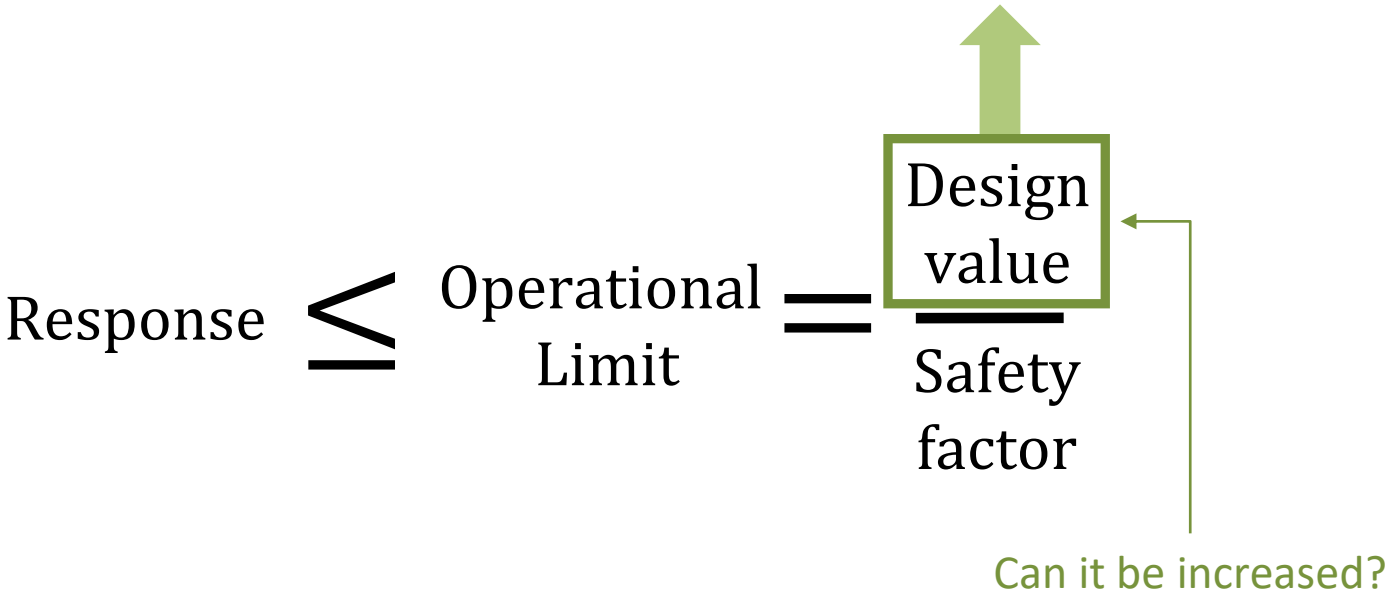
Maybe.

It could not be done for our studied cases…

The main takeaway is that reliability analyses of composite materials are very sensitive to choices we are really uncertain of.

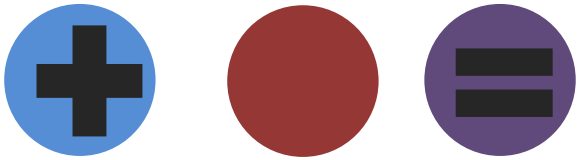
Material Characterization

Research Question



Methodology

Measure twice. Cut once.

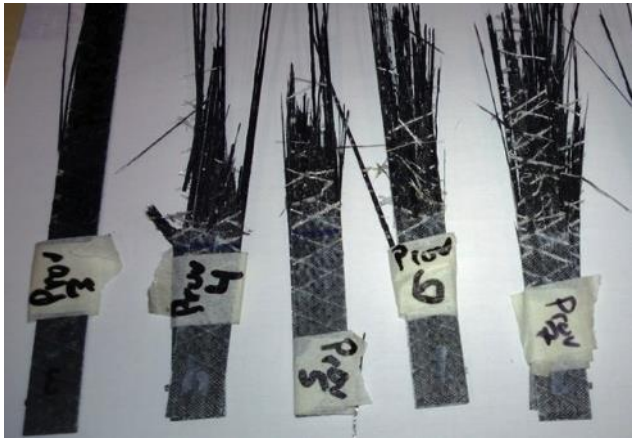


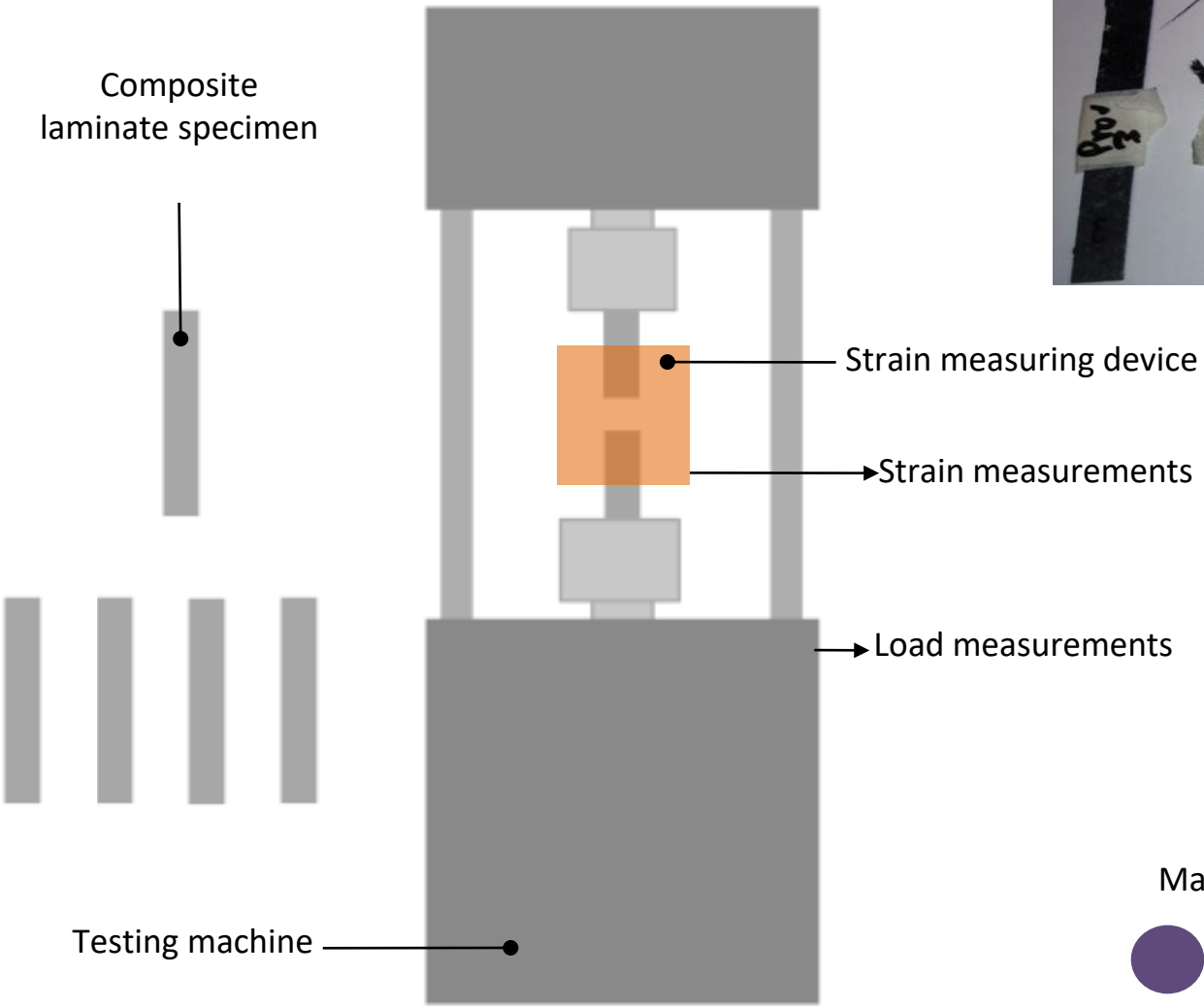
Value of the thing being measured

Measurement

Result of the error measurement

Methodology



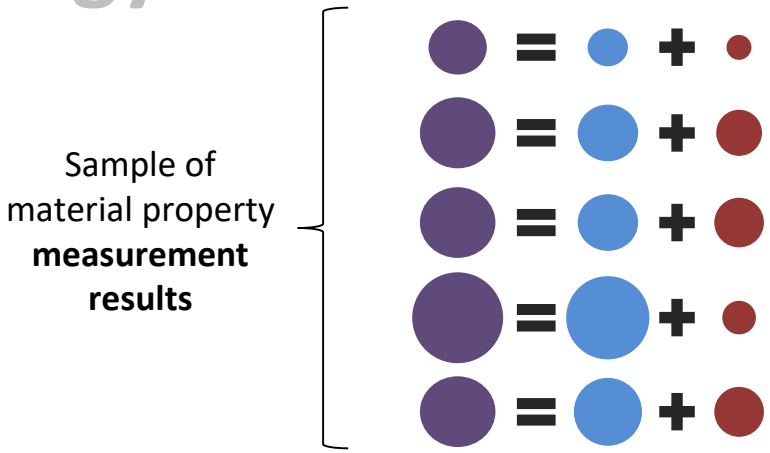


Measurement
Analysis

5

Material property measurement results

Methodology



Sample of material property **measurement results**

Dimensions of the structure

WEIGHT

Analytical Analyses

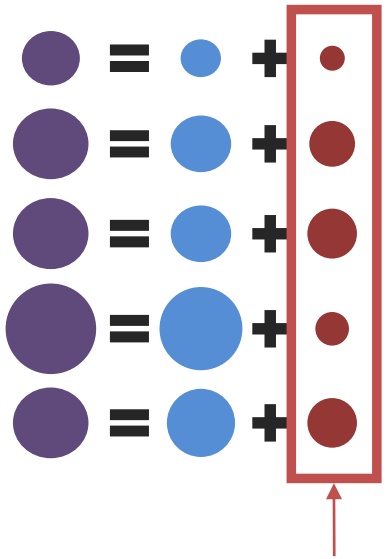
Numerical Analyses

Defined by design rules or standards

Statistical Analysis

Design value of a material property

Methodology



Hypothesis

Improved material characterization methods can reduce measurement errors, resulting in higher design values.

Methodology

Measurement Error
Error induced by a large number of factors

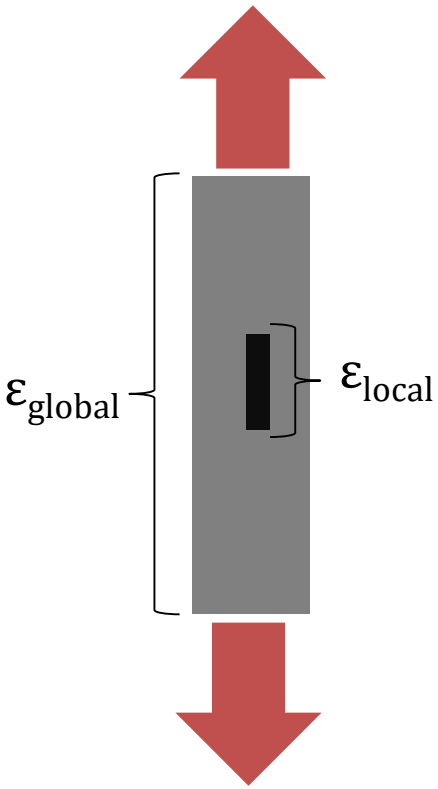
Error induced by a single factor: the strain measurement method used for textile composites

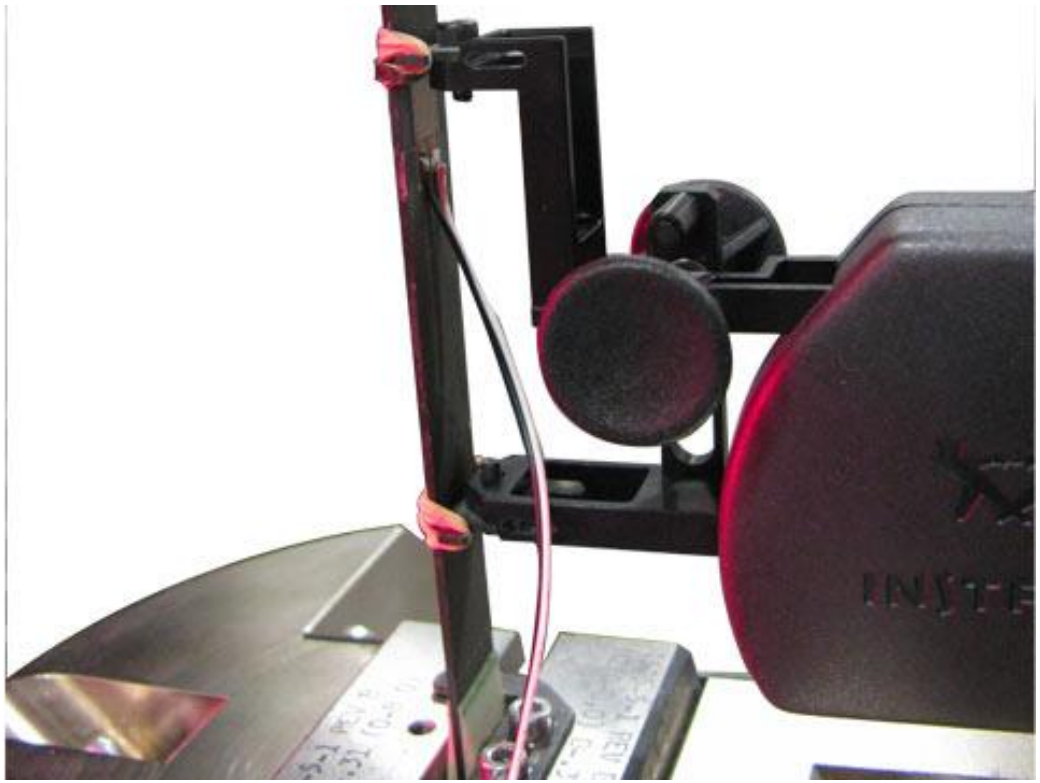
Strain measurement error

Methodology

Strain measurement error for textile composites

← Local surface strain measurements are not a good proxy for the laminate strain

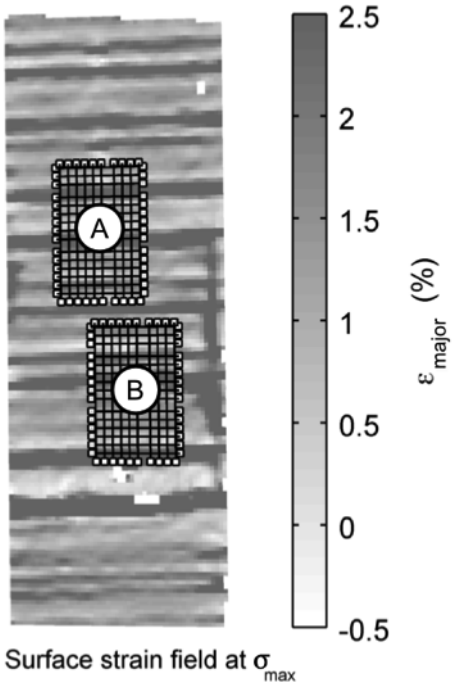


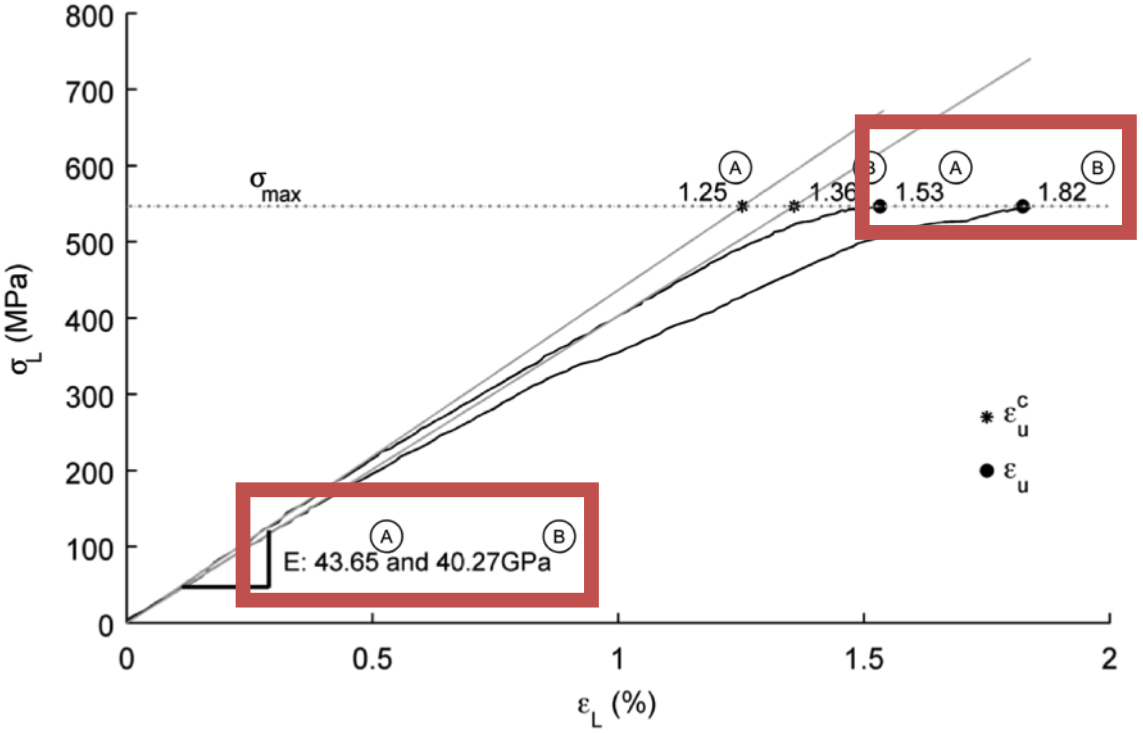


Methodology

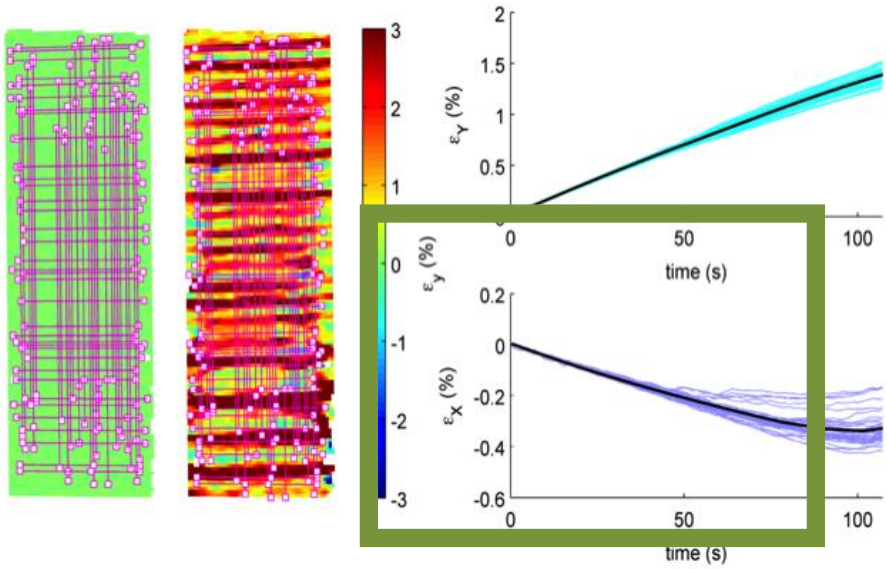
Strain measurement error

Local surface strain measurements are not a good proxy for the laminate strain





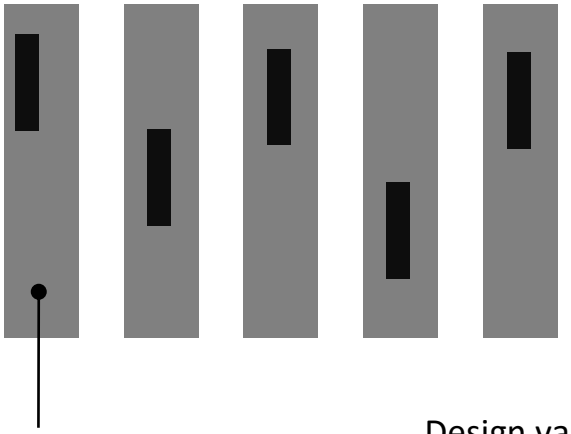
Methodology



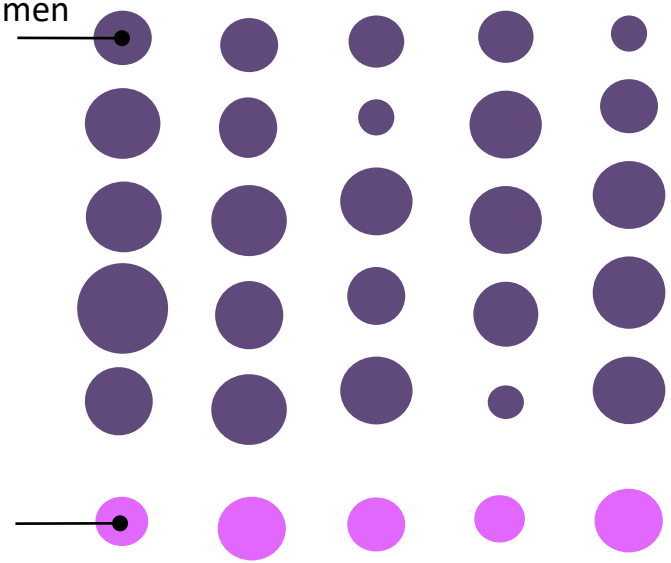
Strain measurement error

How to determine its effect on the design value?

Measurement result for one specimen



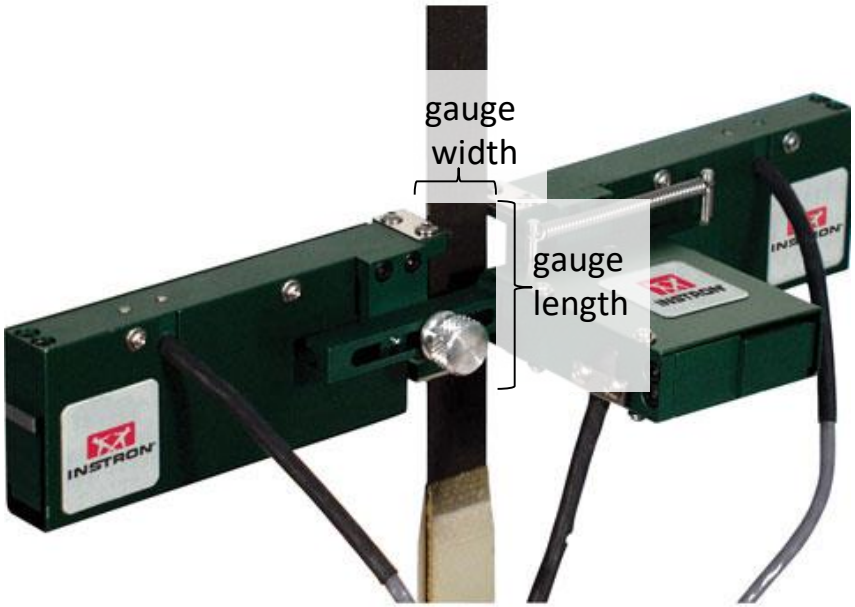
Test specimen

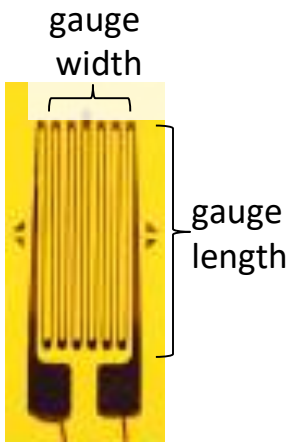


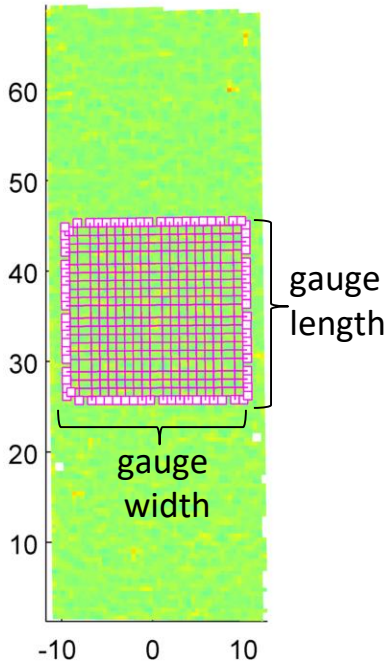
Design value

Variations only due to the strain measurement error

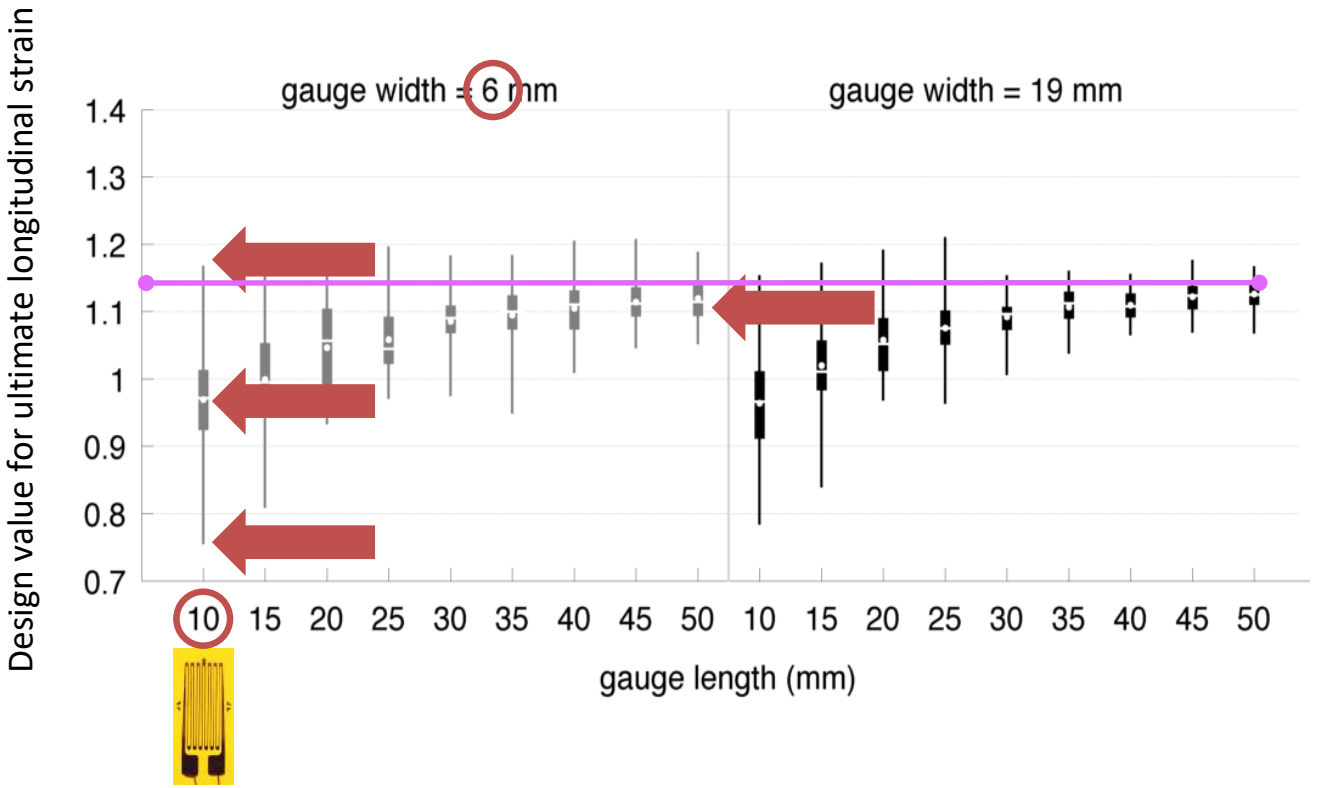
Gauge size

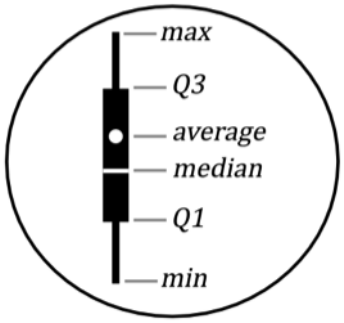

gauge
width
gauge
length
INSTRON


gauge
width
gauge
length


60
50
40
30
20
10
-10
0
10
gauge
length
gauge
width

Results


Design value for ultimate longitudinal strain
gauge width = 6 mm
gauge width = 19 mm
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
10 15 20 25 30 35 40 45 50 10 15 20 25 30 35 40 45 50
gauge length (mm)


max
Q3
average
median
Q1
min

Concluding Remarks

Can higher design values be obtained through improved material characterization methods?

Yes.

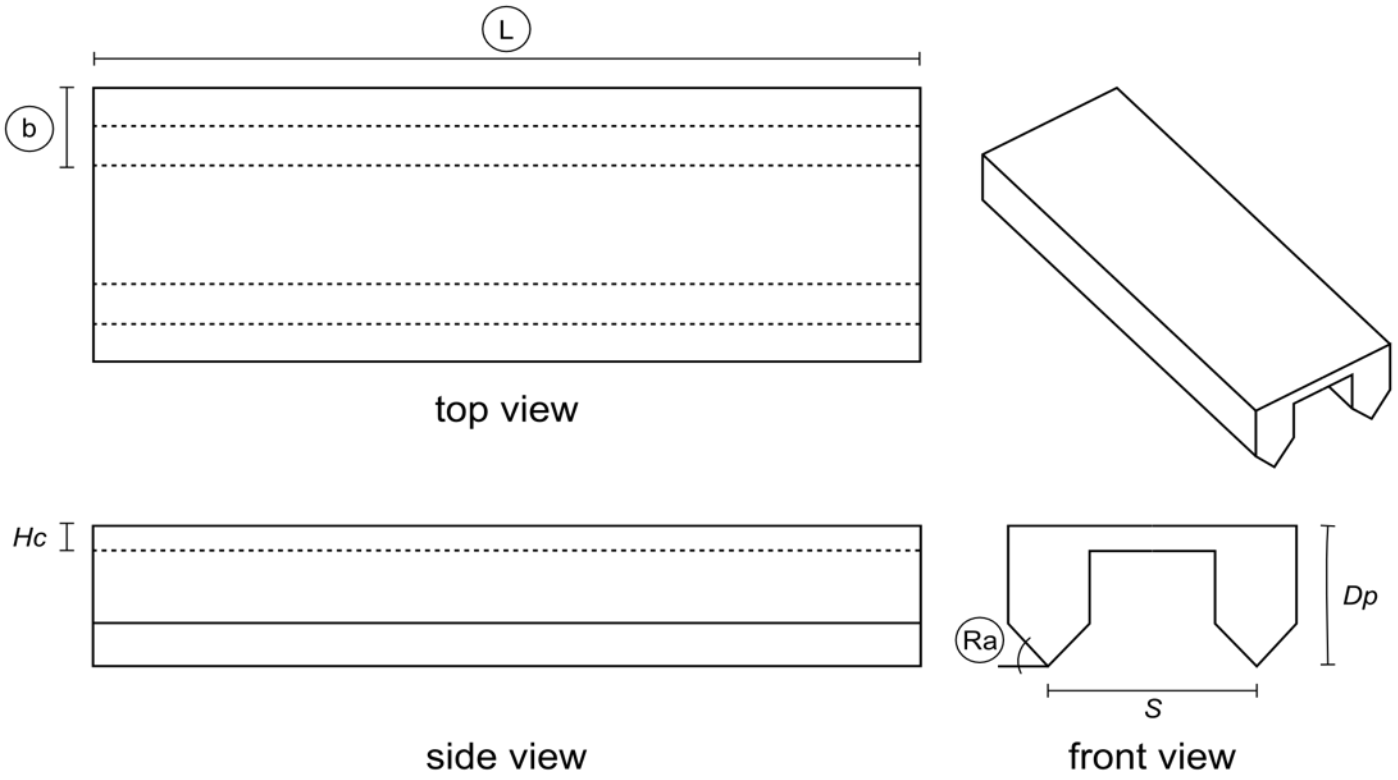
Use strain measuring devices with very large gauge sizes...

… or a Digital Image Correlation system.

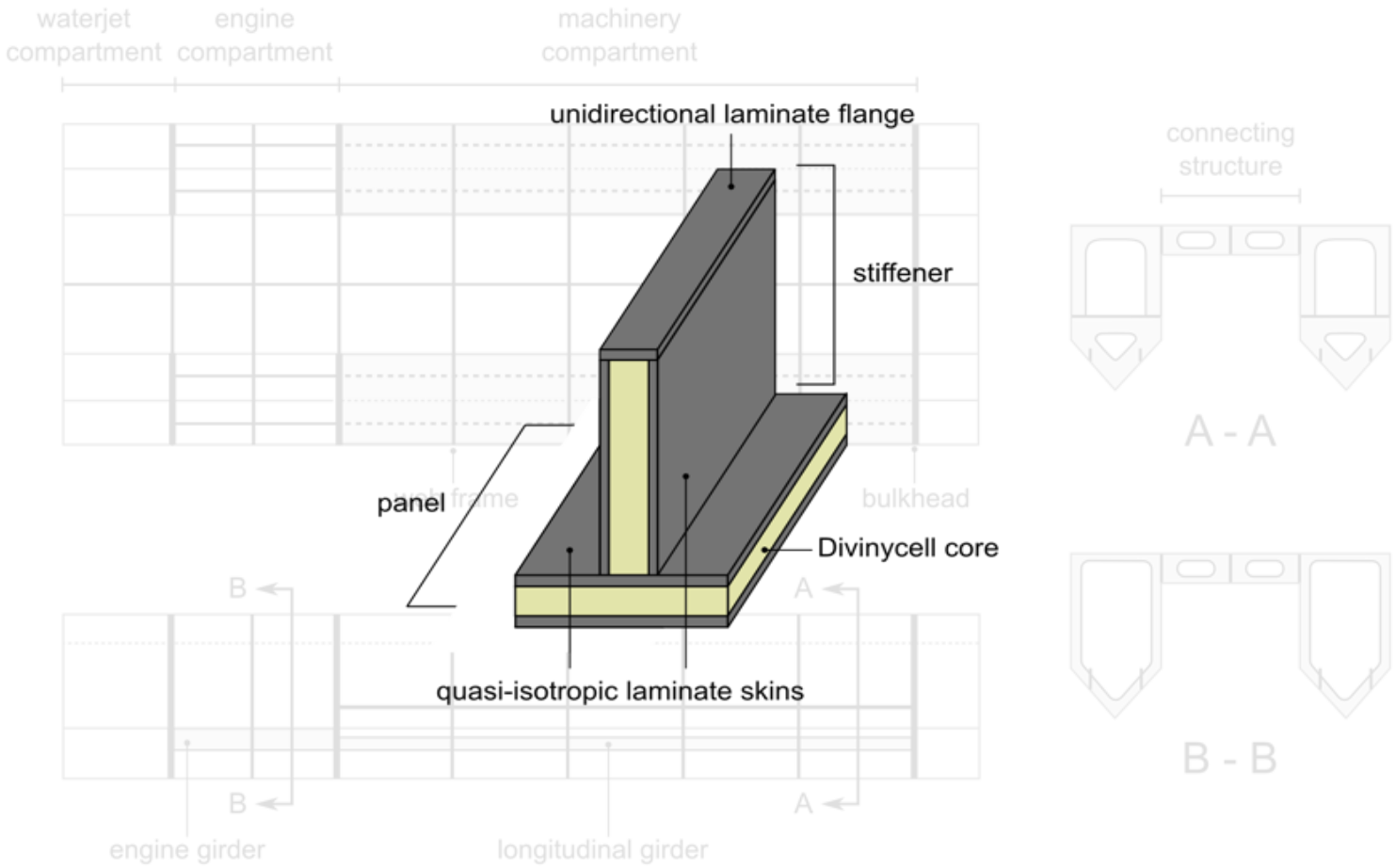
Structural Design Exploration

Test case: Carbon sandwich Catamaran

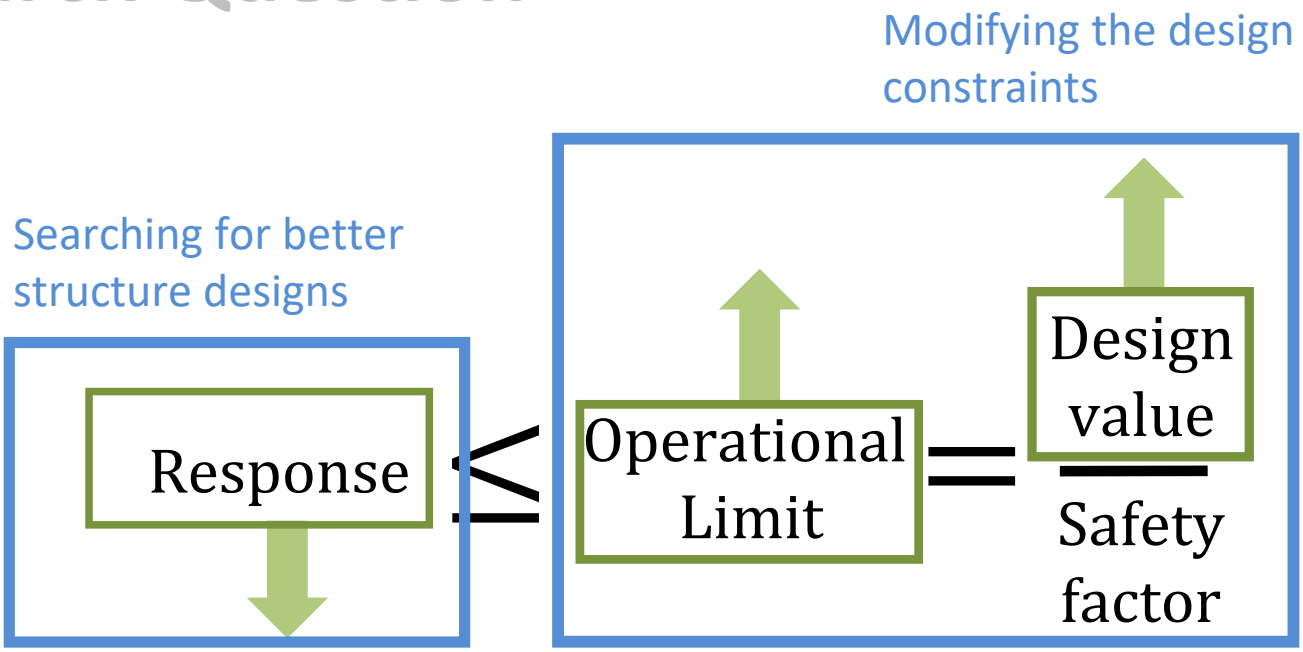
Waterline length (L)	34.3 m
Breadth of the pontoons (b)	2.83 m



Test case


waterjet compartment
engine compartment
machinery compartment
unidirectional laminate flange
stiffener
panel
bulkhead
Divinycell core
quasi-isotropic laminate skins
B
A
B
A
engine girder
longitudinal girder
connecting structure
A - A
B - B

Research Question



Which is a better approach for reducing the structure's weight?

Methodology: Example

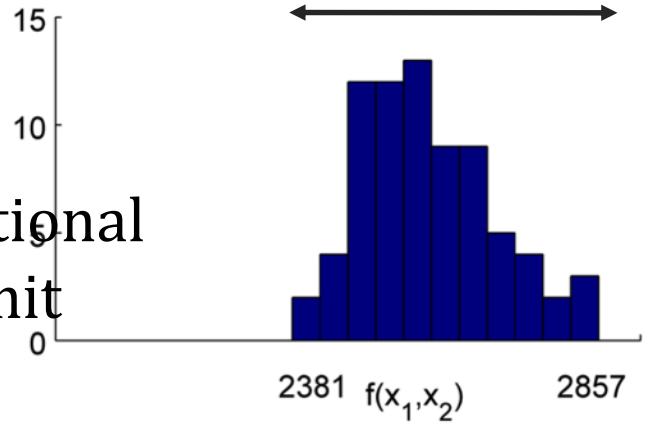
$$\text{Weight} = f(x_1, x_2)$$

$$-10 \leq x_1 \leq 10$$

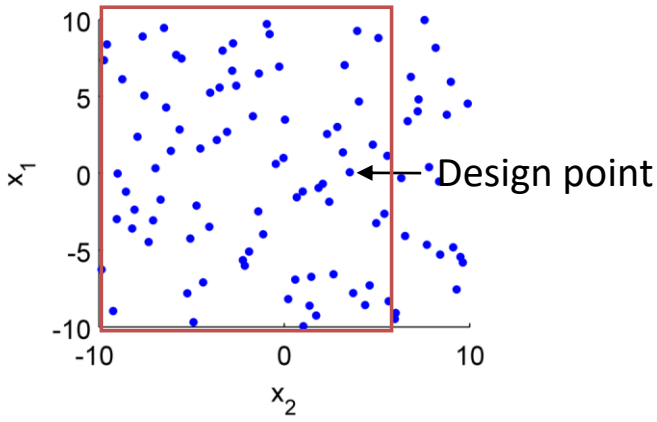
$$-10 \leq x_2 \leq 5$$

Response ≤ Operational Limit

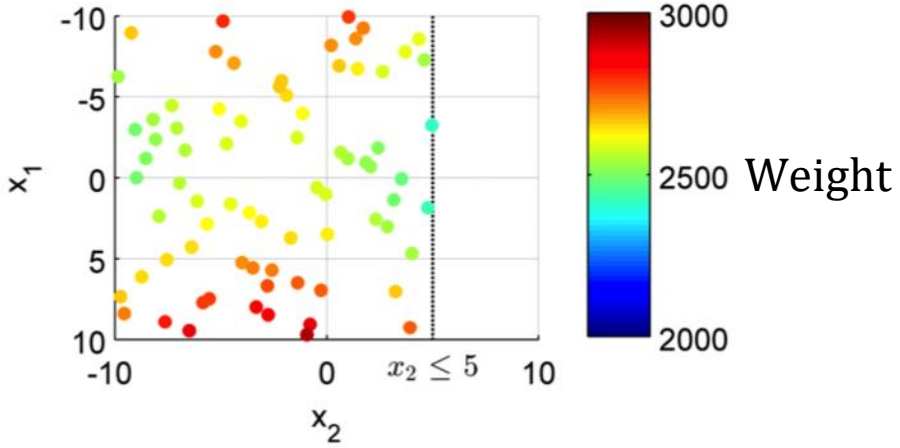
Approximate range of structure design weights that can be found



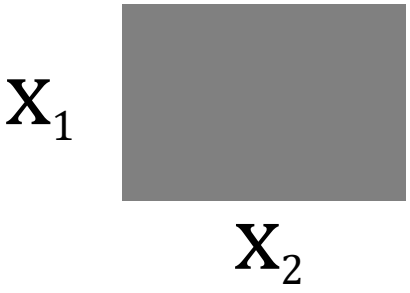
Design space



Possible designs



Methodology: Example

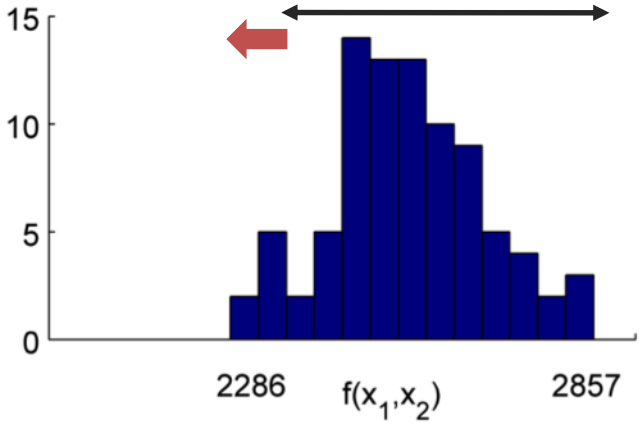


$$\text{Weight} = f(x_1, x_2)$$

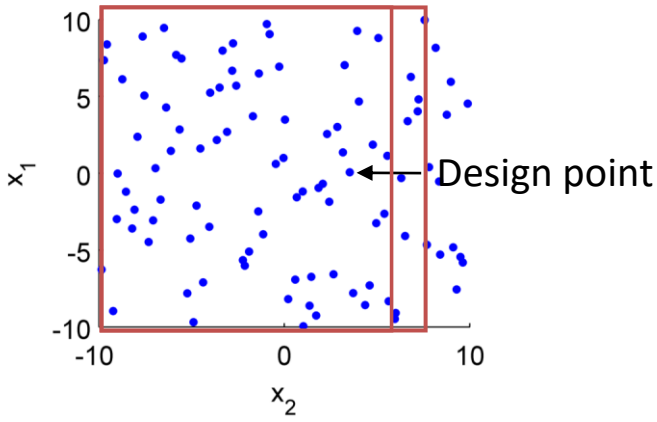
$$-10 \leq x_1 \leq 10$$

$$-10 \leq x_2 \leq 7.5$$

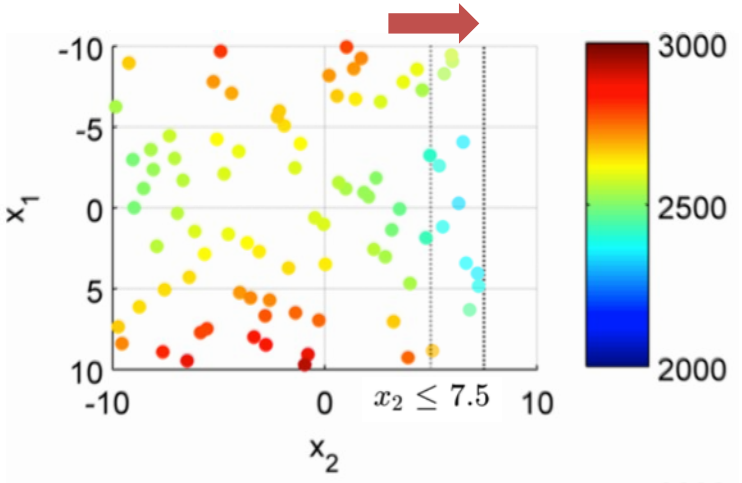
Approximate range of structure design weights that can be found



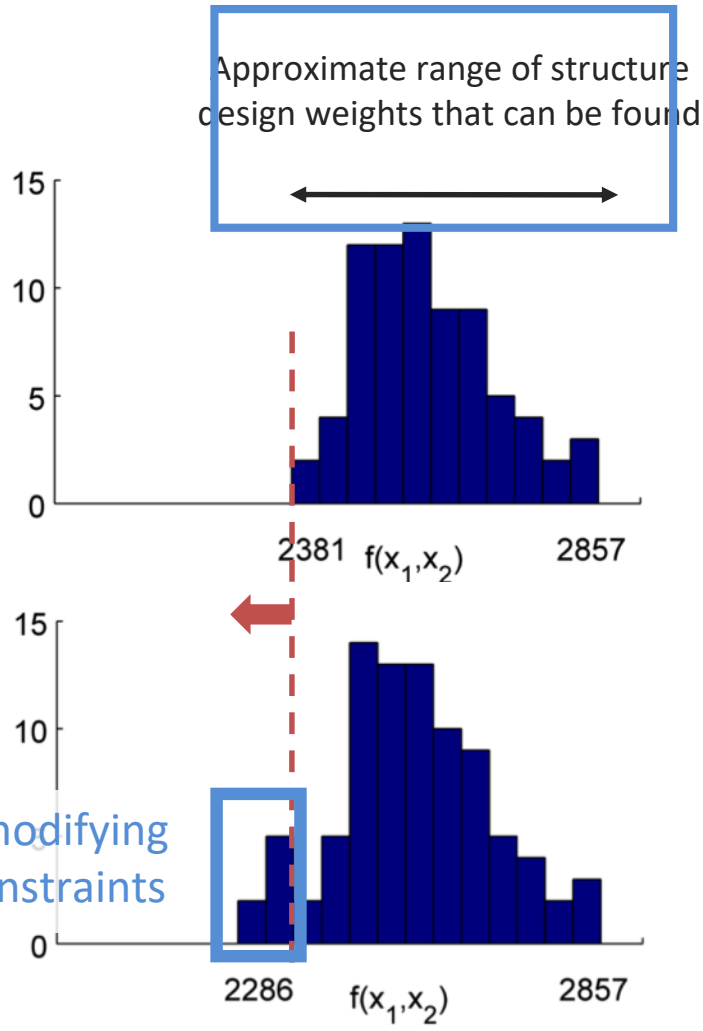
Design space



Possible designs

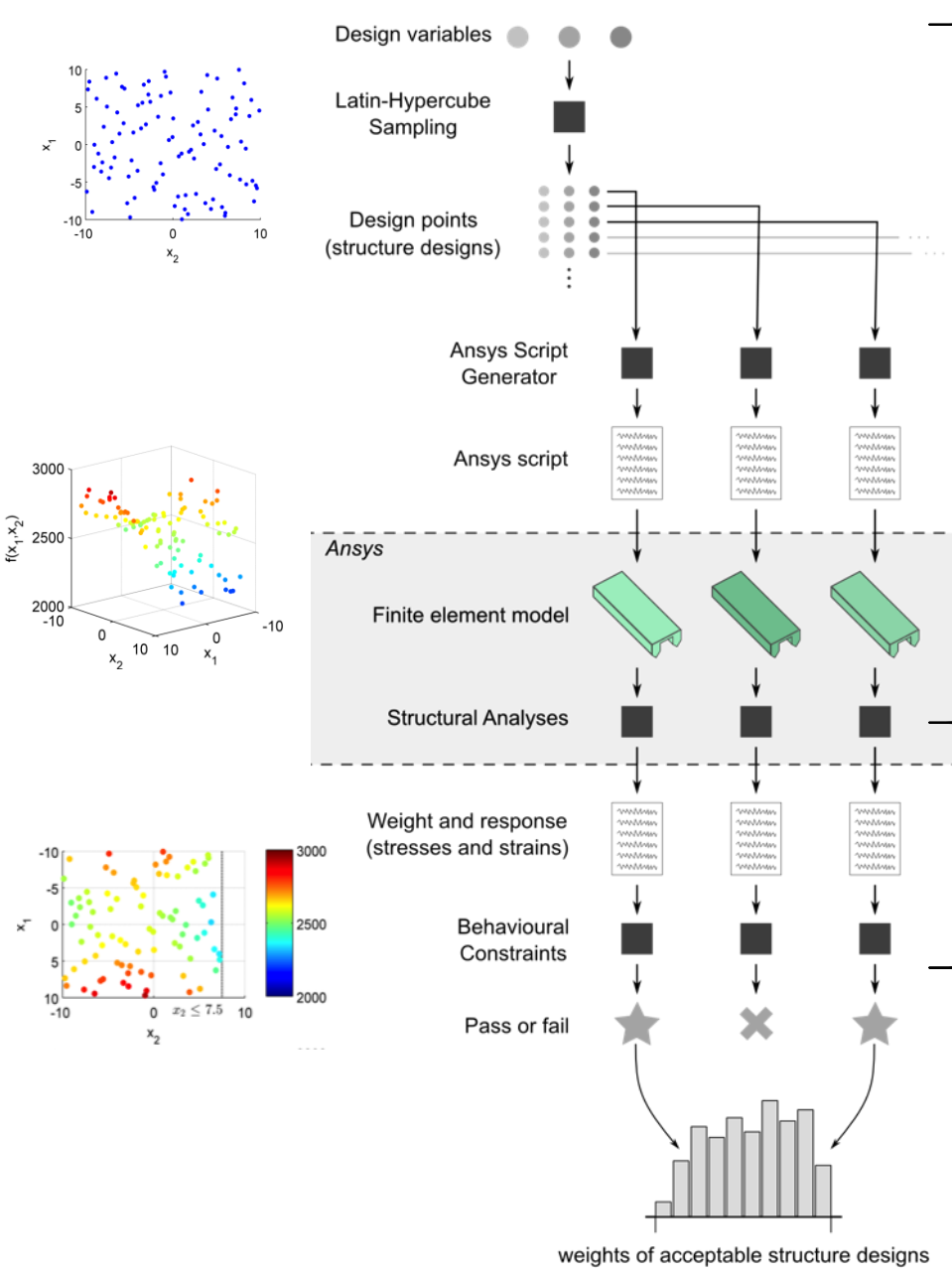


Methodology



Potential of searching for better structure designs

Potential of modifying the design constraints



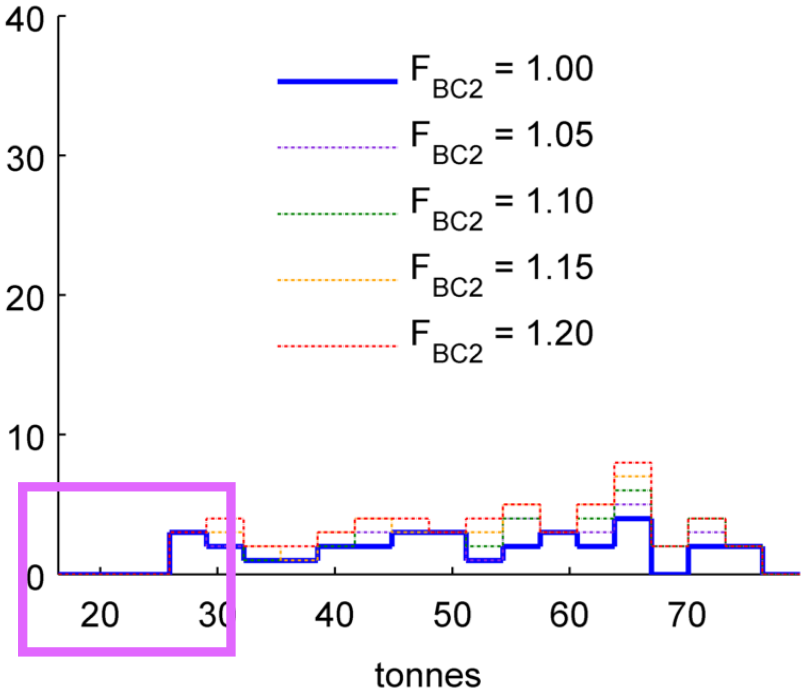
- Laminate thicknesses
- Location and number of scantlings
- Location of local loads
- Type of core
- Etc.

- Local loads
- Sea loads

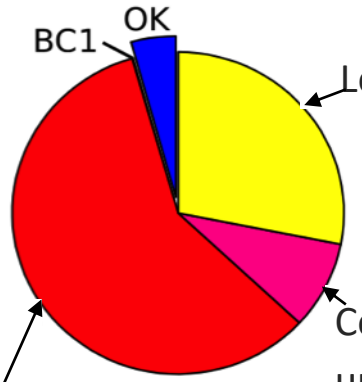
- BC1: Tensile strength of the quasi-isotropic laminate
- BC2: Compressive strength of the quasi-isotropic laminate
- BC3: Tensile strength of the unidirectional laminate
- BC4: Compressive strength of the unidirectional laminate
- BC5: Core shear strength
- BC6: Local skin buckling

Results

Weight of the designs meeting the Design Constraints



Of 758 different structure designs



$$\varepsilon_c \leq \varepsilon_{c,max}$$

$$\varepsilon_c \leq \varepsilon_{c,max} * F_{BC2}$$

Concluding Remarks

How does improving the design of a structure compare to the two other opportunities as an approach for weight reduction?

Our results indicate that improving the design of a structure has the largest potential…

… but this conclusion is based on one simple study case.

More and better study cases are necessary to strengthen this conclusion.

FINAL CONCLUSIONS

OBJECTIVE

To reduce the weight of composite marine structures,
so as to make them more economically attractive

Was it achieved?

Through higher **operational limits** estimated with reliability analyses…

No…

Through more accurate mechanical properties determined with improved **material characterization** methods …

Yes.

Our **structural design exploration** analysis indicates that improving the design of a structure has the largest potential for weight reduction in large composite marine structures.

Acknowledgements

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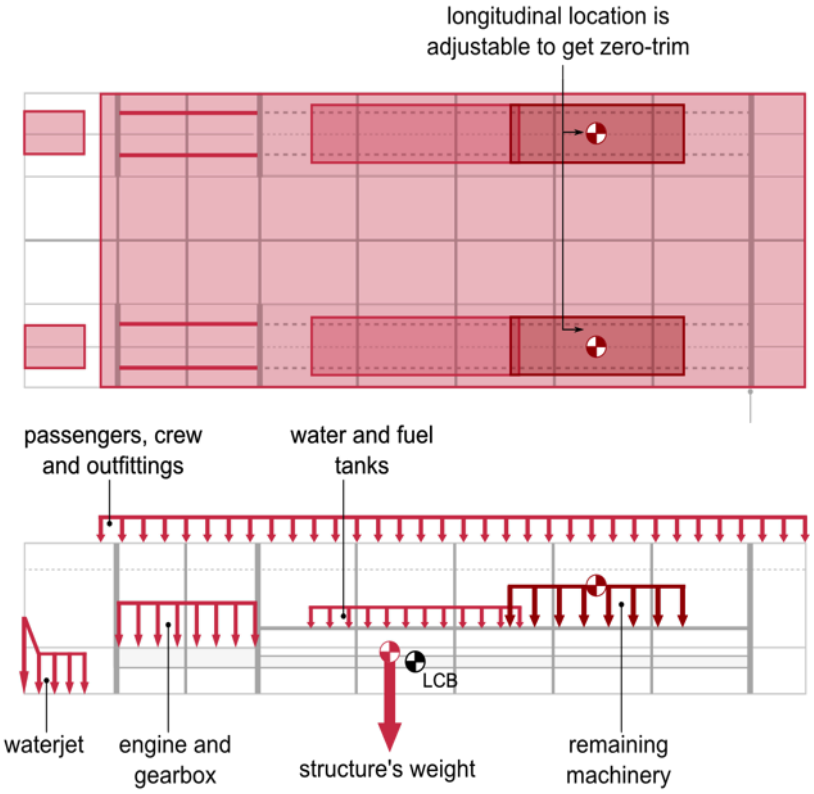
EU project BESST: Breakthrough in European Ship and Shipbuilding Technologies

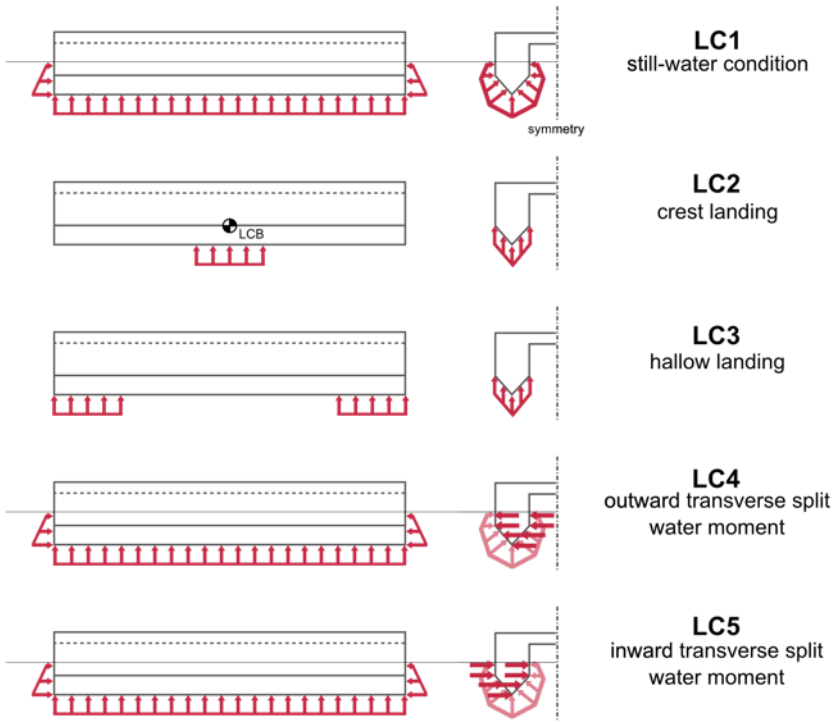
Future Work

- Further develop the work presented in the Structural Design Exploration section to publish it as a journal paper.
- Compare the results of structural optimization algorithms coupled to numerical and analytical structural analyses.

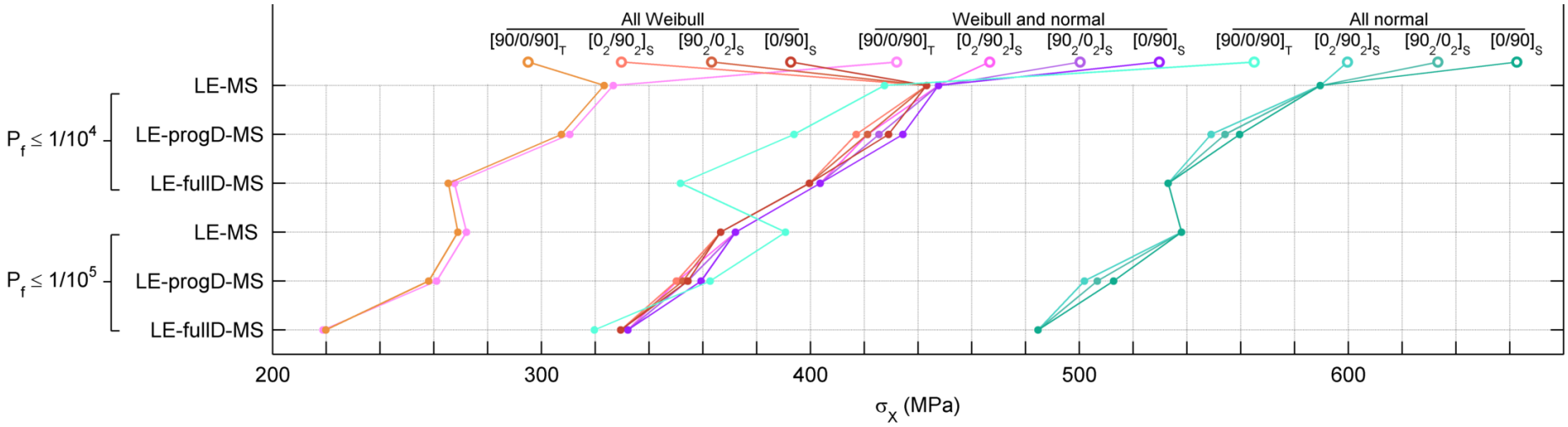
Test case

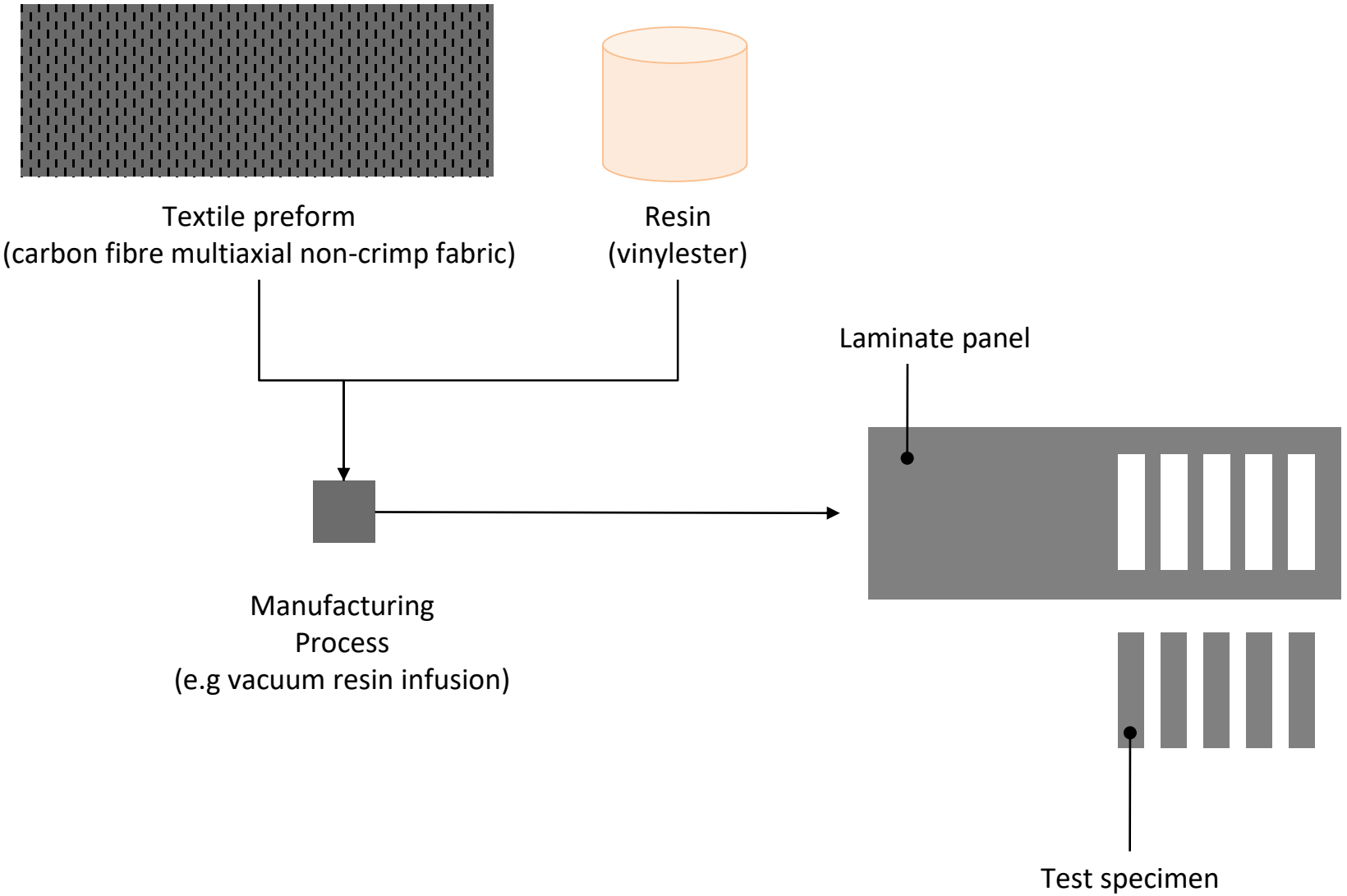


Local loads



Sea loads


All Weibull
[90/0/90]T
[02/902]S
[902/02]S
[0/90]S
Weibull and normal
[90/0/90]T
[02/902]S
[902/02]S
[0/90]S
All normal
[90/0/90]T
[02/902]S
[902/02]S
[0/90]S
LE-MS
LE-progD-MS
LE-fullD-MS
LE-MS
LE-progD-MS
LE-fullD-MS
Pf ≤ 1/10^4
Pf ≤ 1/10^5
200
300
400
500
600
σX (MPa)


Textile preform
(carbon fibre multiaxial non-crimp fabric)
Resin
(vinylester)
Laminate panel
Manufacturing
Process
(e.g vacuum resin infusion)
Test specimen

Opportunities For Weight Reduction In **Composite Marine Structures**

PAPER I

Optimization of composite maritime structures – effects of uncertainties on design criteria and limits

Sánchez L., Ringsberg J.W., Johnson E. (2011). Proceedings of the Third International Conference on Maritime Structures (MARSTRUCT 2011).

PAPER II

Study on the possibility of increasing the maximum allowable stresses in Fibre-Reinforced Plastics

Sánchez-Heres L.F., Ringsberg J.W., Johnson E. (2012). Journal of Composite Materials.

Operational Limits

PAPER III

Influence of mechanical and probabilistic models on the reliability estimates of fibre-reinforced cross-ply laminates

Sánchez-Heres L.F., Ringsberg J.W., Johnson E. (2014). Structural Safety.

Operational Limits

PAPER IV

Characterization of non-crimp fabric laminates – Loss of accuracy due to strain measuring techniques

Sánchez-Heres L.F., Ringsberg J.W., Johnson E. (2015). Submitted for publication to the ASTM Journal of Testing and Evaluation.

Material Characterization

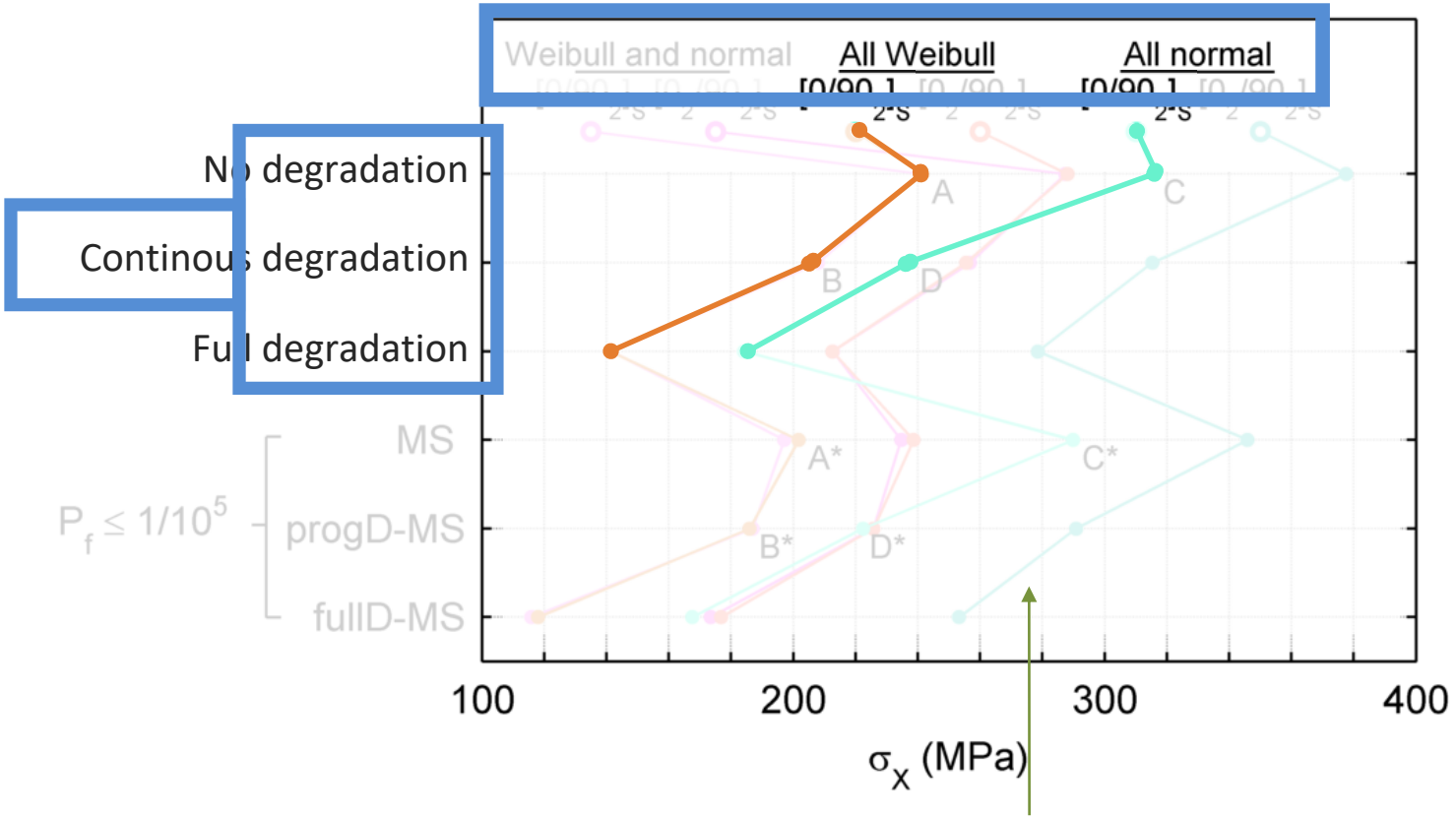
PhD thesis summary

Opportunities for weight reduction in composite marine structures

Sánchez-Heres L.F. (2015). Gothenburg, Sweden: Chalmers University of Technology.

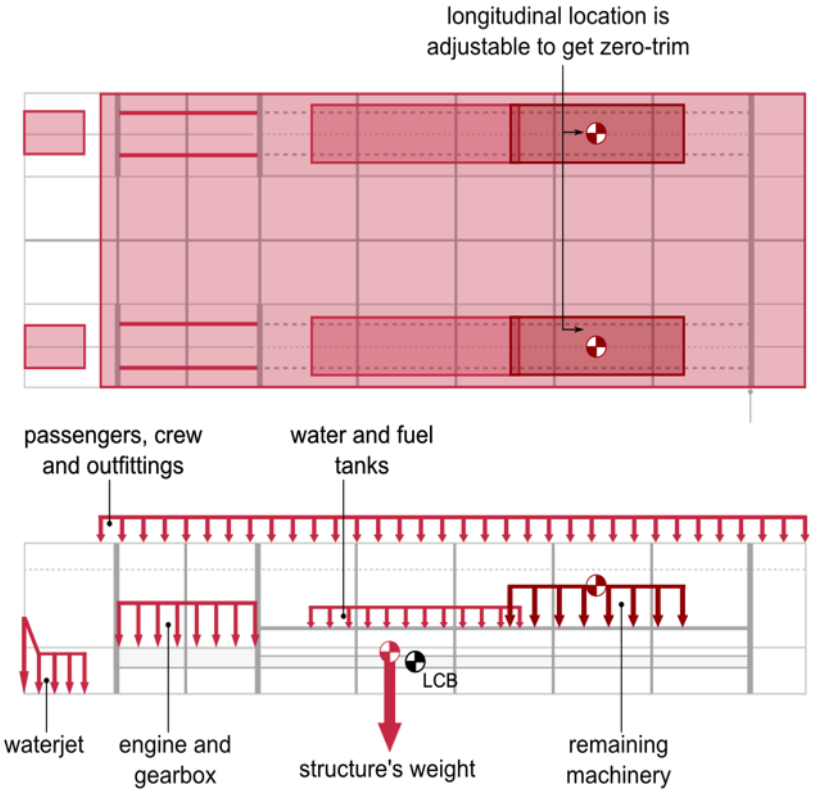
Structural Design

Results: Paper III

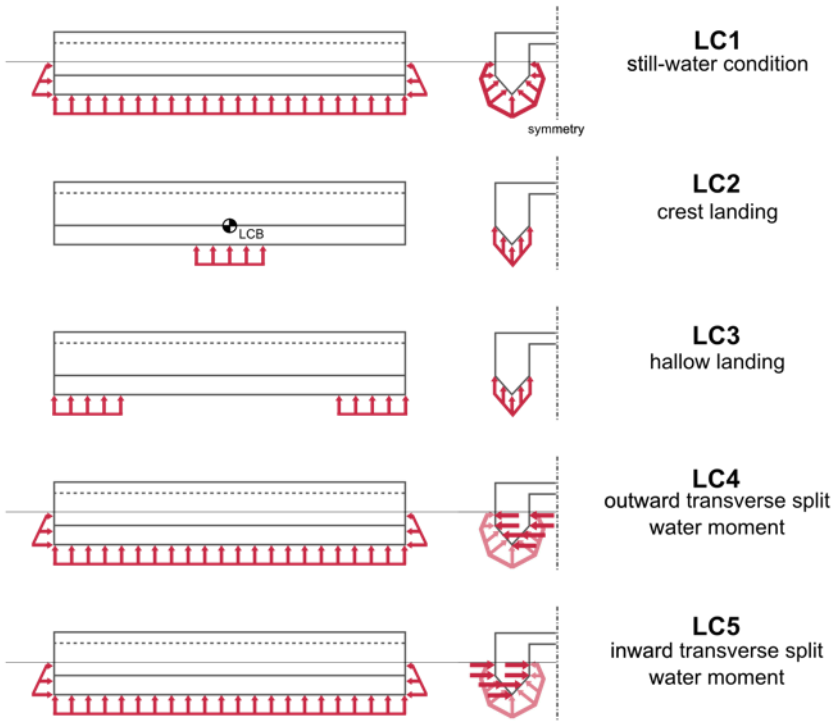


Operational Limits of **glass/epoxy** cross-ply laminates

Test case



Local loads

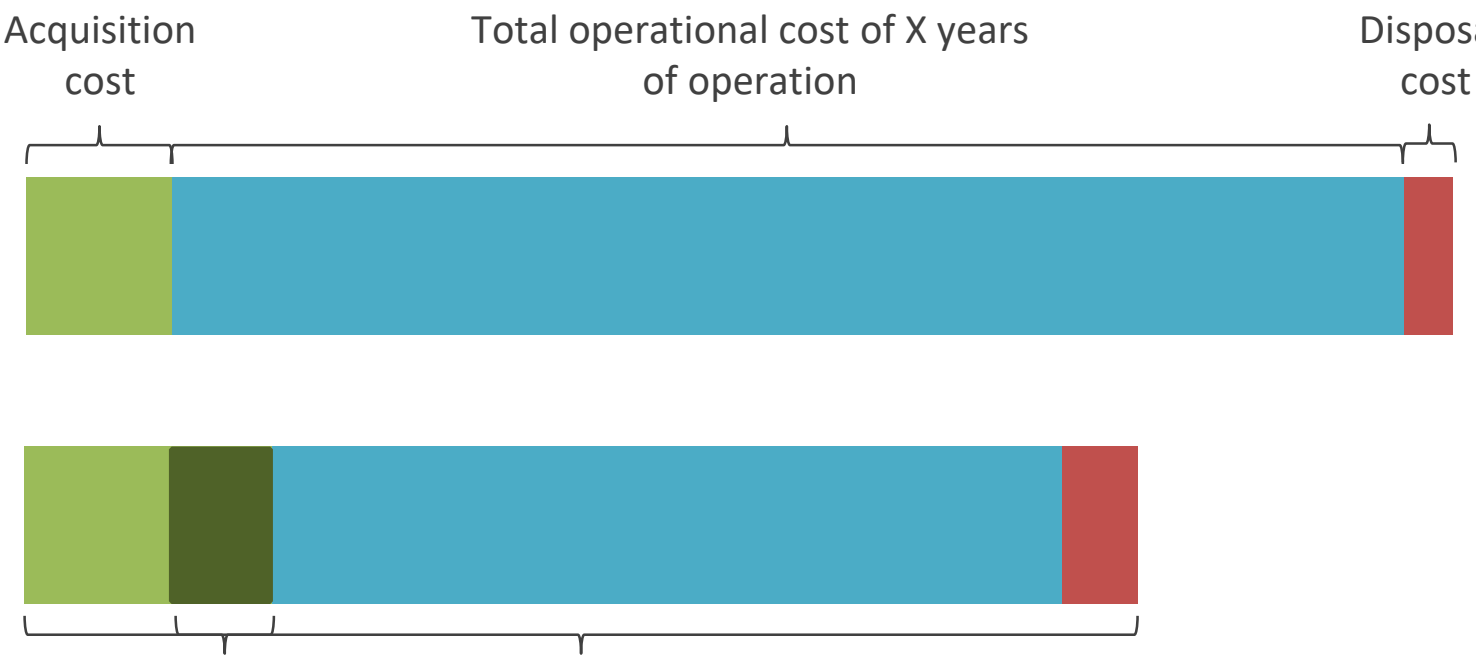


Sea loads

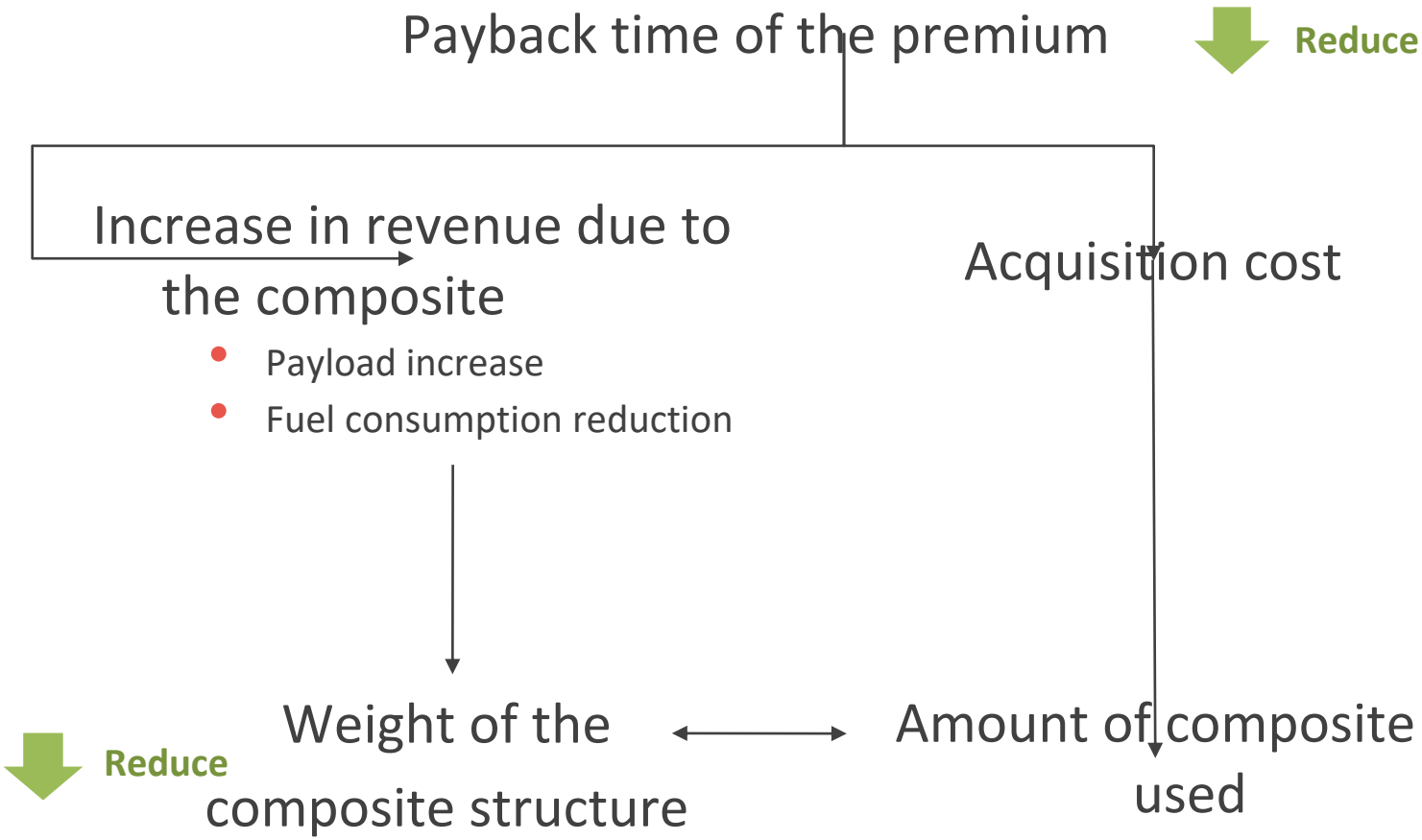
Why is cost reduction important?

Metal

Composite



Premium payback time is critical!
Economically unattractive if it is too long!

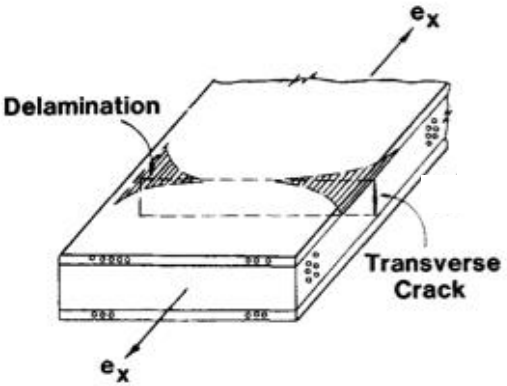


The structure must be as lightweight as possible!

Methodology

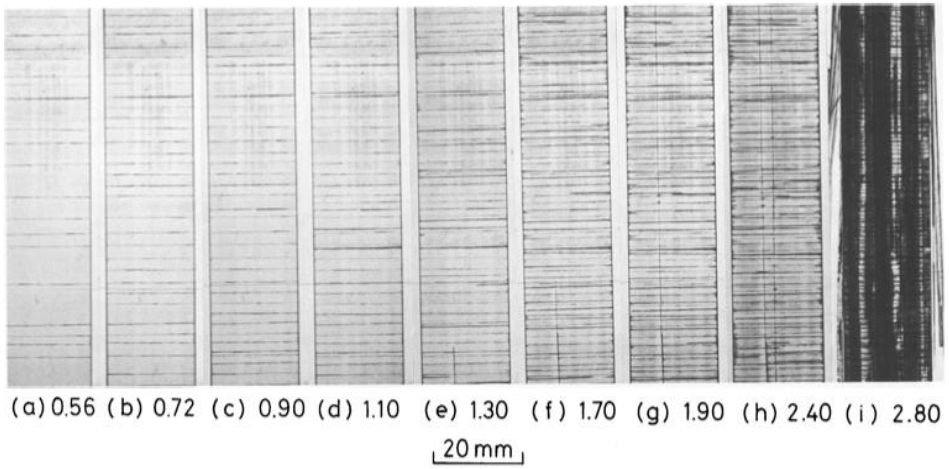
X-ray showing the damage in a $[\pm 25/90_4]_S$ carbon/epoxy prepreg laminate caused by a tensile load

©Wang, 1984



X-ray showing the number of matrix cracks in a $[90/0/90]_T$ glass/epoxy prepreg laminate as a tensile load increases

©Manders et al., 1983



One aspect of matrix cracking and delamination is

…

degrades the stiffness of the laminate

$E_X \rightarrow E_X^d$