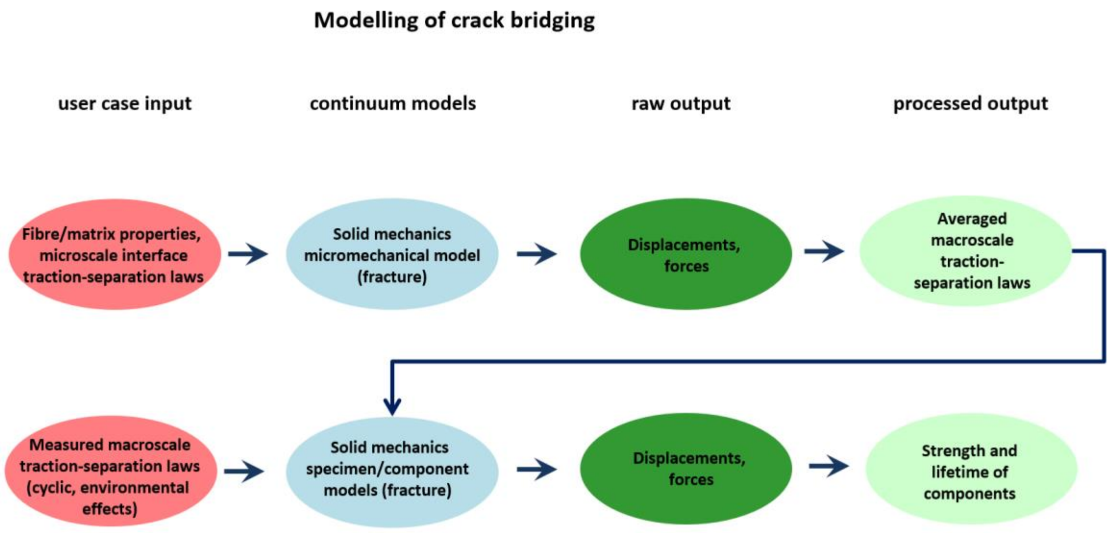
MODA
Crack bridging during delamination of composites
Simulated in project DACOMAT

	OVERVIEW of the SIMULATION		
1	**USER CASE**		Delamination crack growth in composite laminates with focus on damage tolerance enhancement due to crack bridging by fibres, with the aim of identifying the fracture mechanical properties of the fibre/matrix interface that maximize the macroscopic damage tolerance of composite structures. Components made of more damage tolerant materials can then sustain larger damages without failing. The composites structures are taken to be processed by pre-pregs (autoclave) or by vacuum infusion and to be subjected to varying mechanical loads, varying temperature and humidity during in service, based on metrological data from the North Sea for a wind turbine rotor blade and on-shore data for a bridge in Spain.
2	**CHAIN OF MODELS**	**MODEL 1**	Continuum micro-mechanics, solid mechanics (conservation laws) (PE), and cohesive laws representing fibre/matrix debond process (MR).
		MODEL 2	Continuum macro-mechanics, solid mechanics (conservation laws) (PE) and cohesive laws representing delamination of laminas (MR).
		DATA-BASED MODEL	no
3	**PUBLICATION PEER-REVIEWING THE DATA**		n/a
4	**ACCESS CONDITIONS**		Commercial solver software: Finite element methods (explicit and implicit), ex. Abaqus and LS Dyna, that can take in user-defined cohesive laws (traction-separation laws). User-defined cohesive elements will be available from the DACOMAT project home page: https://www.sintef.no/projectweb/Dacomat
5	**WORKFLOW AND ITS RATIONALE**		The dimension of fibres is in the order of several microns, the length of active process zone is in the order of several cm and the dimensions of specimens and components is in the order of metres. The time-scale for fracture and cyclic crack growth goes from the order of seconds to year (the latter for cyclic crack growth). Continuum mechanics (solid mechanics) applied to different scales using different MRs is well suited for problems at these length and time scales.

Workflow picture



MODA

Physics-based Model

MODEL 1: Fibre bridging on the microscale

1	ASPECT OF THE USER CASE/SYSTEM TO BE SIMULATED	
1.1	ASPECT OF THE USER CASE TO BE SIMULATED	Simulation of crack bridging on the level of the individual fibres (microscale) bridging a crack. Different fibre/matrix treatment, different temperature and humidity give different fibre bridging.
1.2	MATERIAL	Solid materials, linear elastic fibres (glass and carbon fibres), elastic-plastic matrix materials (polymer matrix). Cohesive zone (fracture process zone of the fibre/matrix interface/coating).
1.3	GEOMETRY	Long, aligned fibres with a circular cross section. A single fibre is bridging two crack faces. The thickness of the fibre coating is very thin in comparison with the fibre diameter.
1.4	TIME LAPSE	Quasi-static monotonic increase in local crack openings (in the order of tenths of a second to minutes).
1.5	MANUFACTURING PROCESS OR IN-SERVICE CONDITIONS	Ambient temperature and pressure.
1.6	PUBLICATION ON THIS DATA	

2	Generic Physics Of The Model Equation		
2.0	Model type and name	Solid mechanics (micro-mechanics)	
2.1	Model entity	Finite volumes	
2.2	Model Physics/ Chemistry equation PE	**Equation**	Static equilibrium, conservation of energy, minimization of potential energy.
		Physical quantities	Stiffness, displacements, external force.
2.3	Materials relations	**Relation**	Hooke's law (fibre), non-linear stress-strain law (matrix), traction-separation laws (fibre/matrix interface). Different traction-separation laws are used to represent the fibre/matrix debonding (fracture process) of various types of coatings / surface treatments and under various environmental conditions (temperature and humidity).
		Physical quantities/ descriptors for each MR	Young's moduli, Poisson's ratio, shear modulus (fibre), non-linear stress strain law (matrix), traction-separation law parameters as peak stress, critical separation and work of separation (fibre/matrix interface).
2.4	Simulated input	none	

3	Solver and Computational translation of the specifications		
3.1	Numerical Solver	Implicit and/or explicit finite element methods. Incremental solutions, since the stress-strain laws of the matrix material and the cohesive laws are non-linear.	
3.2	Software tool	Abaqus and/or LS Dyna.	
3.3	Time step	Incremental solutions. Maybe thousands of increments. For explicit solutions the time step should be less that element size divided by speed of fastest wave.	
3.4	Computational Representation	Physics Equation, Material Relations, Material	
3.5	Computational boundary conditions	As we do not need to simulate a long crack with many bridging fibres, we restrict the application domain to unit cells with a single fibre. The displacements of the boundaries of the unit cells will be prescribed to mimic normal - (Mode I), tangential - (Mode II) and mixed mode opening displacements.	
3.6	additional Solver Parameters	Mass scaling for explicit finite element simulations	

4	**POST PROCESSING**	
4.1	**THE PROCESSED OUTPUT**	Output: Resulting forces at the external surfaces of the unit cells are averaged to a uniform "effective" normal and shear tractions (average stresses) that, given as a function of the normal and tangential displacements, are to be used as macroscale cohesive laws for simulation of specimens and structures.
4.2	**METHODOLOGIES**	
4.3	**MARGIN OF ERROR**	

MODA

Physics-based Model

MODEL 2: Crack bridging on the macroscale

1	**ASPECT OF THE USER CASE/SYSTEM TO BE SIMULATED**	
1.1	**ASPECT OF THE USER CASE TO BE SIMULATED**	Simulation of crack bridging on the level of laminates.
1.2	**MATERIAL**	Linear elastic orthotropic materials representing layers (laminas). Interfaces (with crack bridging by many fibres during fracture) between different laminas in the laminates.
1.3	**GEOMETRY**	Plane layers (laminates). Test specimens (e.g. ply-drop for wind turbine rotor blade) and sub-component (a part from a composite bridge).
1.4	**TIME LAPSE**	In the order of seconds to minutes (quasi-static loadings).
1.5	**MANUFACTURING PROCESS OR IN-SERVICE CONDITIONS**	The in-service conditions (cyclically varying mechanical loads, varying temperature and humidity) will be based on metrological data from the North Sea for a wind turbine rotor blade (representing an off-shore wind turbine park) and on-shore data for a bridge in Spain. The external loads are increased monotonic or cyclically in the order of seconds to minutes.
1.6	**PUBLICATION ON THIS DATA**	n/a

2	**GENERIC PHYSICS OF THE MODEL EQUATION**	
2.0	**MODEL TYPE**	

	and name	Solid mechanics (macro-mechanics)	
2.1	Model entity	Finite volumes	
2.2	Model Physics/ Chemistry equation PE	**Equation**	Static equilibrium, conservation of energy, minimization of potential energy.
		Physical quantities	Stiffness, displacements, external force.
2.3	Materials relations	**Relation**	Orthotropic elastic properties (laminas) Hooke's law, macroscale traction-separation laws (fibre bridging zone), using macroscale cohesive laws, from micromechanical models or determined experimentally, to represent bridging by many fibres.
		Physical quantities/ descriptors for each MR	Young's moduli, Poisson's ratio, shear modulus (orthotropic laminas), traction-separation laws parameters (fibre bridging zone). Different traction-separation law parameters are used to represent the crack bridging of various types of coatings / surface treatments under various environmental conditions (temperature and humidity).
2.4	Simulated input	Macroscale cohesive laws representing bridging by many fibres are obtained from output from post-processing of the results of Model 1. Prescribed displacements and applied loads applied to the sub-models are determined from larger models of the entire components.	

3	Solver and Computational Translation of the Specifications		
3.1	Numerical Solver	Implicit and/or explicit finite element methods. Incremental solutions, since the cohesive laws are non-linear.	
3.2	Software tool	Abaqus and/or LS Dyna.	
3.3	Time step	Incremental solutions. Maybe thousands of increments. For explicit solutions the time step should be less that element size divided by speed of fastest wave.	
3.4	Computational Representation	Physics Equation, Material Relations, Material	
3.5	Computational boundary conditions		
3.6	additional Solver Parameters	Mass scaling for explicit finite element simulations	

4	POST PROCESSING
4.1	The processed output	Output: Resulting forces and displacements will be used calculate relationship between fracture process zone, crack length and overall applied load - data that can be compared with experimental measurements.
4.2	Methodologies	
4.3	Margin Of Error	