



EPFL



POLITECNICO
MILANO 1863



GRoMeC
Composite Mechanics Group

Selected topics on advanced composites in engineering structures

Prof. Anastasios P. Vassilopoulos
Dr. Angelo Savio Calabrese

Course structure/philosophy

- A mix of lectures and individual work (research work) and structural design
- A research-oriented project

In brief:

- Few lectures (Introduction to composites, failure and fracture, fatigue and fatigue design, Joining techniques, strengthening)
- Hard individual work 😊 to present a project at the final workshop

What is this course about?



Are they new?

- Composites are used since the ancient times
- Mesopotamia (glued wood strips at dif. Angles to create plywood)
- Mongolian arcs
- Japanese swords
- Achilles buckler
 - more...

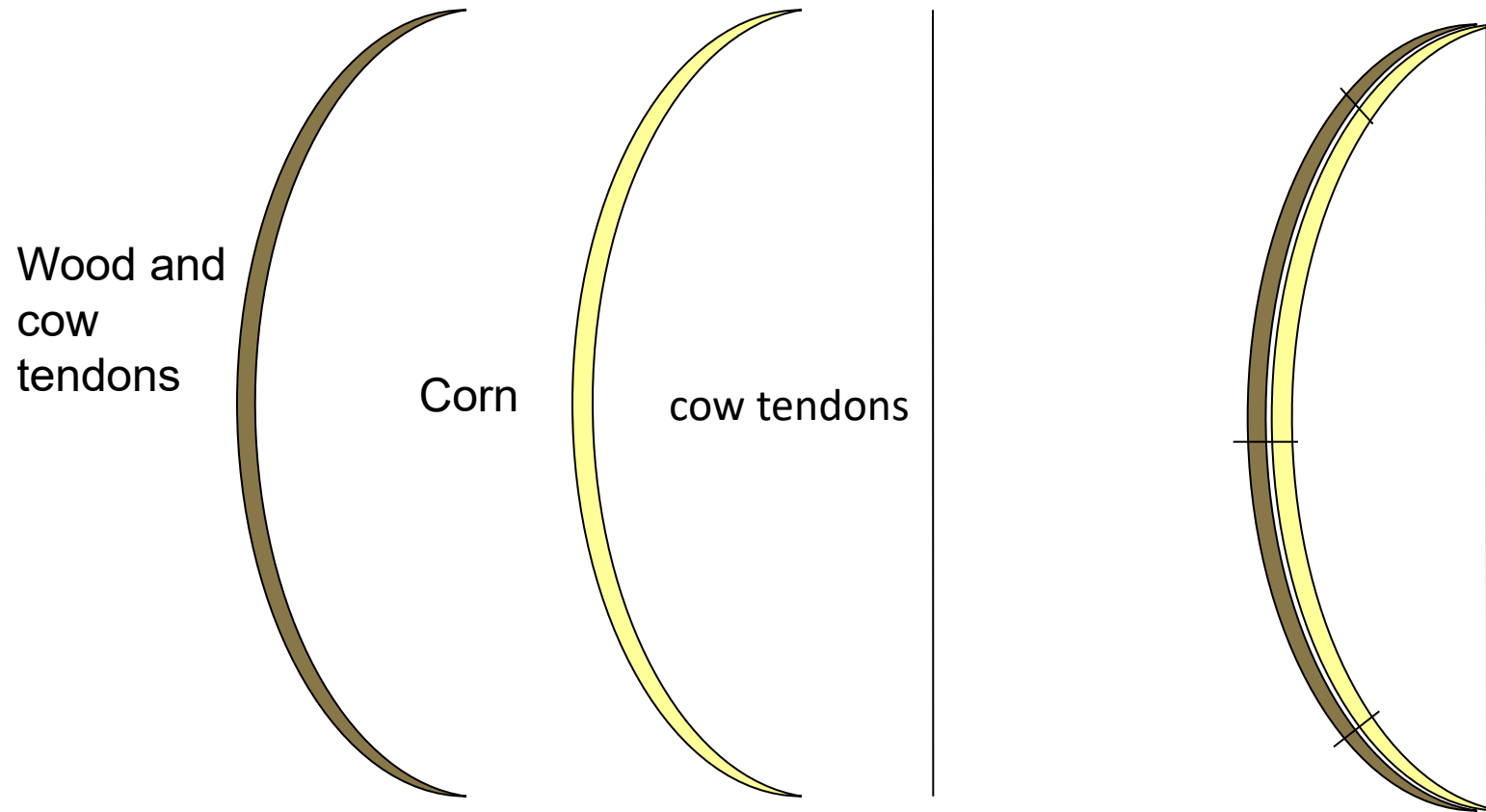


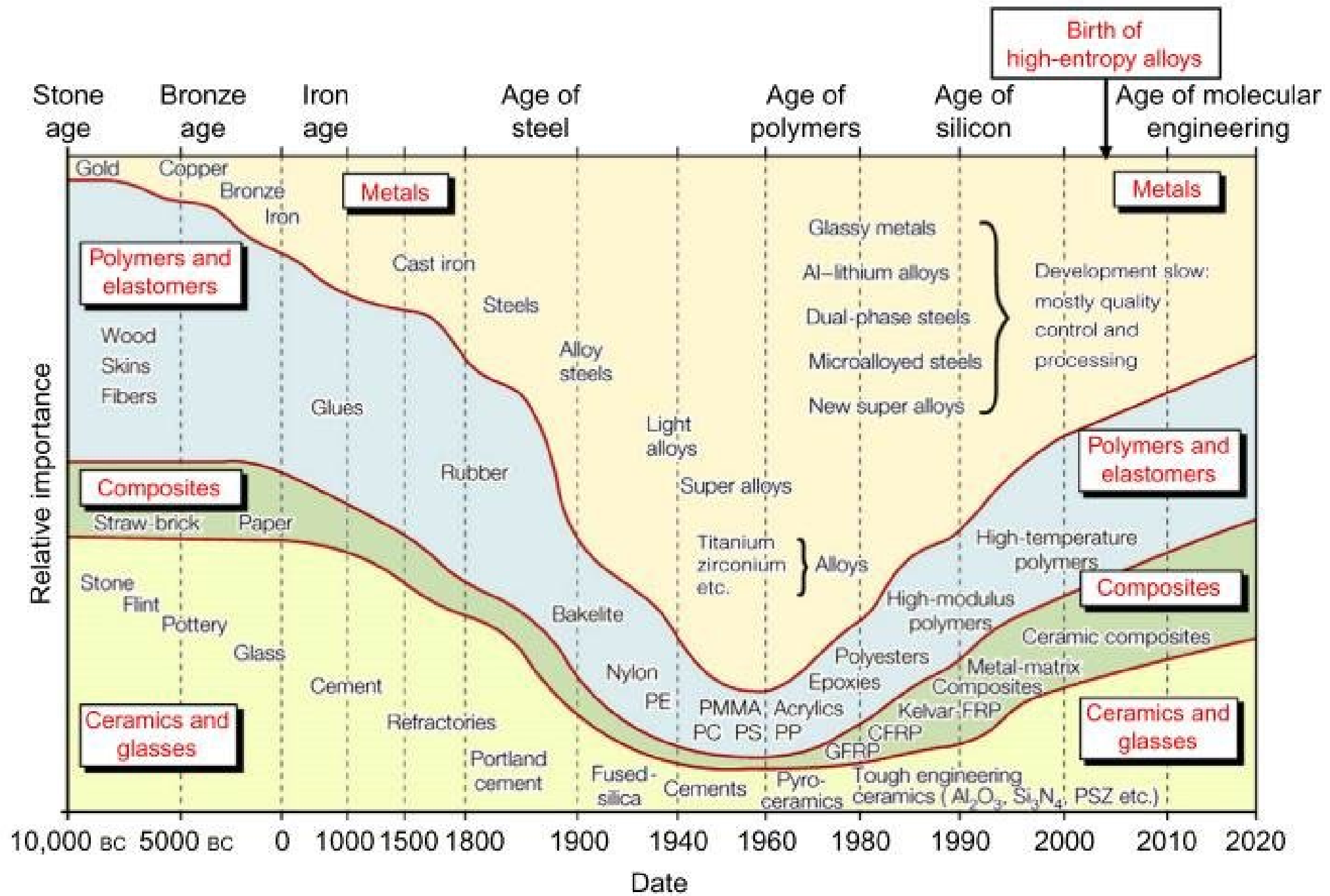
The Mongolian arcs

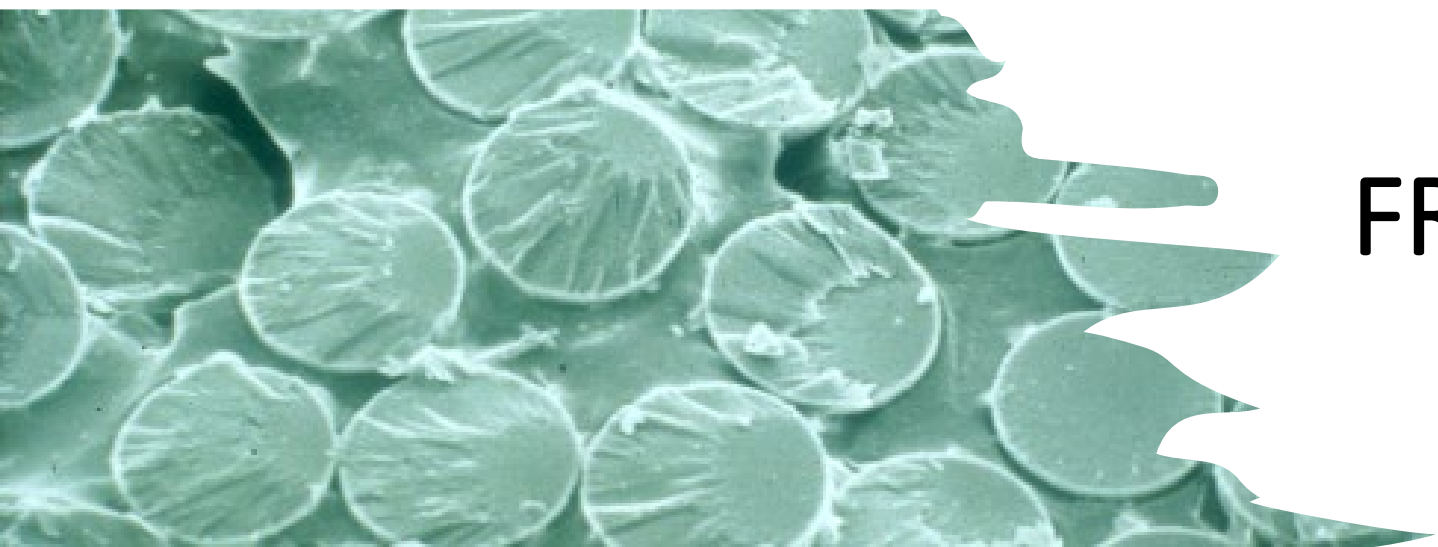
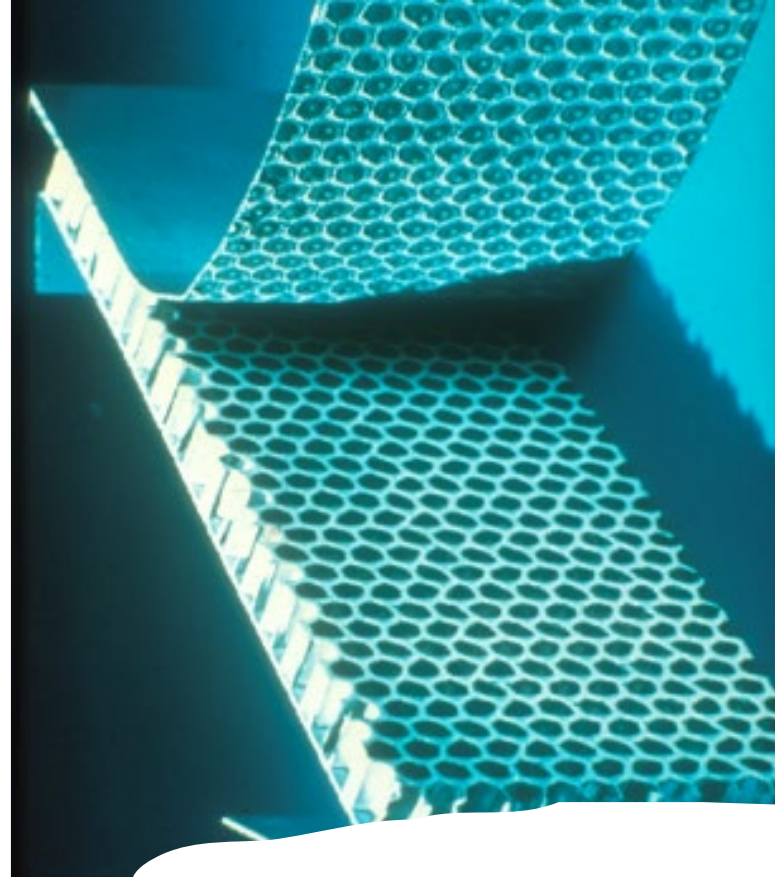
- Mongol Bow is a composite bow made of wood, tendons, and horn held together by a glue made from fish bladder, with the compressed parts made of corn,



The Mongolian arcs



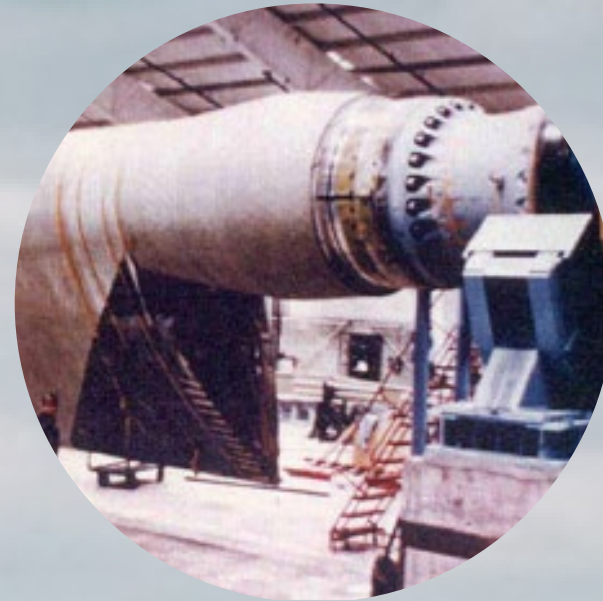




FRP Materials



Applications



Applications

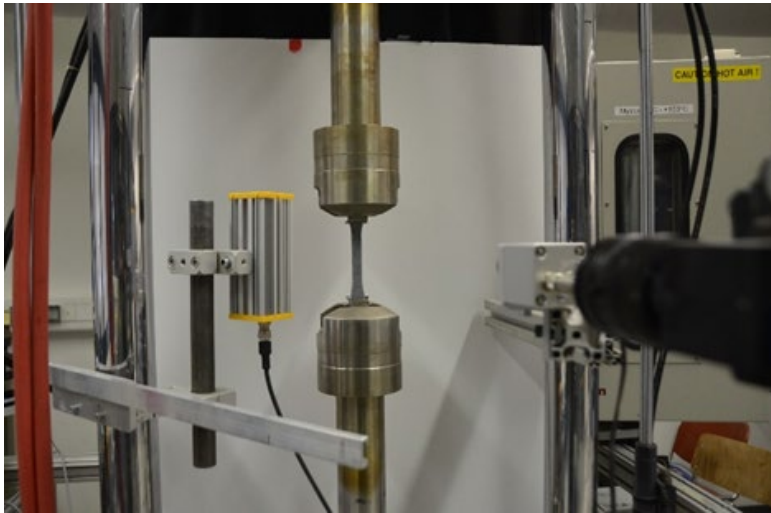
Civil 705

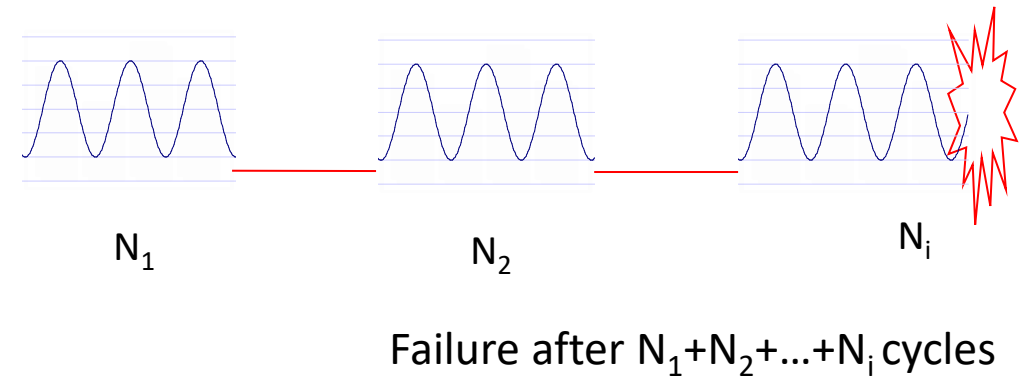
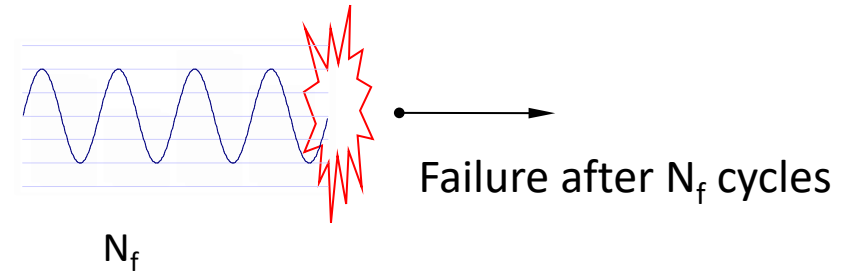
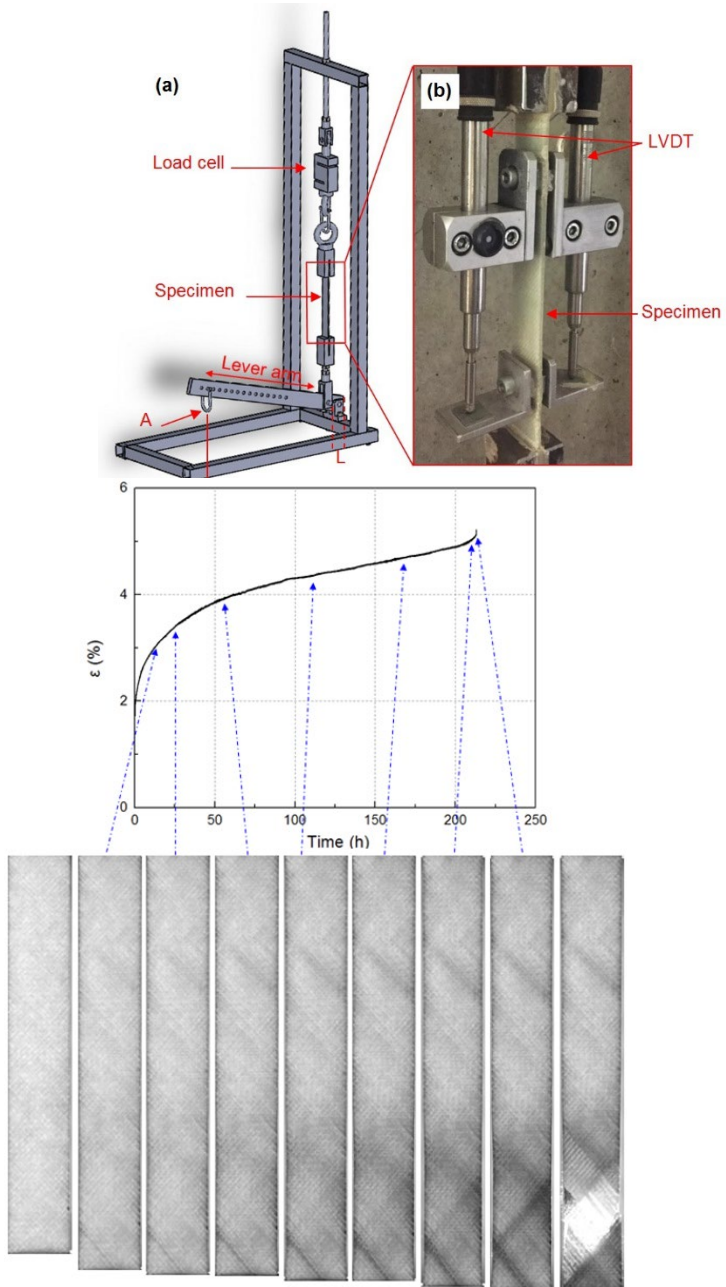
Course plan

Week	Date	Title	
1	10.09.2025	Introduction (APV/AC)	13:00-14:00
2	17.09.2025	Individual work – project selection	
3	24.09.2025	Failure criteria – Project validation (APV)	13:00-15:00+1hPV
4	01.10.2025	Individual work	
5	08.10.2025	Fracture mechanics concepts (APV)	13:00-16:00
6	15.10.2025	Individual work	
7	22.10.2025	Individual work	
8	29.10.2025	Joining technologies (AC)	13:00-16:00
9	05.11.2025	Individual work	
10	12.11.2025	Strengthening of existing structures (AC)	13:00-16:00
11	19.11.2025	Individual work	
12	26.11.2025	Fatigue of composites (APV)	13:00-16:00
13	03.12.2025	Individual work	
14	10.12.2025	Repair of fatigue damaged structures (AC)	13:00-16:00
		January 2026: Oral exam/workshop @ EPFL	

APV: Anastasios P. Vassilopoulos

AC: Angelo Calabrese



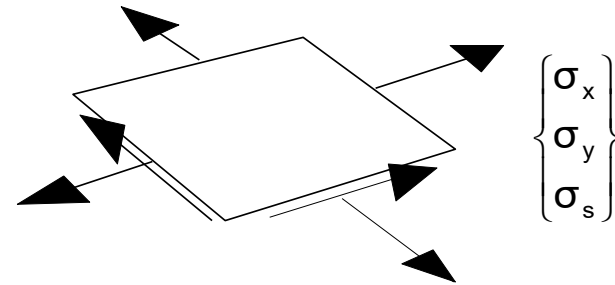
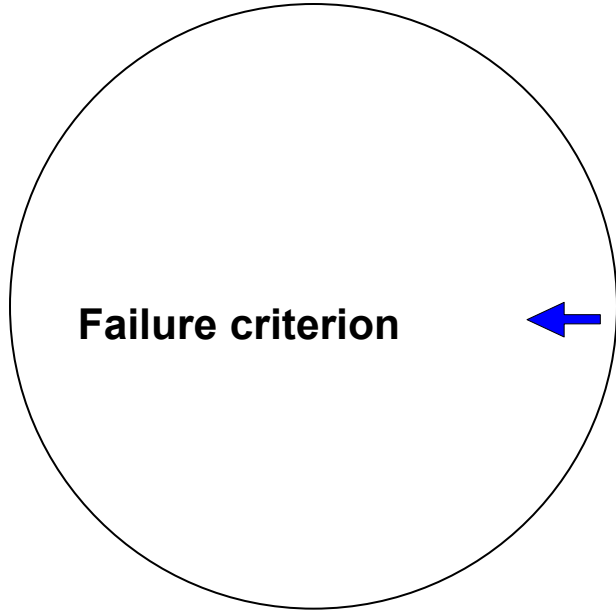
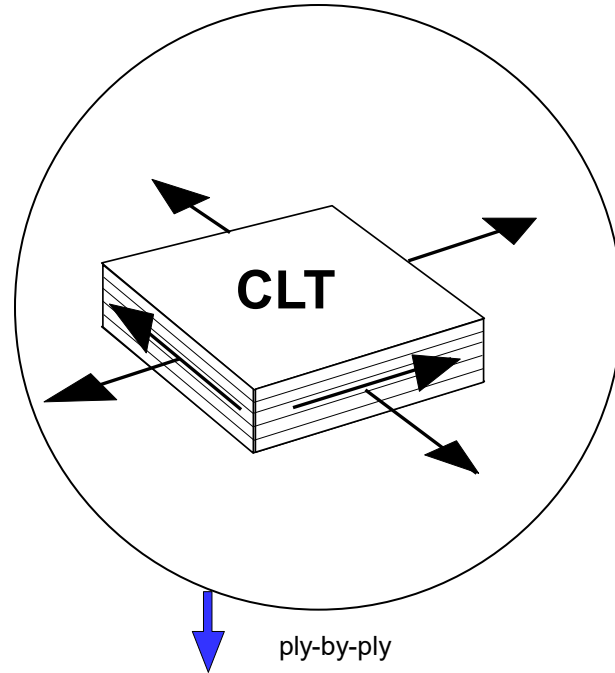
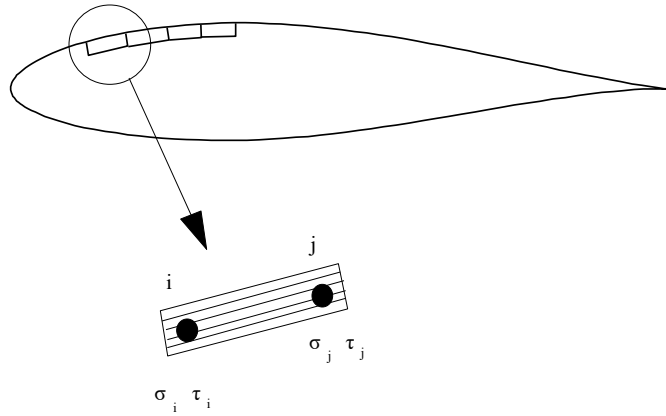




Failure

Failure

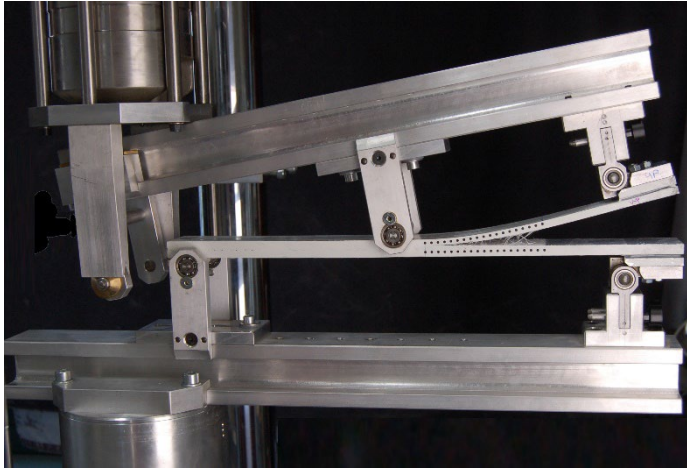
- M_{flap}
- M_{edge}
- M_{torsion}
- F_{flap}
- F_{edge}
- F_{axial}



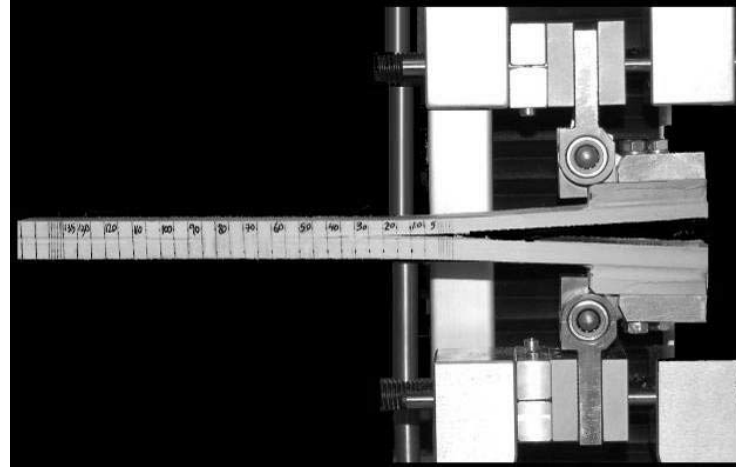


Fracture

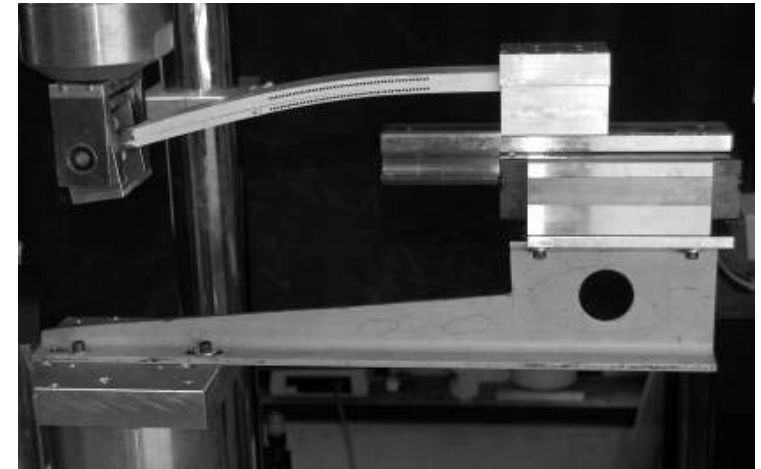
Mode I, Mode II, mixed-Mode I/II



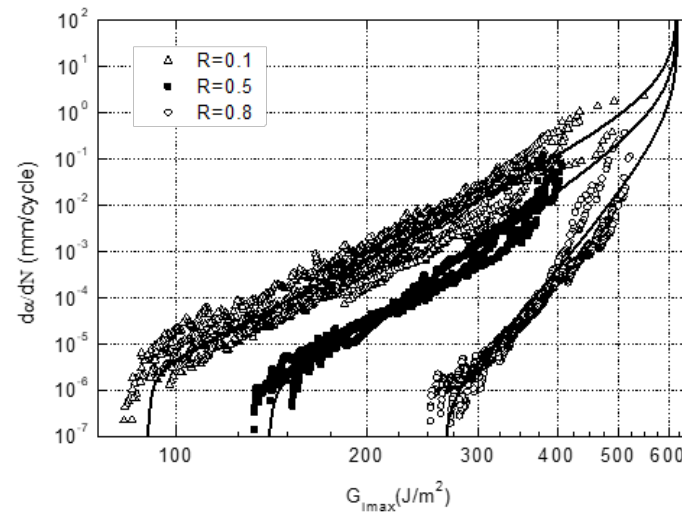
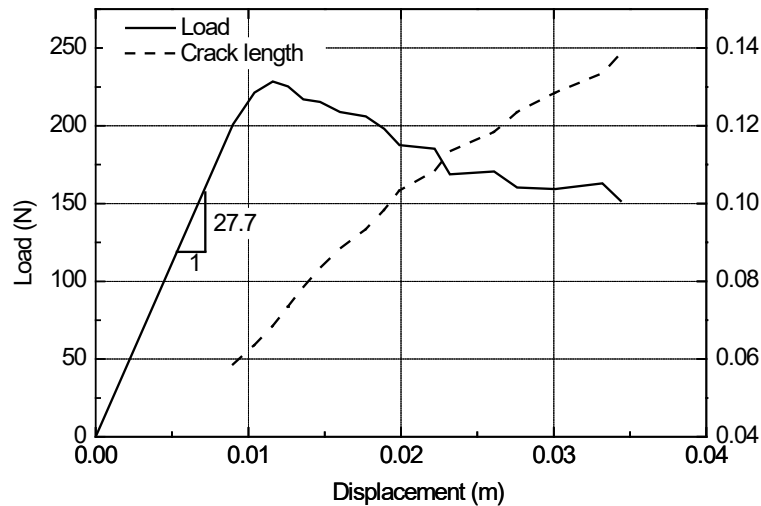
Mode I



Mode II

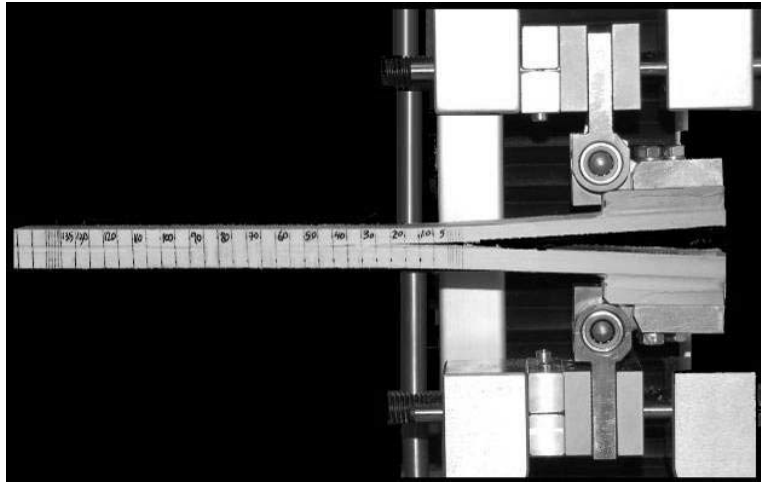


Mixed-Mode I/II

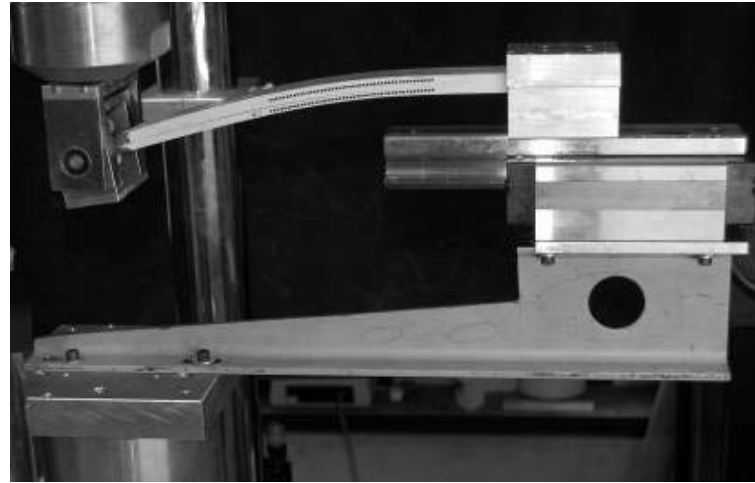
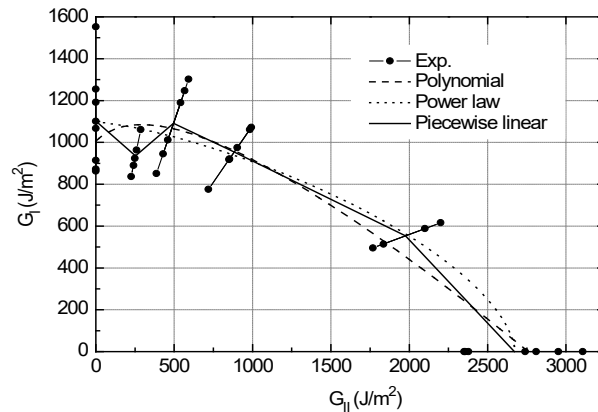


$$\frac{da}{dN} = D(G_{max})^m \frac{\left(1 - \left(\frac{G_{th}}{G_{max}}\right)^{Q_1}\right)}{\left(1 - \left(\frac{G_{max}}{G_c}\right)^{Q_2}\right)}$$

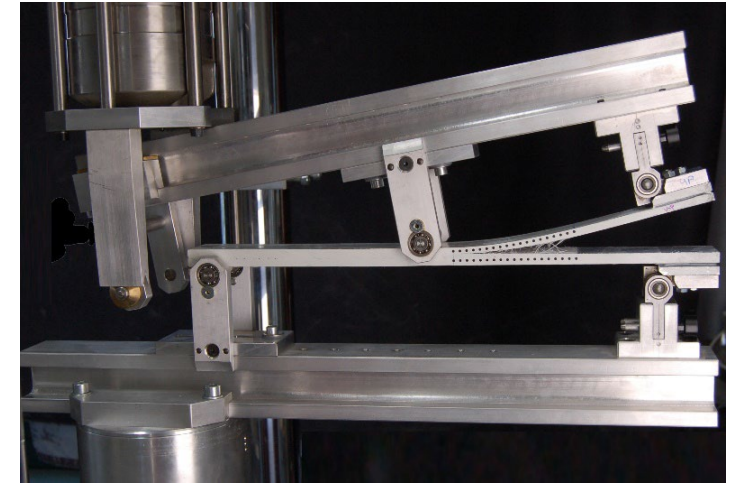
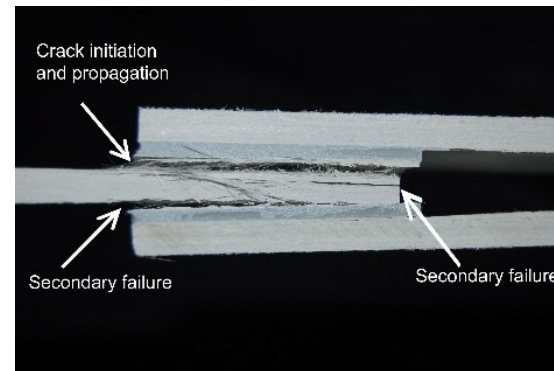
Simple mode to mixed-mode prediction



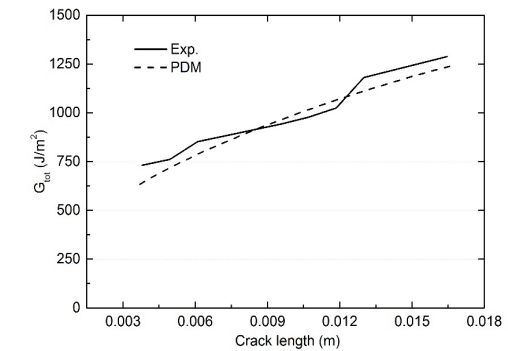
Mode I



Mode II

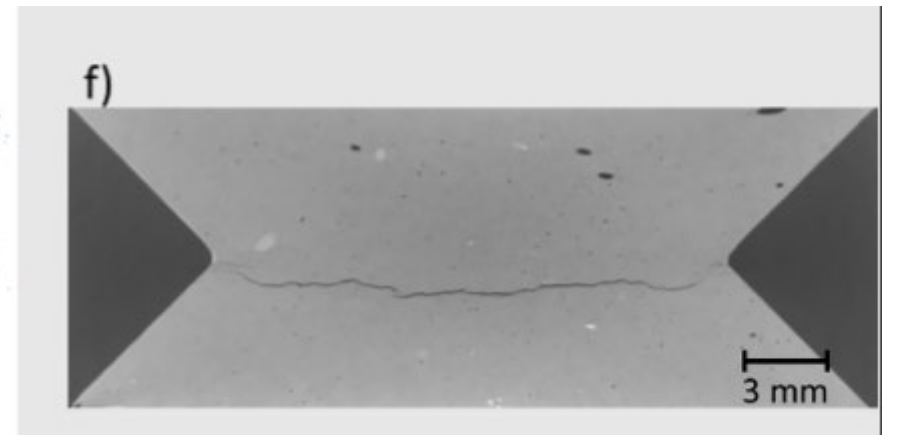
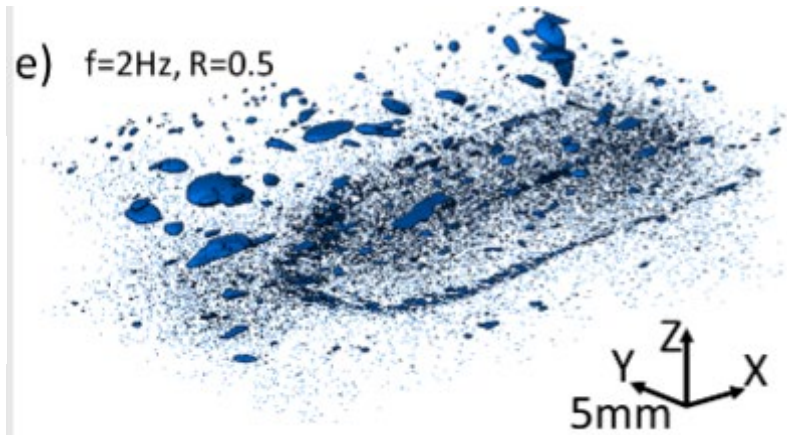
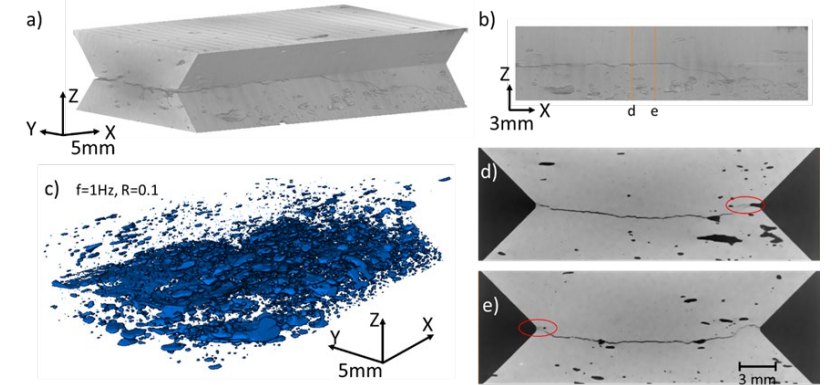
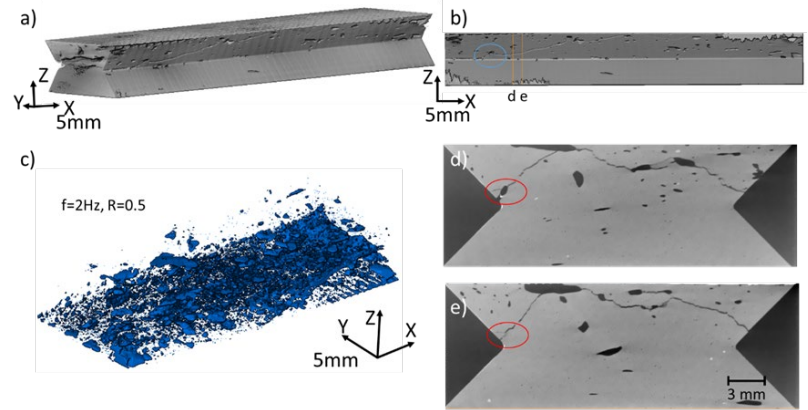
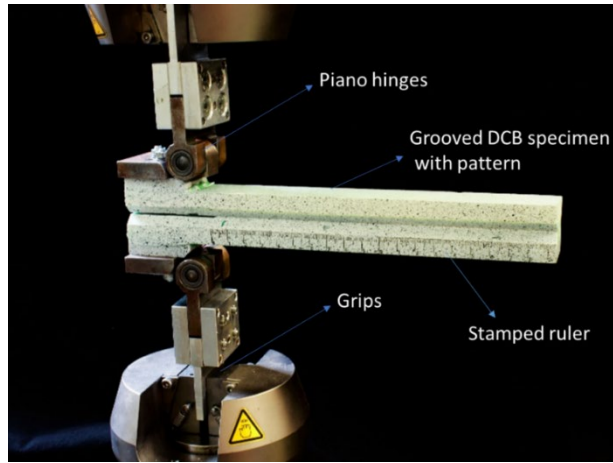


Mixed-Mode I/II



*A. Cameselle-Molares, R. Sarfaraz, M. Shahverdi, A. P. Vassilopoulos, T. Keller "Fracture mechanics-based progressive damage modelling of adhesively bonded fibre-reinforced polymer joints" FFEMS, 2017;40(12):2183-2193

Thick adhesive joints



International Journal of Fatigue 188 (2024) 108508

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

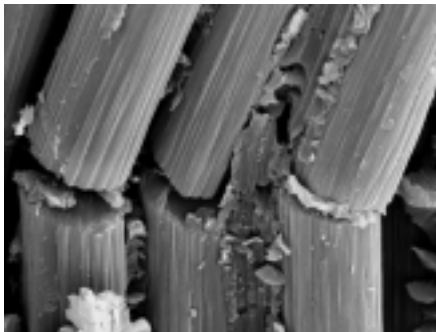



Void content and displacement ratio effects on fatigue crack growth in thick adhesively bonded composite joints under constant amplitude loading

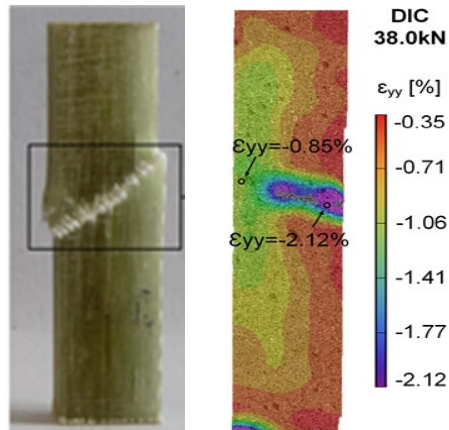
Jialiang Fan^a, Keiyu Ikeda^b, Anastasios P. Vassilopoulos^c, Veronique Michaud^{a,*}

Fracture mechanics – supported by imaging methods

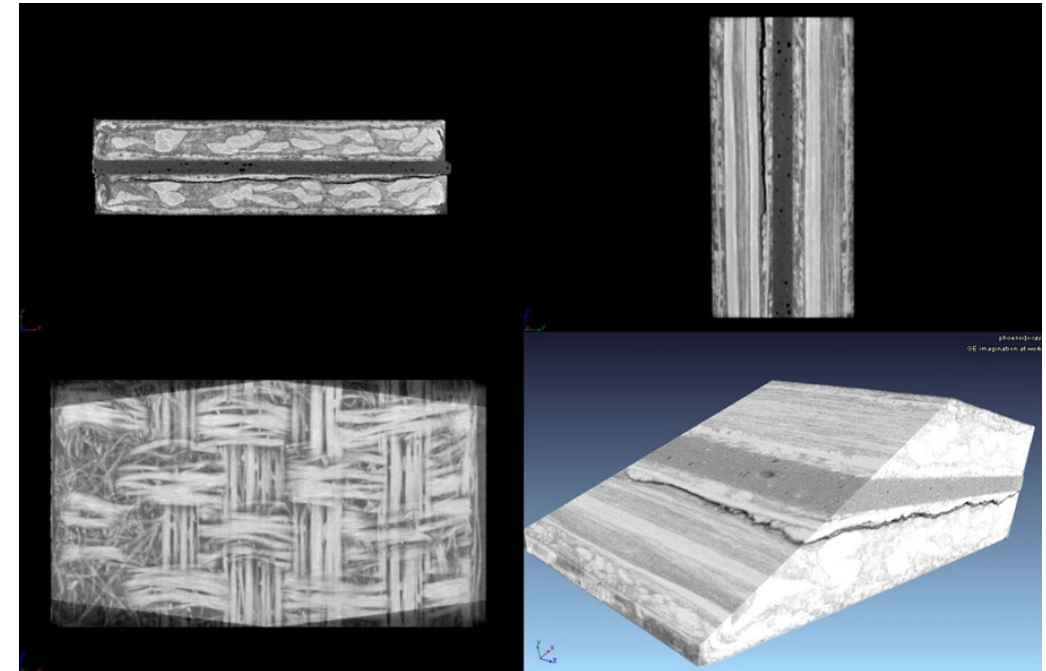
- It was in early **1900s** when Ewin and Humfrey* used the optical microscope to pursue the study of fatigue/fracture mechanisms
- In the **1950s** the scanning electron microscope
- Today DIC/ x-ray tomography



SEM: Fiber kinking due to compression



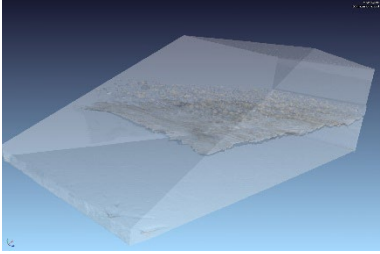
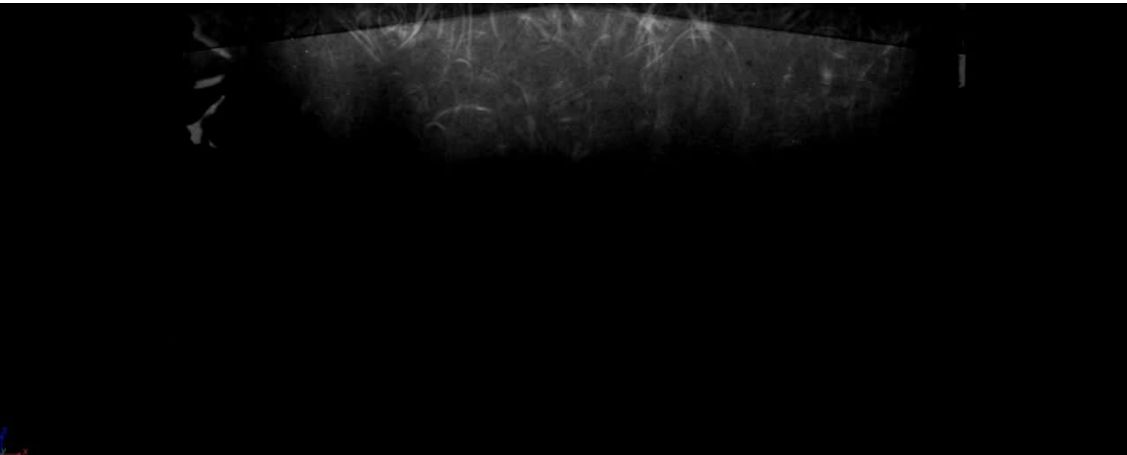
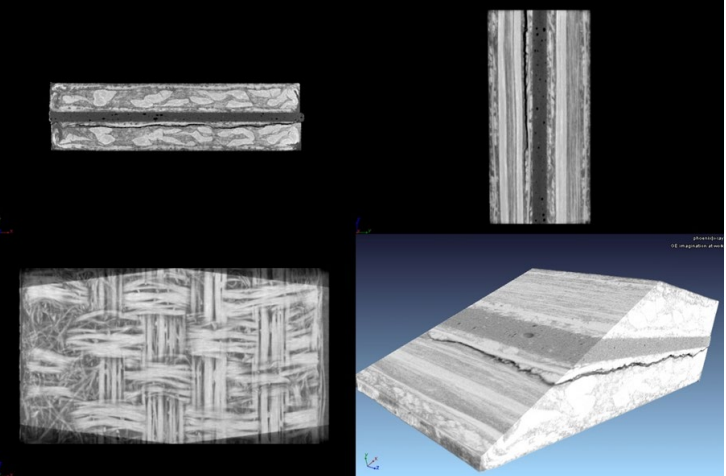
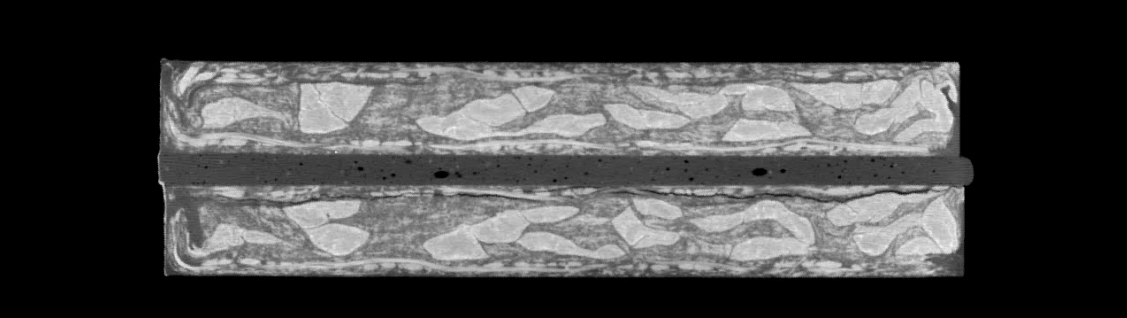
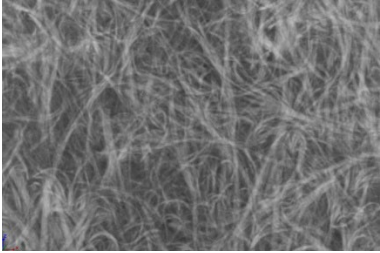
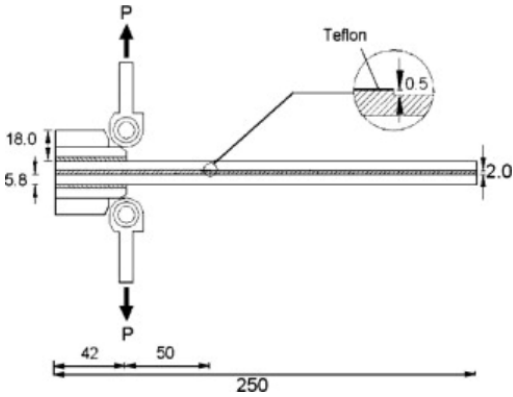
DIC measurement of strain fields



Tomography: Architecture of, and crack in an adhesively bonded joint

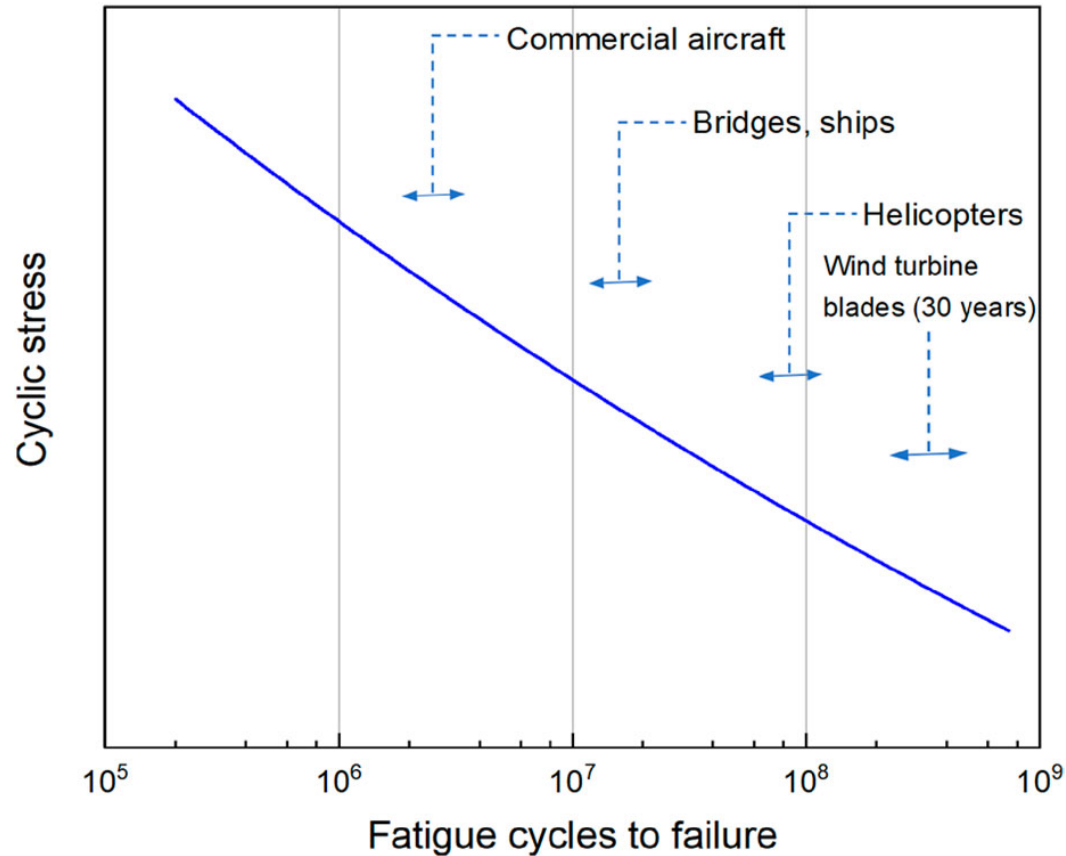
*J. A. Ewin, J. C. W. Humfrey. "The fracture of metals under repeated alternations of stress" Philosophical transactions of the royal society A. Mathematical, physical and engineering sciences, 01 Jan 1903

X-ray digital tomography



Fatigue of composites

Fatigue in (composite) structures



107 meters, LM Wind Energy's blades for the Haliade-X, 12MW

INTERNATIONAL MATERIALS REVIEWS
2021, VOL. 66, NO. 5, 313-338
<https://doi.org/10.1080/09506608.2020.1845110>

iom
The Institute of Materials,
Minerals and Mining

ASM
INTERNATIONAL

Taylor & Francis
Taylor & Francis Group

Check for updates

FULL CRITICAL REVIEW

Review of fatigue of bulk structural adhesives and thick adhesive joints

Peiyuan Zuo^a and Anastasios P. Vassilopoulos^b



Applications of COMPOSITES on existing structures

Externally bonded reinforcements (FRP EBR): scope and motivation



Strengthening ✓
Rehabilitation ✓
Retrofitting ✓
Repair ✓

Add extra
structural capacity
beyond original²⁶

Externally bonded reinforcements (FRP EBR): scope and motivation



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Externally bonded reinforcements (FRP EBR): scope and motivation



Strengthening ✓
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Retrofitting ✓
Repair ✓

Restore overall
usability and
extend life

Externally bonded reinforcements (FRP EBR): scope and motivation



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Externally bonded reinforcements (FRP EBR): scope and motivation



Strengthening ✓
Rehabilitation ✓
Retrofitting ✓
Repair ✓

Adapt structure
for new demands
or standards. ³⁰

Externally bonded reinforcements (FRP EBR): scope and motivation



Strengthening ✓
Rehabilitation ✓
Retrofitting ✓
Repair ✓

Adapt structure
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Externally bonded reinforcements (FRP EBR): scope and motivation



Strengthening ✓
Rehabilitation ✓
Retrofitting ✓
Repair ✓

Fix damage,
restore original.³²

Externally bonded reinforcements (FRP EBR): scope and motivation



Strengthening ✓
Rehabilitation ✓
Retrofitting ✓
Repair ✓

Fix damage,
restore original.³³

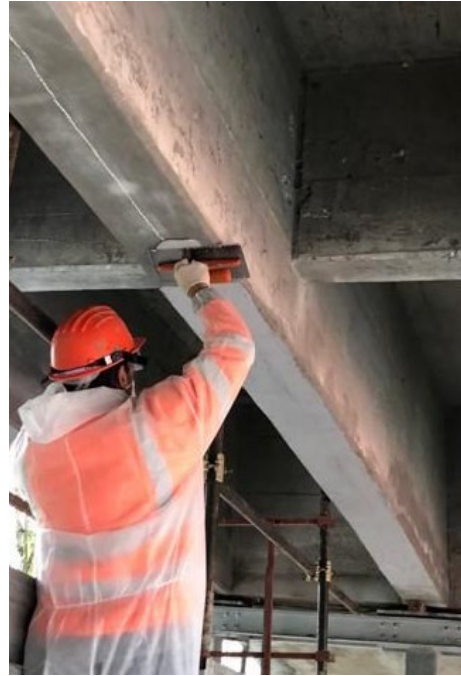
Why bond matters: relevance of interface behavior to structural performance



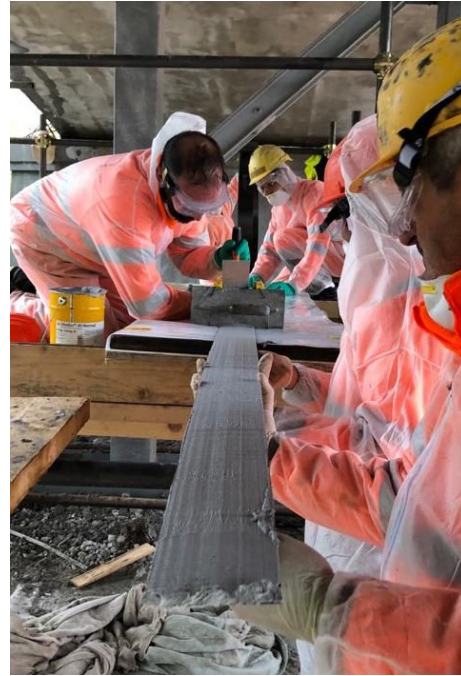
Preparation



Treatment



Adhesive application



Bonding

Why bond matters: relevance of interface behavior to structural performance



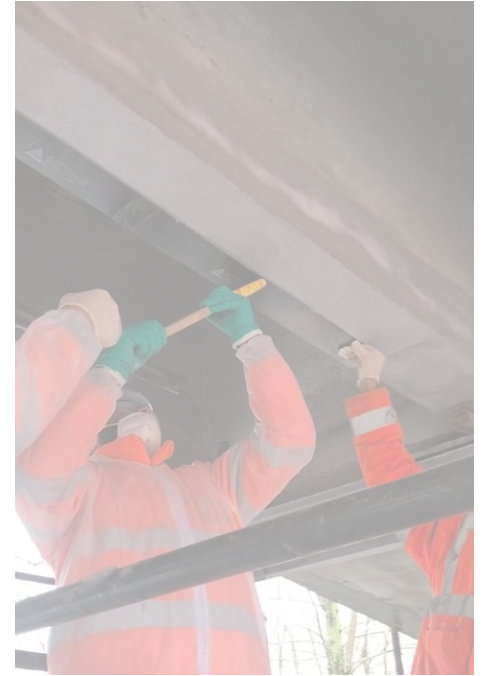
Preparation



Treatment

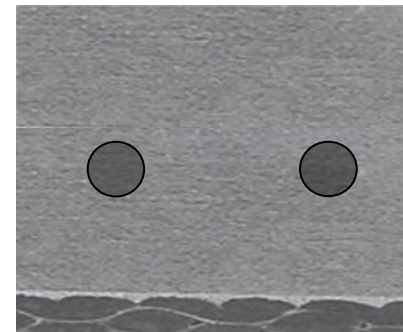


Adhesive application



Bonding

- RC beam
- Steel rebar
- Adhesive
- Composite



Why bond matters: relevance of interface behavior to structural performance



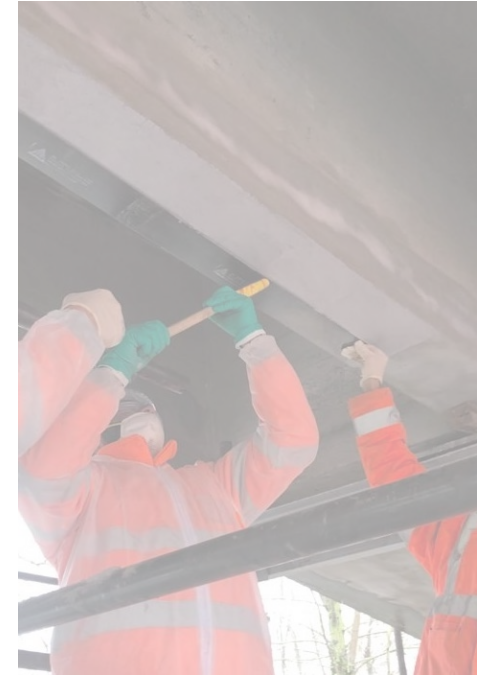
Preparation



Treatment

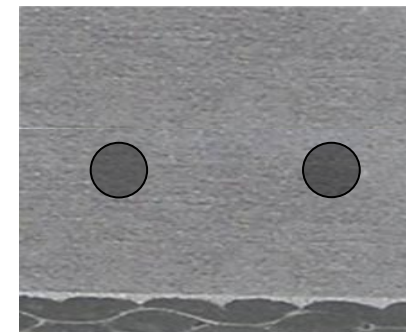
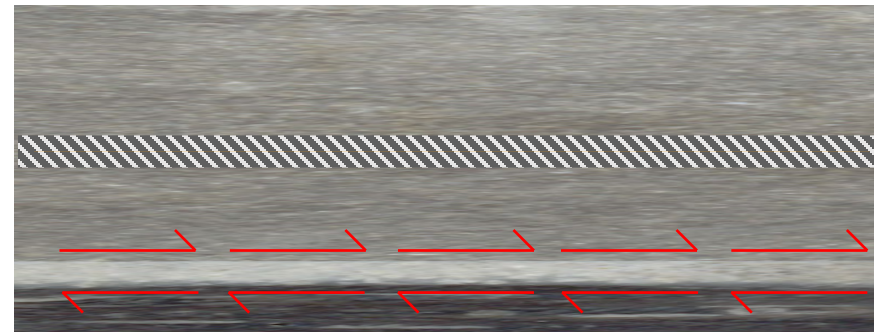


Adhesive application



Bonding

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Design teaser: FRP strengthening of RC structures (standards-based overview)

Main current Design Standards

American Concrete Institute (ACI) – US

ACI 440.2R-23, *Guide for the Design and Construction of Externally Bonded Fiber-Reinforced Polymer (FRP) Systems for Strengthening Concrete Structures*

fib (fédération internationale du béton)

fib Bulletin 90 (2019), *Externally applied FRP reinforcement for concrete structures*

CNR – Consiglio Nazionale delle Ricerche – IT

CNR-DT 200 R2/2025, *Guidelines for the Design, Execution and Inspection of Structural Strengthening Interventions Using Fiber-Reinforced Composites*



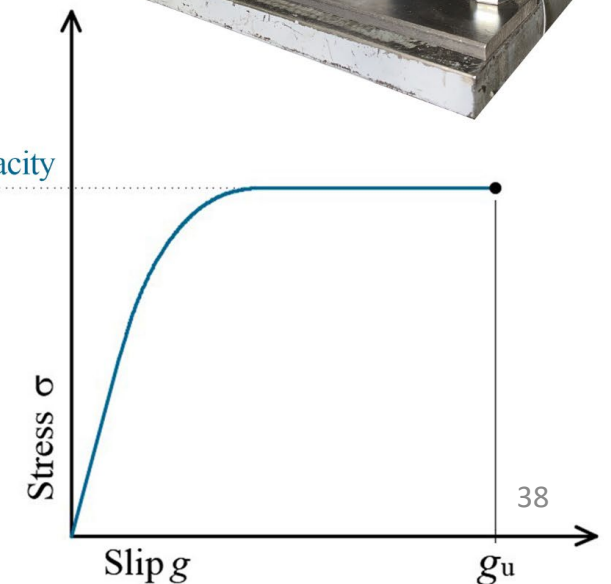
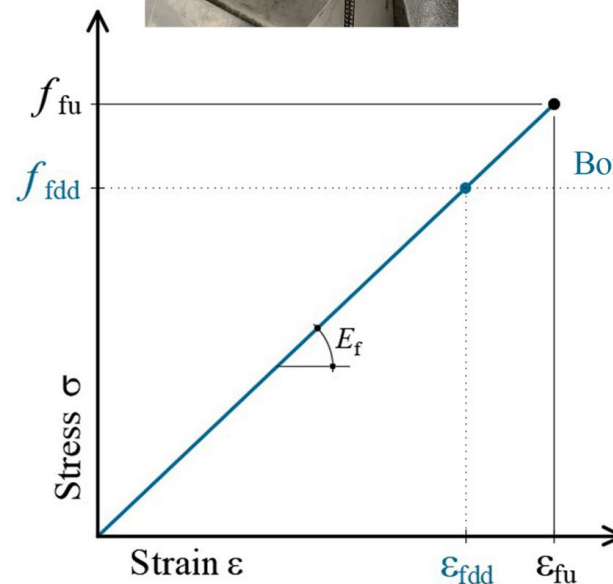
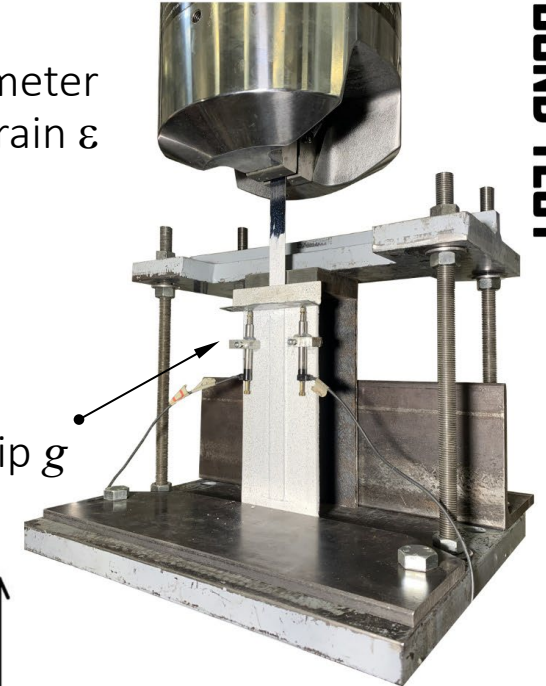
TENSILE TEST



Extensometer measuring Strain ϵ

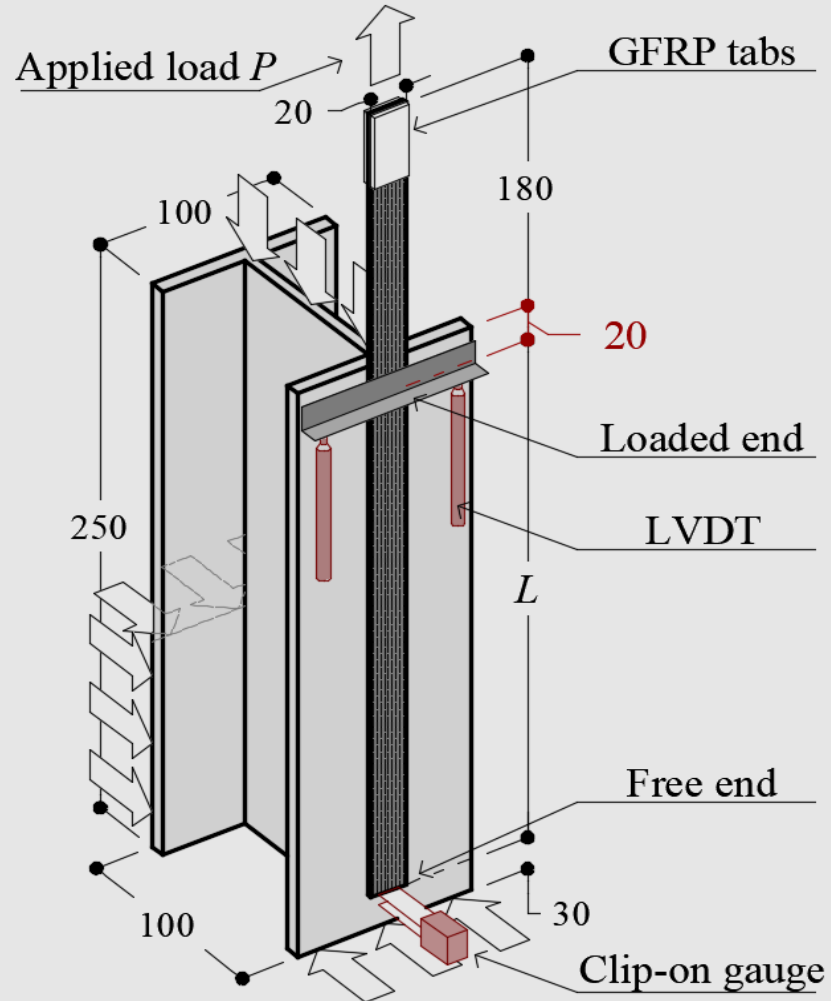
LVDTs measuring Slip g

BOND TEST

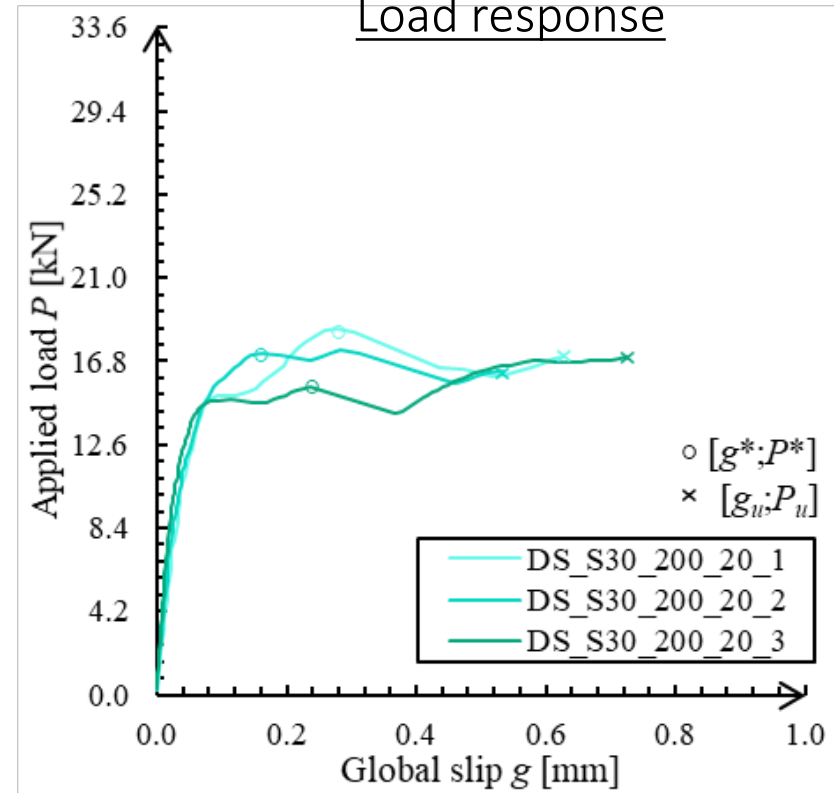


Experimental assessment of bond capacity: typical setup & key observations

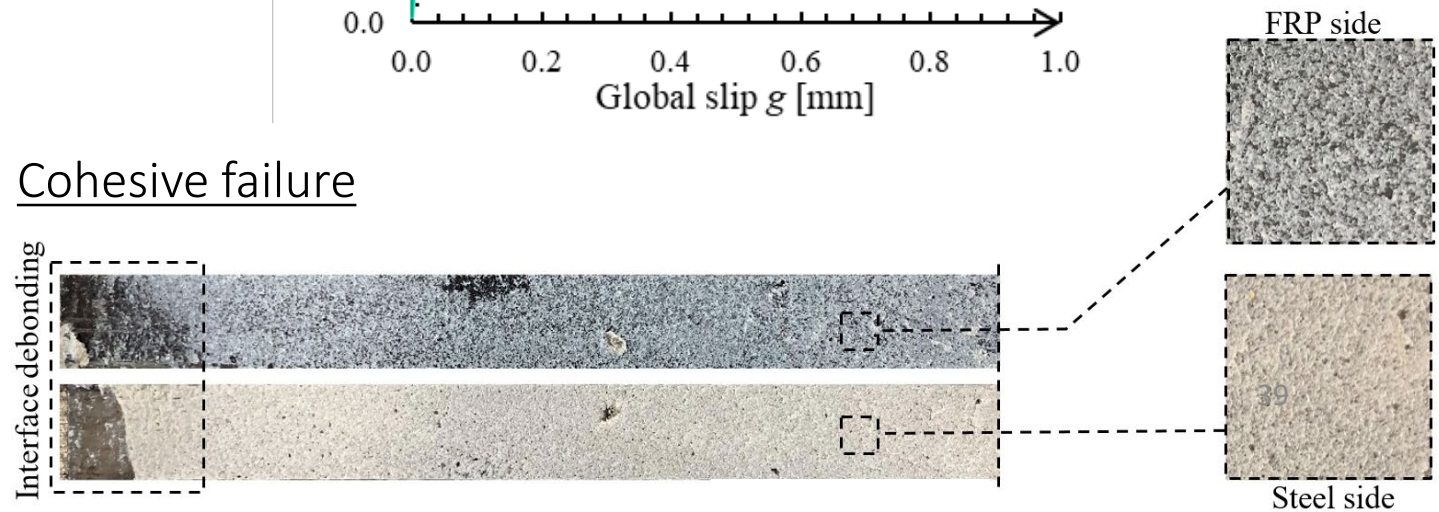
DIRECT SHEAR SETUP



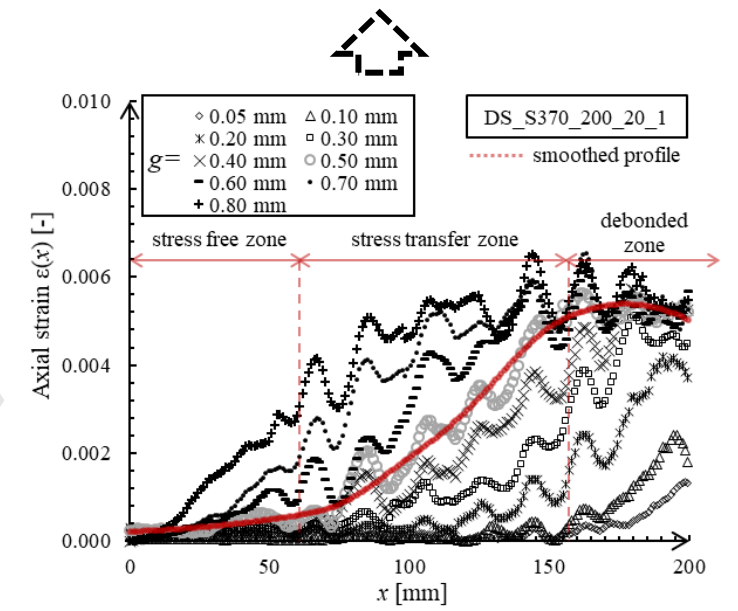
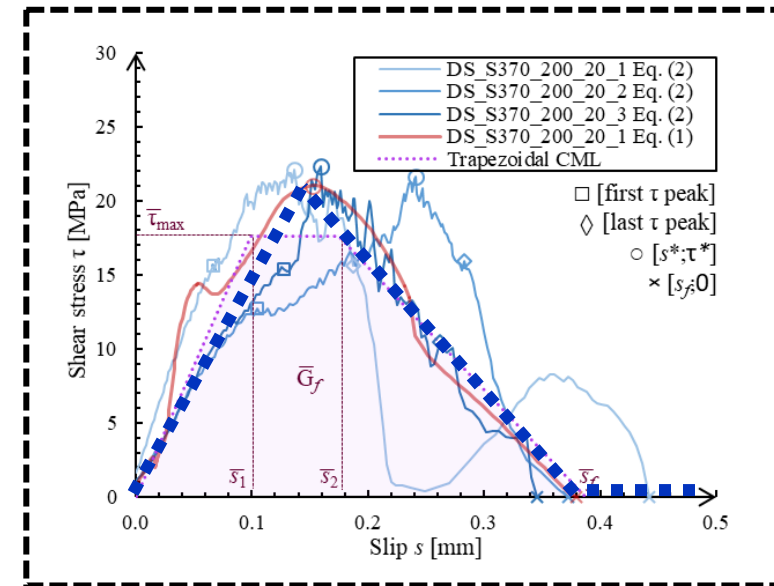
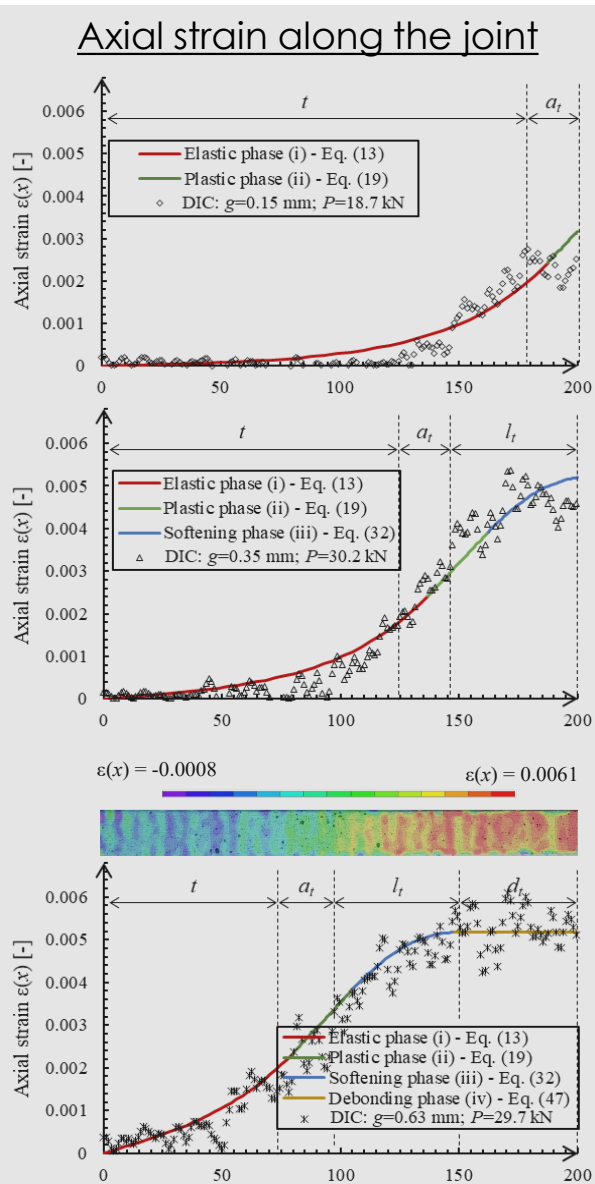
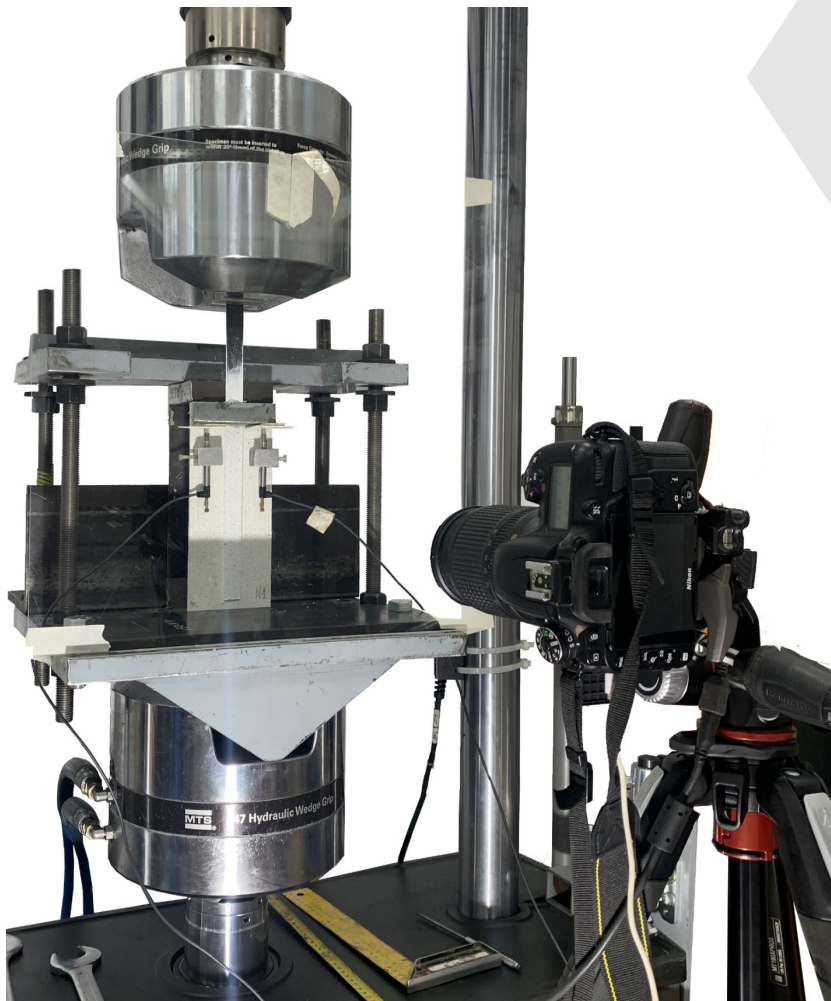
Load response



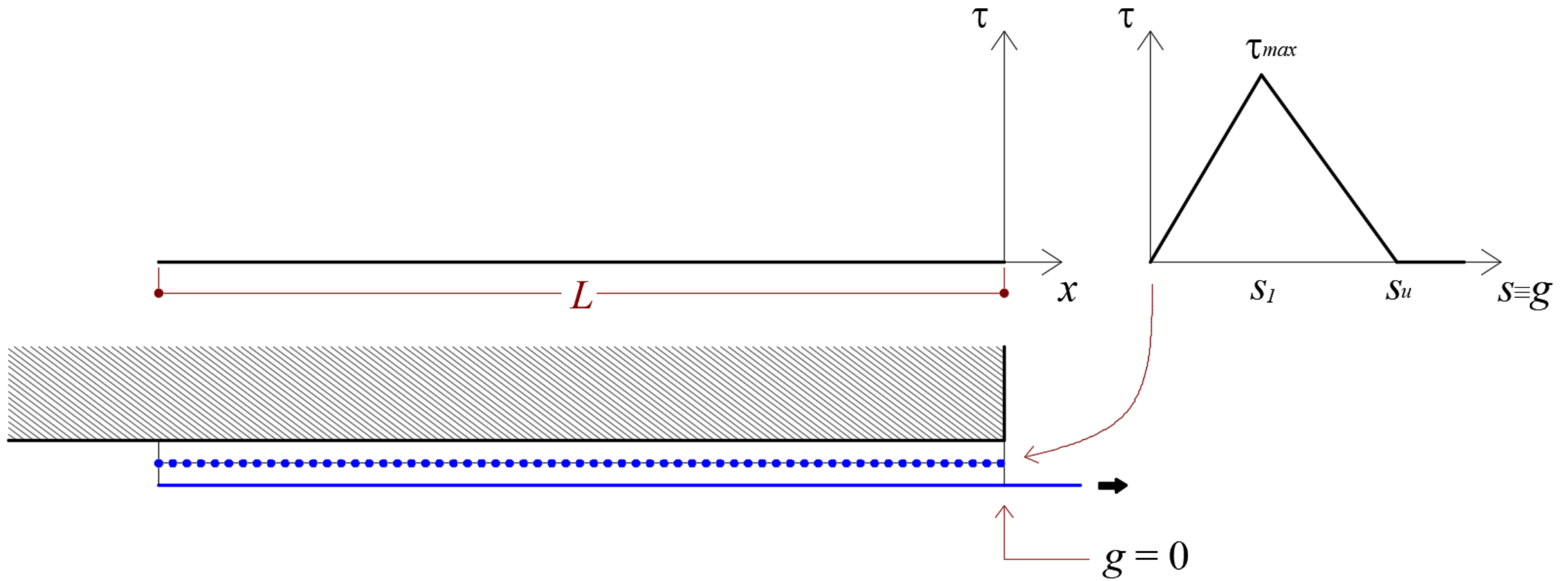
Cohesive failure



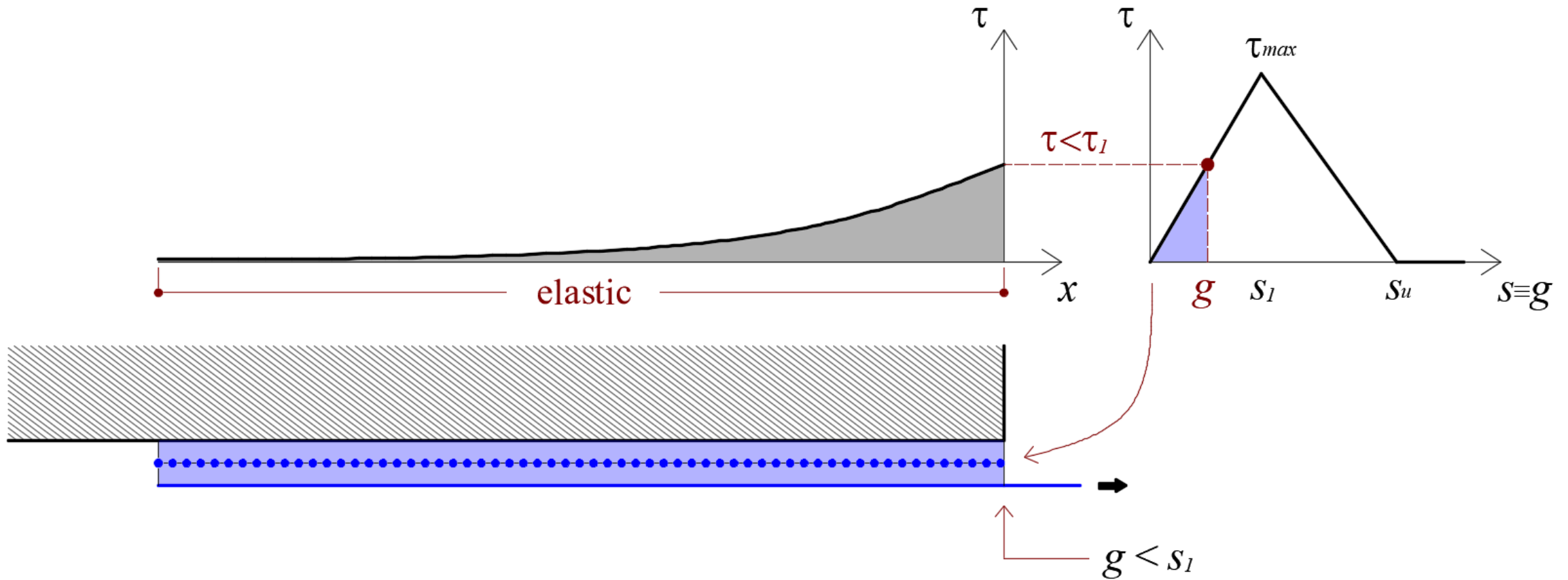
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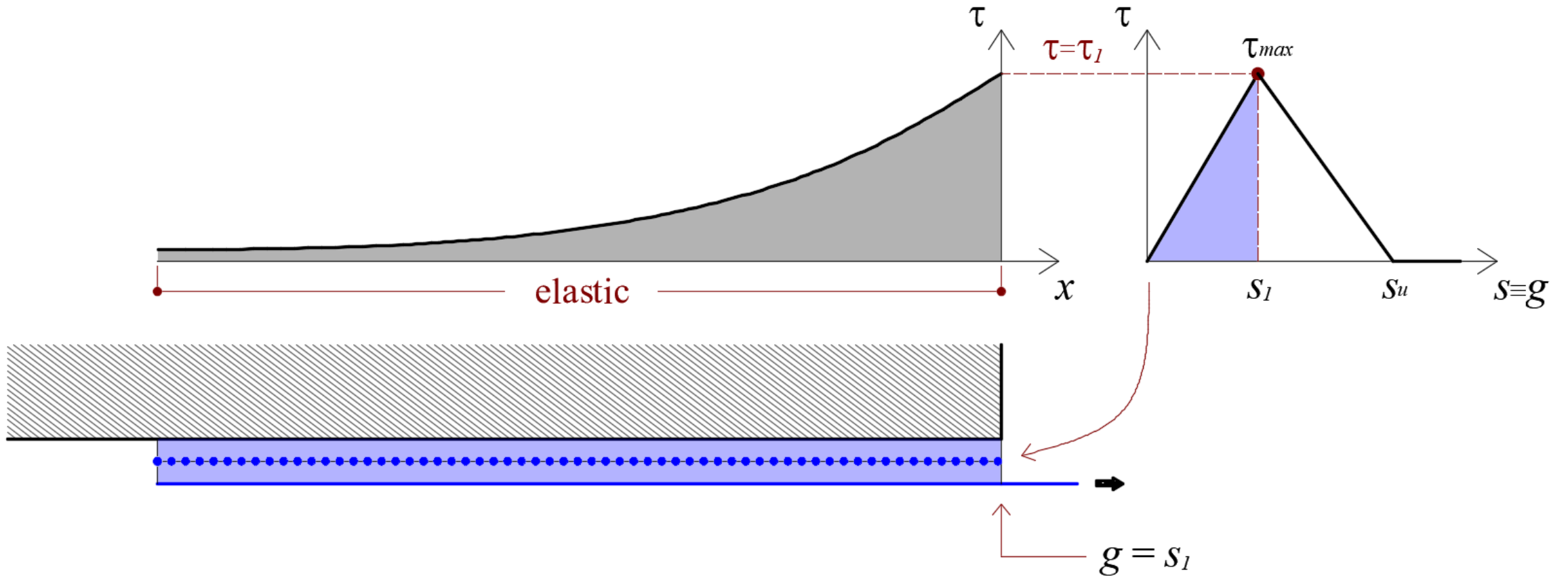
Analysis of bond: cohesive/fracture-mechanics perspective



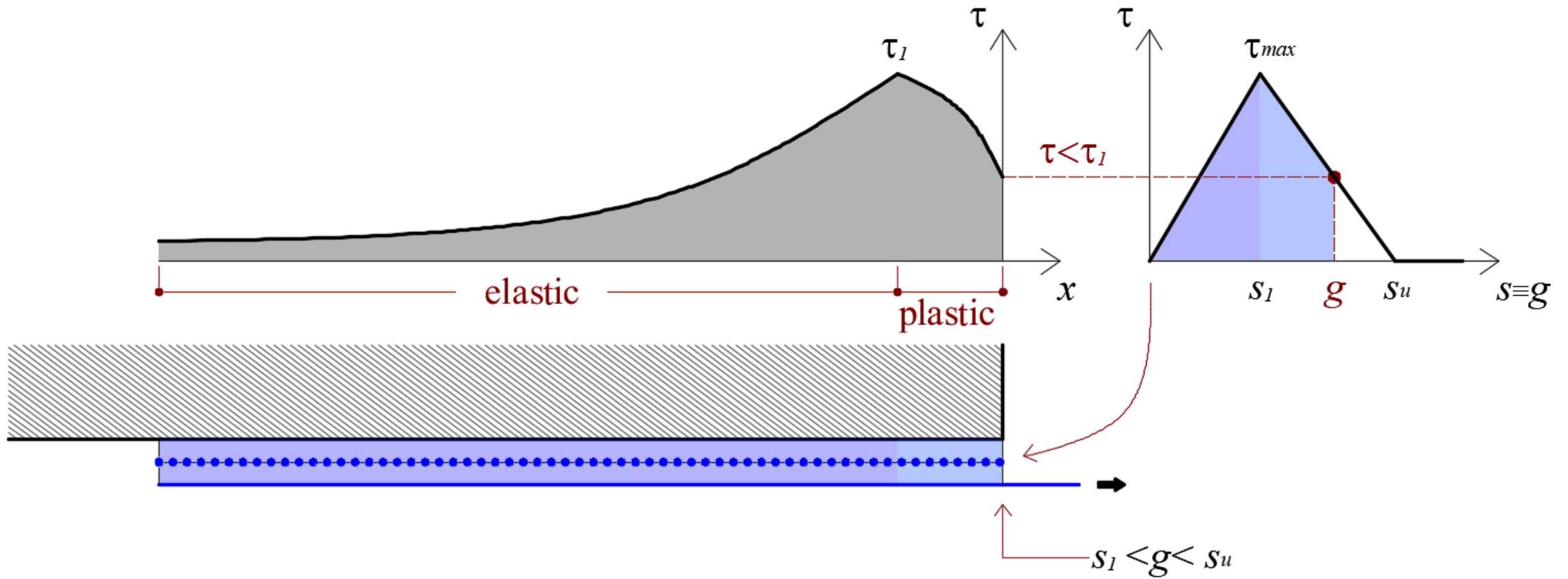
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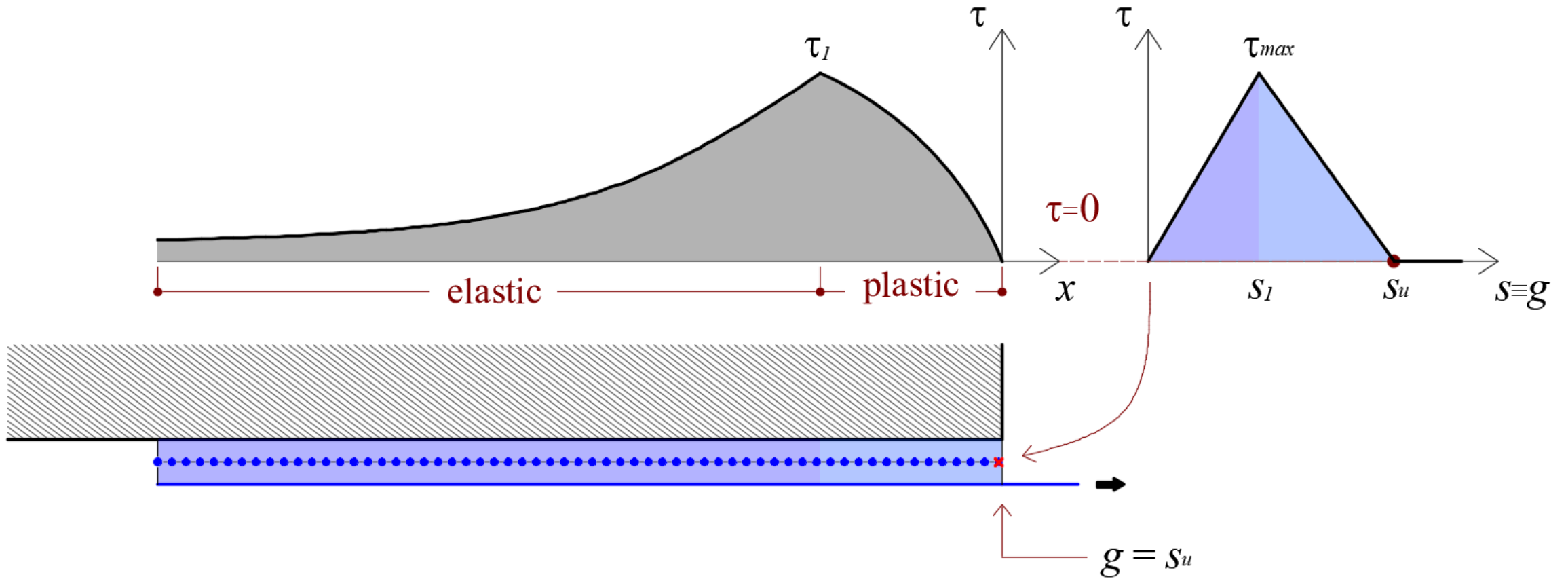
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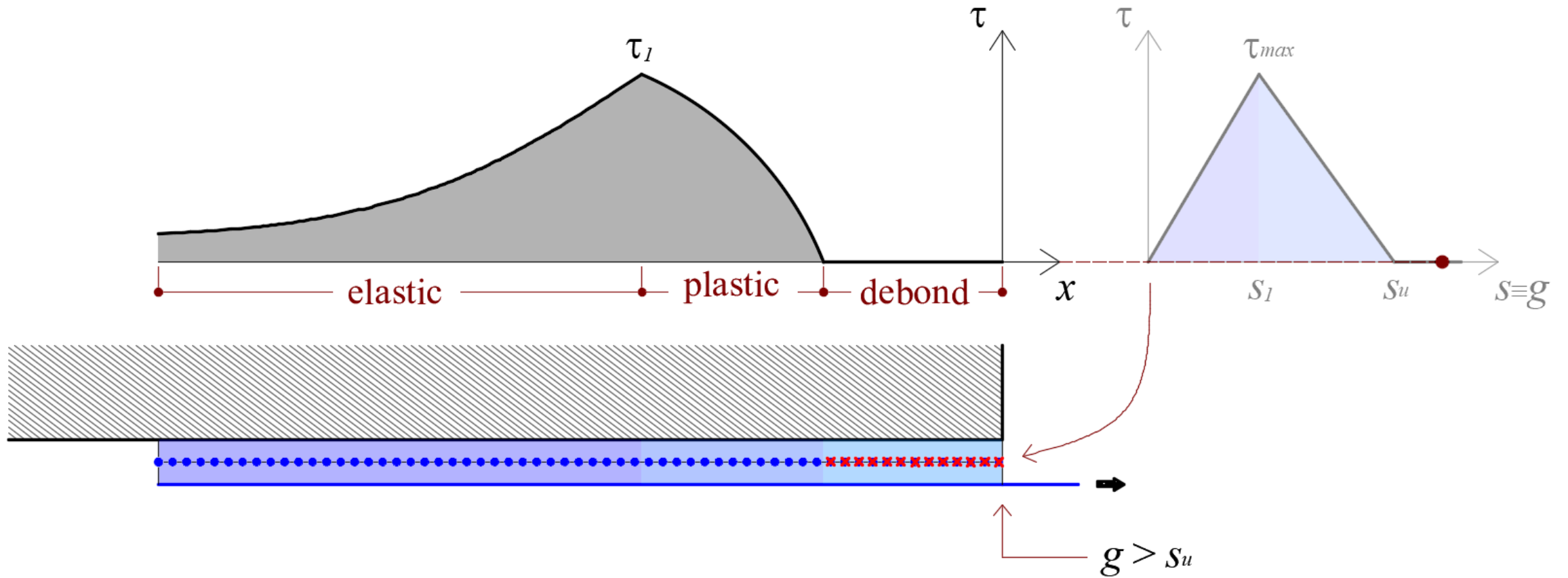
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Analysis of bond: cohesive/fracture-mechanics perspective

