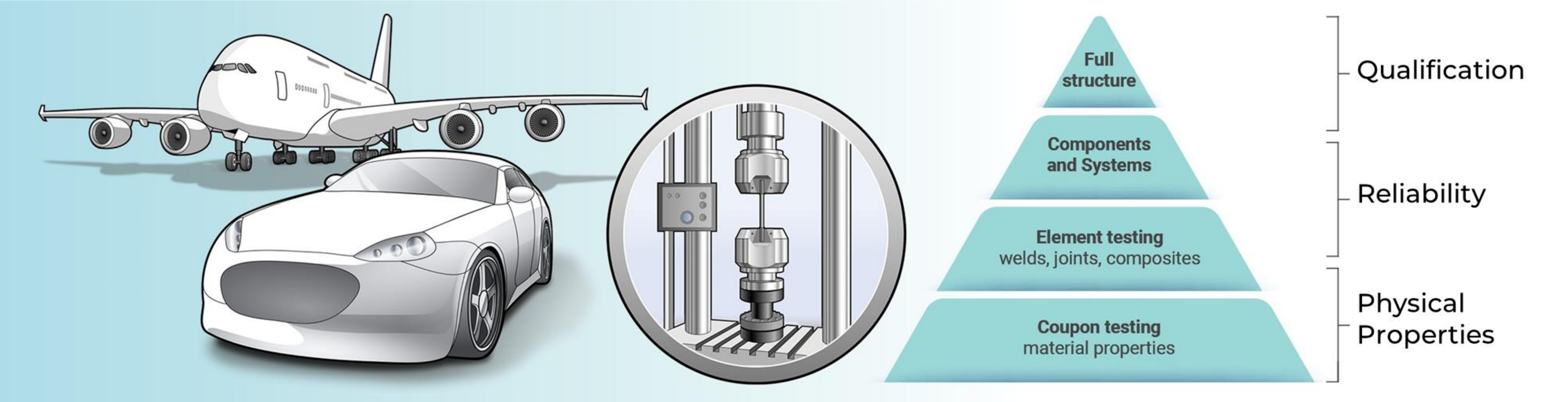
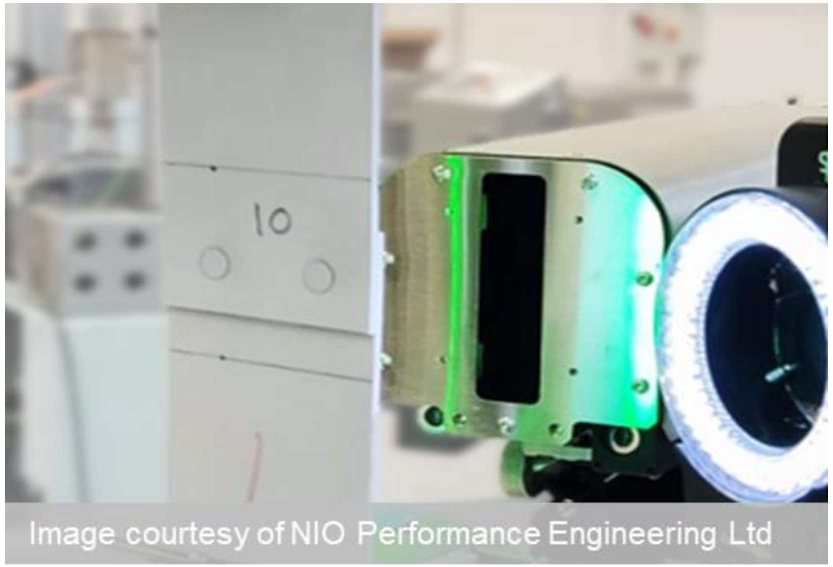


2023 HBK Technology Days

21 November 2023



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- **A practical approach for the fatigue life estimation of adhesive and hybrid joints**

Dr. Cristian Bagni,
Technologist of Fatigue and Fracture, HBK

A practical approach for the fatigue life estimation of adhesive and hybrid joints

Abstract

- The need for more environmentally sustainable ways of transportation and for a reduction in emissions and fuel consumption make lightweight structures essential. The use of adhesive and/or hybrid joints represents one way to reduce the weight of components and it is becoming increasingly popular in the transportation industry. To optimise the design of adhesive and hybrid joints and minimise the risk of in-service fatigue failures, the transportation industry needs efficient, robust, and easy-to-use approaches for the modelling and fatigue life estimation of such joints.

- This work presents a practical approach, easily adoptable by companies in the transportation industry, for estimating the fatigue life of adhesive and hybrid joints. The proposed approach includes Finite Element (FE) modelling guidelines to recover the needed stresses, that provide FE models computationally not too onerous, reasonably mesh insensitive and that do not require congruent meshes, with limited changes to the typical FE modelling strategies currently used. The fatigue life estimation is then carried out using standard SN-based nCode DesignLife analysis engines, with the stresses recovered from the FE model and bespoke SN curves obtained through testing used as inputs.

A practical approach for the fatigue life estimation of adhesive and hybrid joints

- About the presenter, Dr. Cristian Bagni, Technologist of Fatigue and Fracture, HBK
  - Dr. Cristian Bagni holds a Master's Degree in Civil and Structural Engineering (Unversità degli Studi di Parma, Italy) and a PhD in Structural Engineering (The University of Sheffield) developing a new Finite Element methodology to assess the static and fatigue behaviour of notched and cracked components.
  - He has co-authored papers on Computational Mechanics and Fatigue, and he has reviewed papers for International Journals including 'Fatigue & Fracture of Engineering Materials & Structures' (FFEMS), and 'Theoretical and Applied Fracture Mechanics'.
  - After working for several years at the University of Sheffield's Advanced Manufacturing Research Centre (AMRC) on high profile aerospace research projects, he also gained extensive experience on advanced manufacturing processes.
  - Cristian joined HBK in July 2020 as Technologist for Fatigue and Fracture, and amongst his activities he leads research on the fatigue behaviour of joints. He also supports the Advanced Materials Characterisation & Testing (AMCT) facility with the analysis and post-processing of fatigue test results, and consequent characterisation of both joints and parent materials.

A practical approach for the fatigue life estimation of adhesive and hybrid joints

HBK TECHNOLOGY DAYS 2023

Dr Cristian Bagni

Technologist – Fatigue & Fracture

Agenda

1. Introduction
2. Approach overview
3. Finite element modelling
4. Fatigue analysis using nCode DesignLife
5. Fatigue parameters derivation through physical testing
6. Conclusions

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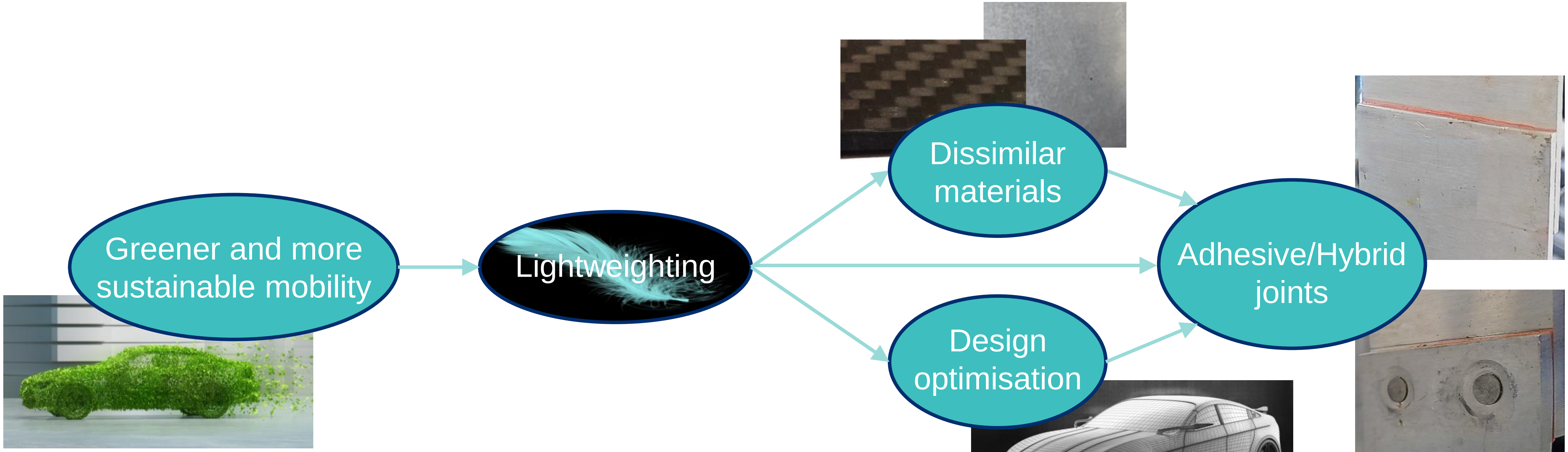
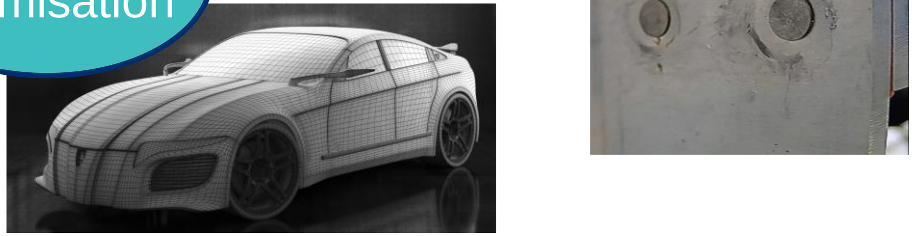
Introduction

- The increasing need and focus on greener ways of transportation has made lighter structures necessary





- Main advantages of adhesives:
  - Reduced weight
  - Ability to join dissimilar materials
  - Equal or improved structural rigidity and fatigue performance

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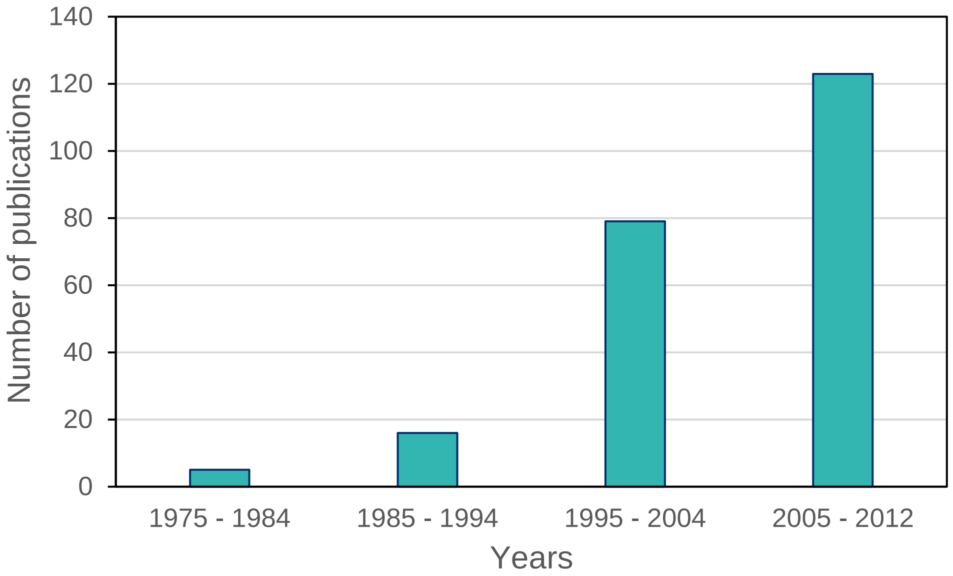
Introduction

- Increased interest in the use of adhesives in structural joints



Data gathered from Abdel Wahab (2012).
These data are not exhaustive, but for illustration purposes only.

- New generation adhesives generally show load-life data with **smaller scatter** and **steeper slopes** compared to early generation adhesives.

- Need for an efficient, robust, and easy to use approach for the modelling and fatigue life prediction of adhesive and hybrid joints

Abdel Wahab, M.M., 2012. Fatigue in Adhesively Bonded Joints: A Review. ISRN Materials Science 2012, 1–25.

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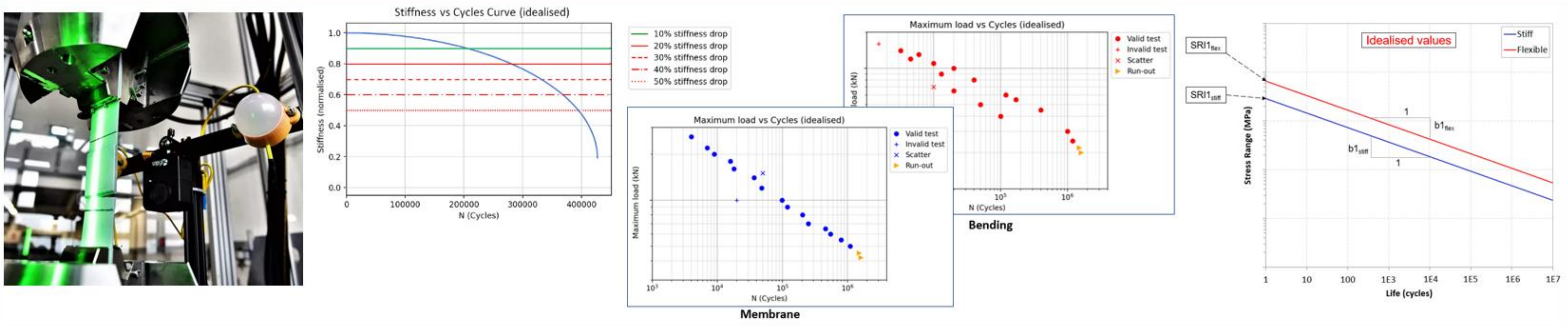
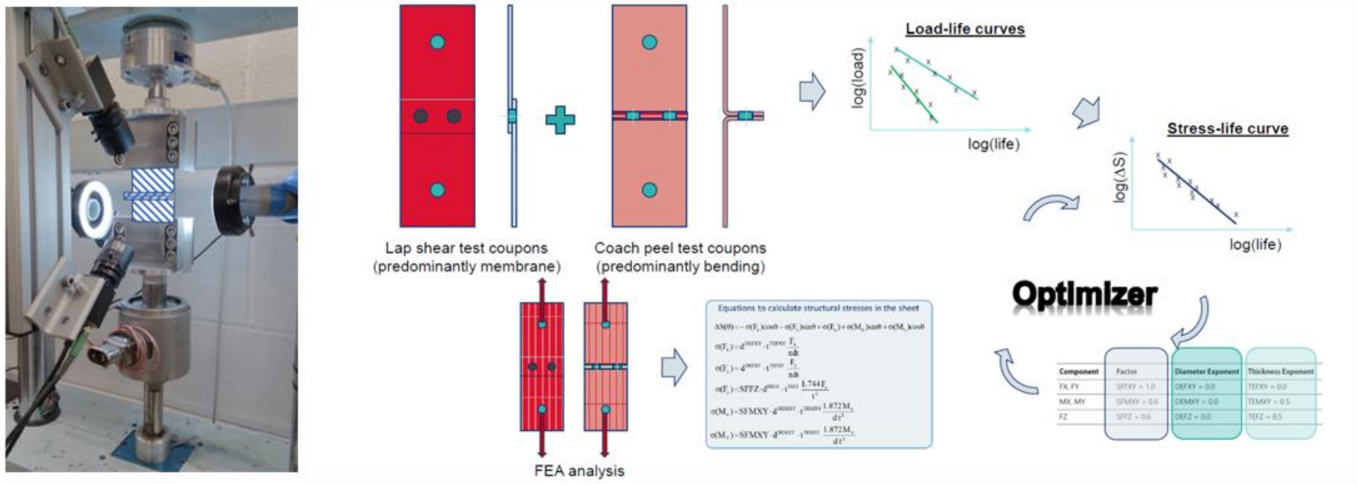
Introduction

- The proposed approach builds upon experience developed in modelling, fatigue testing and characterization of welded joints

Seam Welds



Spot Welds



- HBK Technology Days 2021 – Day 3 (Session 5) – #4: Fatigue characterisation of welded joints

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Approach overview

Main requirements:

- Limited changes to the typical FE modelling strategies currently used
- FE models computationally not too onerous
- Good level of mesh insensitivity
- No need for congruent meshes
- Finite fatigue life estimations

Additional considerations:

- Adhesives stronger under shear loads than under peel loads → Peel (or opening) stress used to estimate the fatigue life
- Fatigue life predictions using nCode DesignLife standard SN Analysis Engine

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Approach overview

Analysis 1

- All the load is carried by the adhesive until complete failure of the adhesive
- Only the adhesive is modelled
- The mechanical fasteners can be modelled to try to replicate their effects on the fatigue performance of the adhesive
- The fatigue life of the joint is evaluated using the standard "SN Analysis Engine" available in nCode DesignLife.

Analysis 2

- The adhesive is considered failed
- All the load is carried by the mechanical fasteners
- The joint is considered as a standard spot welded/riveted joint
- Only the mechanical fasteners are modelled
- The fatigue life of the joint is evaluated using the standard "Spot Weld Analysis Engine" available in nCode DesignLife.

Hybrid joints – 1st method

Hybrid joints – 2nd method

Adhesive joints

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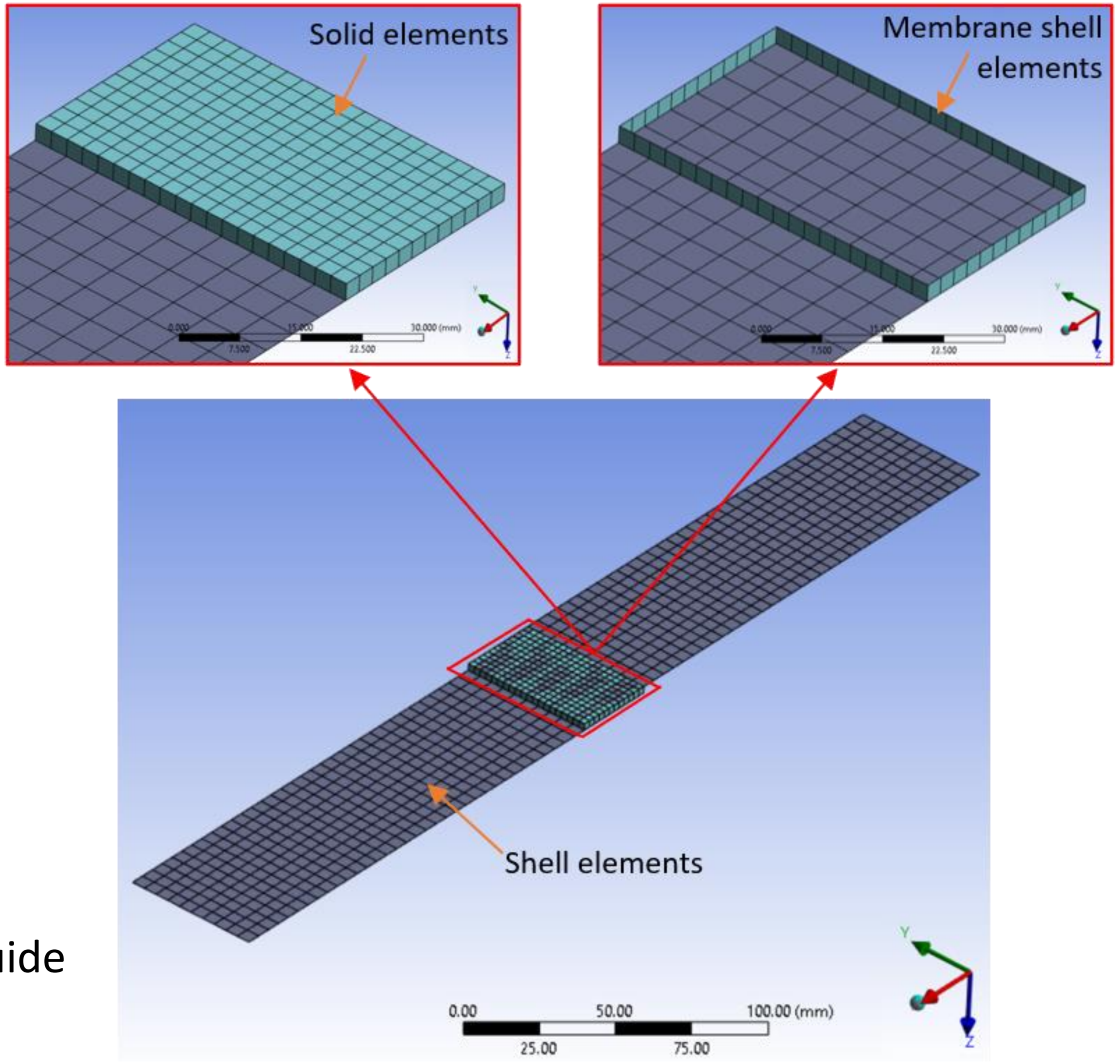
Finite element modelling guidelines – Analysis 1

- Adherends modelled using mid-surface linear shell elements
- Adhesive modelled using linear solid elements
- Exposed faces of the solid elements (adhesive) wrapped with linear shell elements with membrane behaviour only
- Solid and shell elements connected using ‘bonded contacts’ (or similar tools)
- Peel stresses recovered at the centroid of the membrane shell elements
- Optional: the mechanical fasteners can be modelled to try to replicate their effects on the fatigue performance of the adhesive
  - Beam elements
  - Area contact method (ACM)
  - Penta solid elements
  - …

→ nCode DesignLife Theory Guide



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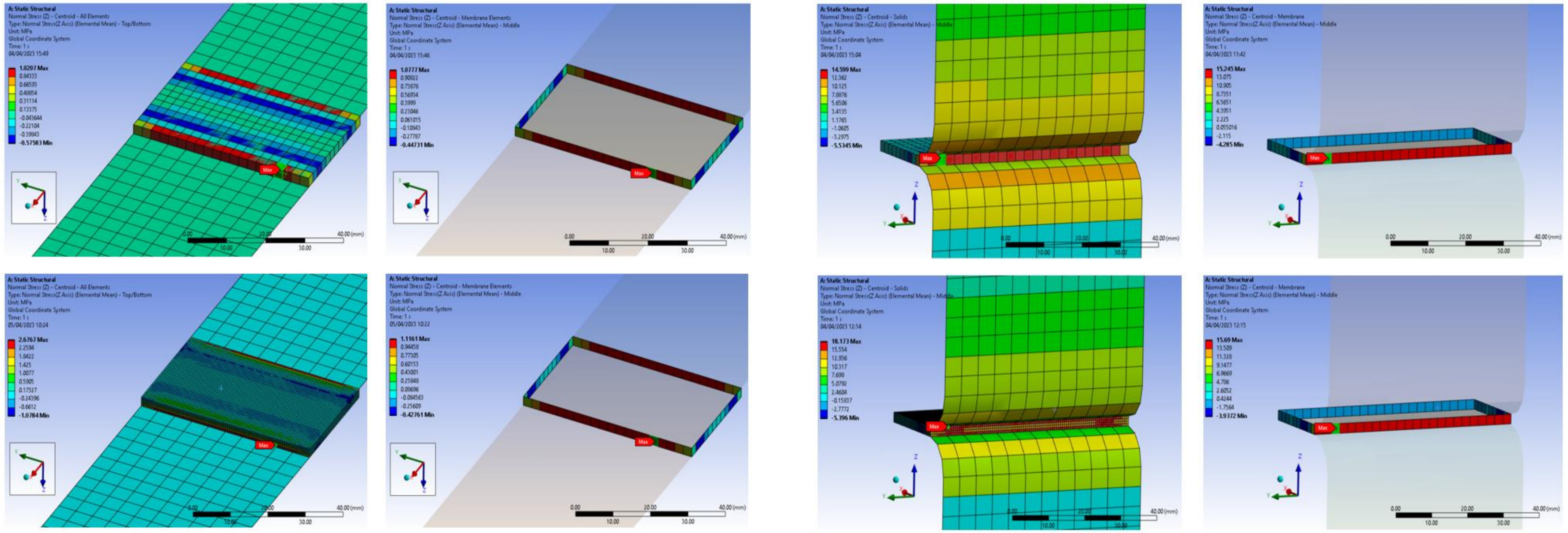
Finite element modelling – Convergence study (Analysis 1)

- Initial mesh:
  - adhesive modelled as one single layer of solid elements
  - membrane shell elements with the same size as the solid elements
- 4 mesh refinements of the solid elements mesh (element size halved at each refinement), with size of the membrane shell elements kept constant.
- Maximum peel stress at the centroid of the solid elements and of the membrane shell elements approximately in the same location, regardless of the mesh refinement.



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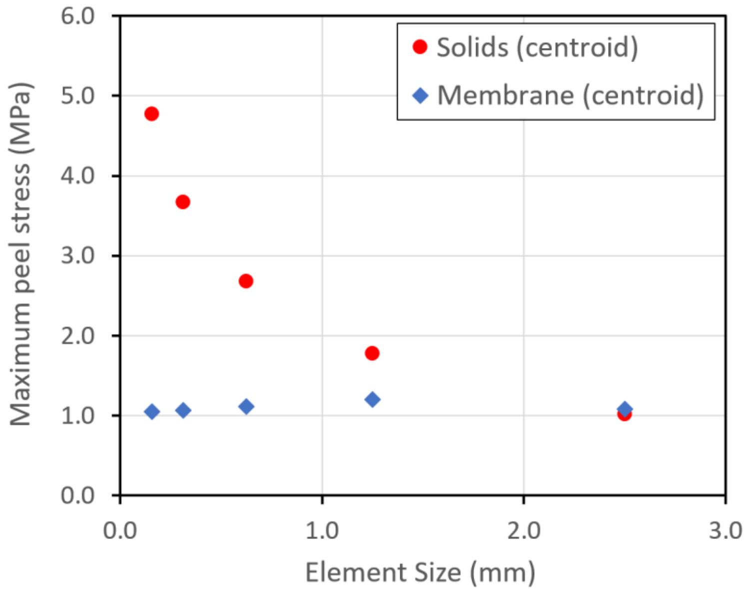
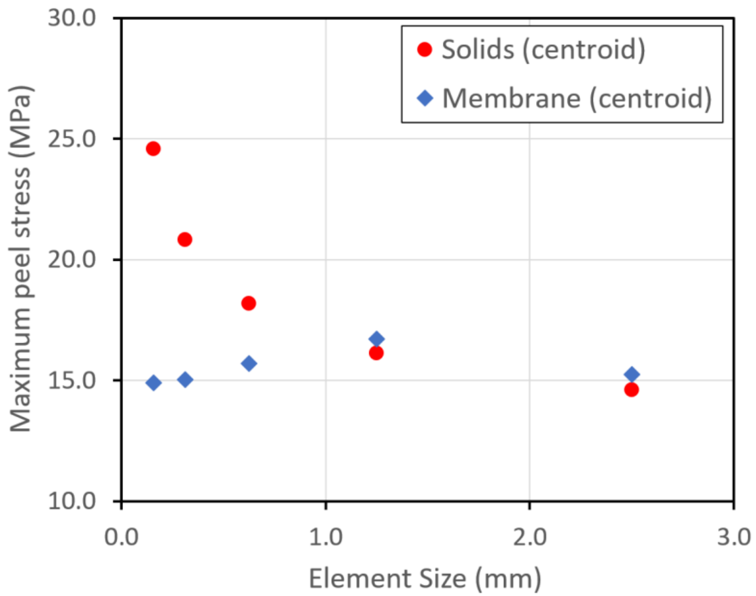
Finite element modelling – Convergence study (Analysis 1)

- Maximum peel stress at the centroid of the solid elements increased at each mesh refinement.
- Maximum peel stress at the centroid of the membrane shell elements remained reasonably constant.



Lap shear



Coach peel

- Addition of the membrane shell elements on the exposed faces of the solid elements effectively transfers the peel stresses from the solid elements, with the advantage of making the stresses of interest reasonably mesh insensitive.

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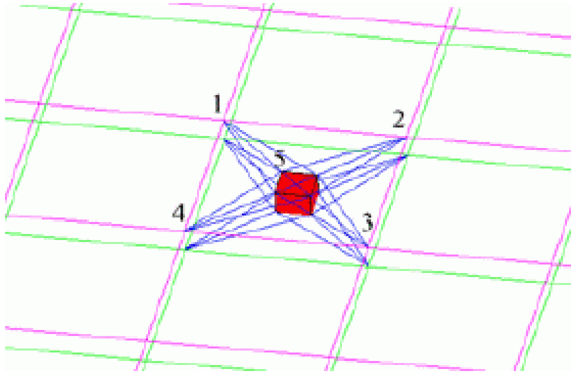
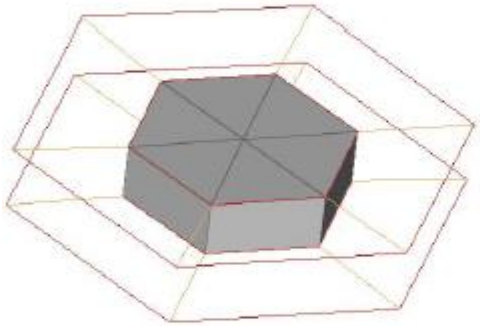
Finite element modelling guidelines – Analysis 2

- Adherends modelled using mid-surface linear shell elements
- Mechanical fasteners can be modelled following the modelling guidelines included in the DesignLife Theory Guide:
  - Beam elements
  - Area contact method (ACM)
  - Penta solid elements



Spot Weld – Area Contact Methods



Spot Weld – PENTA Elements

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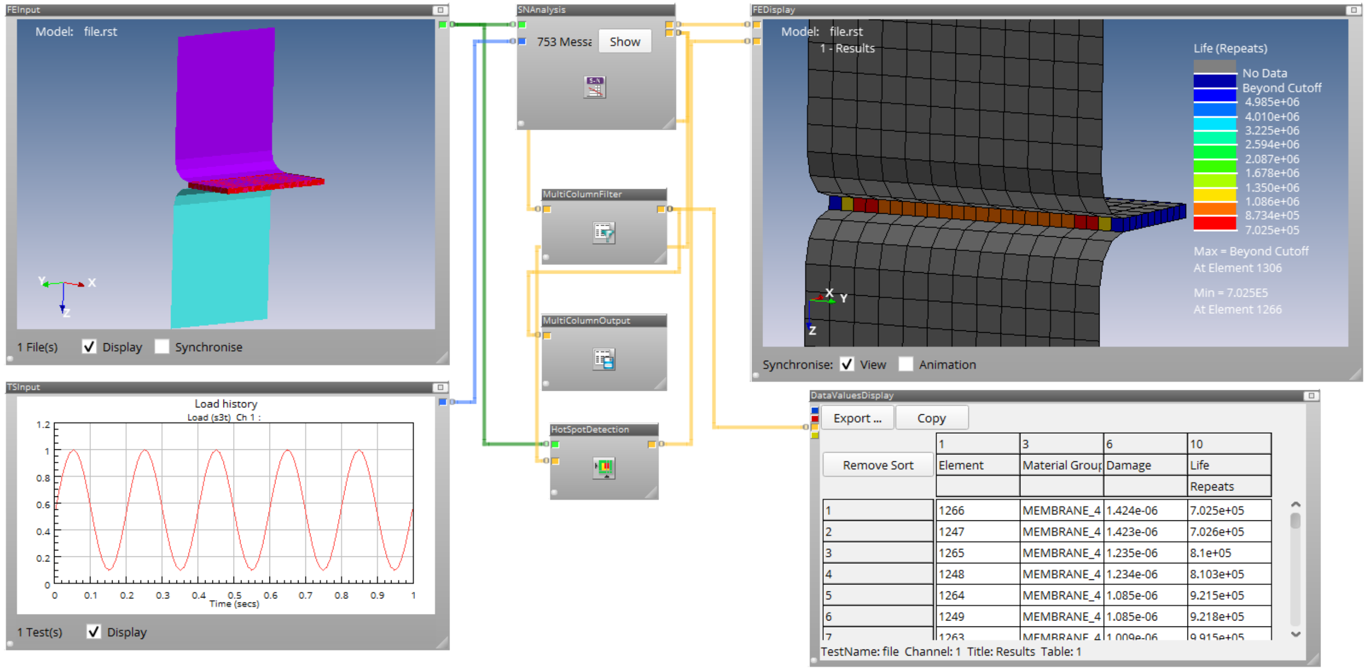
Fatigue analysis using nCode DesignLife (Analysis 1)

- Fatigue life/damage predictions can be performed using the standard nCode DesignLife **SN Analysis Engine**.
- Inputs:
  - Peel stresses at the centroid of the membrane elements from the FE model
  - Load history
  - Materials' properties and **fatigue parameters of the adhesive/hybrid joint** obtained through physical testing



	1	3	6	10
	Element	Material Grou	Damage	Life Repeats
1	1266	MEMBRANE_4	1.424e-06	7.025e+05
2	1247	MEMBRANE_4	1.423e-06	7.026e+05
3	1265	MEMBRANE_4	1.235e-06	8.1e+05
4	1248	MEMBRANE_4	1.234e-06	8.103e+05
5	1264	MEMBRANE_4	1.085e-06	9.215e+05
6	1249	MEMBRANE_4	1.085e-06	9.218e+05
7	1263	MEMBRANE_4	1.009e-06	9.915e+05

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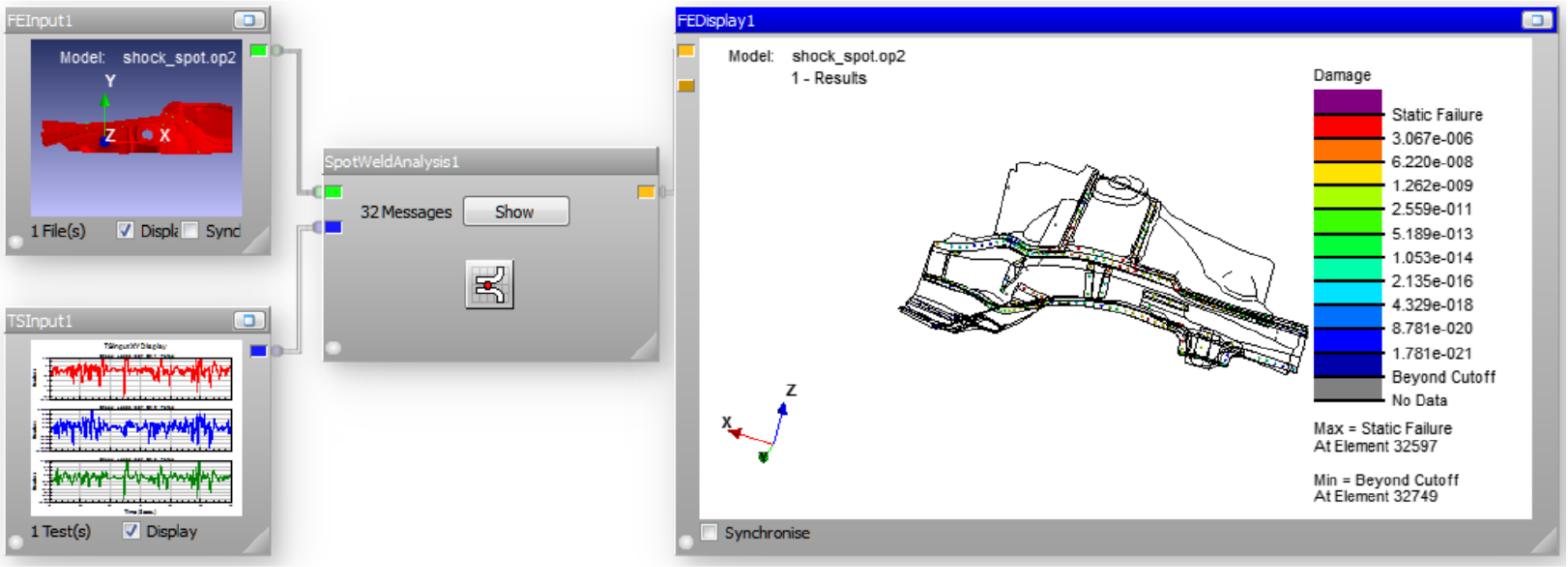
Fatigue analysis using nCode DesignLife (Analysis 2)

- Fatigue life/damage predictions can be performed using the standard nCode DesignLife **Spot Weld Analysis Engine**.
- See more details see the nCode DesignLife Worked Example (3. Fatigue Analysis of a Spot-welded Structure)



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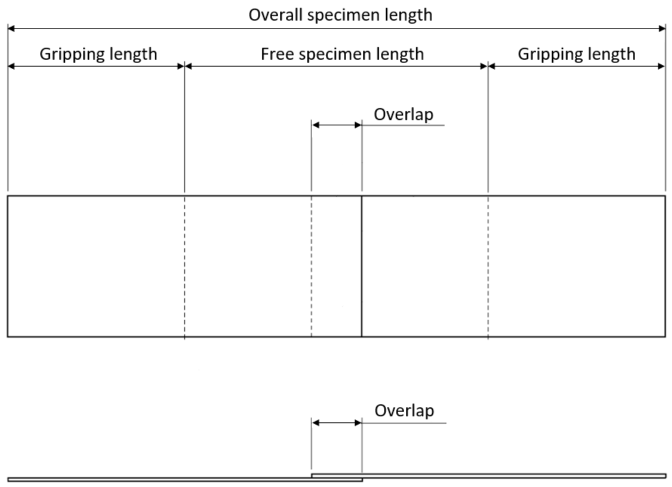
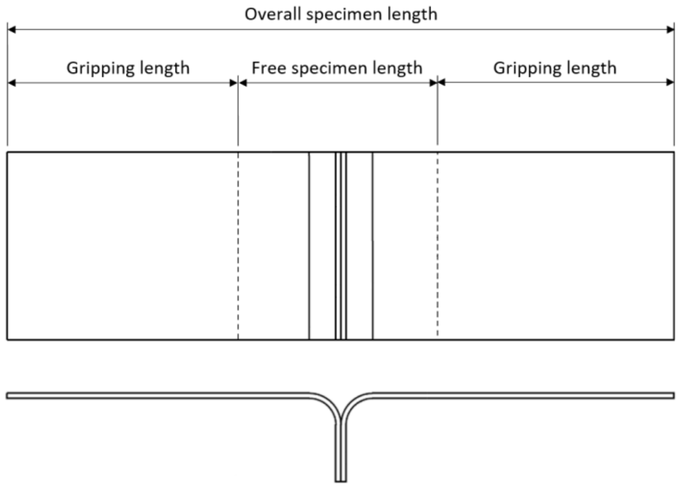
Fatigue parameters derivation through physical testing

- The performance of adhesive joints is strongly influenced by:
  - Material type of adhesive and adherends
  - Thickness of adhesive and adherends
  - Surface preparation of the adherends
  - Presence of adhesive spew, its amount and its shape
  - …
- Recommended to derive bespoke fatigue parameters for the adhesive/hybrid joints through physical testing
- Lap shear and coach peel are the most common specimen geometries used when testing adhesive/hybrid joints.
- When deriving fatigue parameters of adhesive/hybrid joints it is essential to choose the most appropriate failure criterion.



Lap shear



Coach peel

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Fatigue parameters derivation through physical testing – Fatigue tests

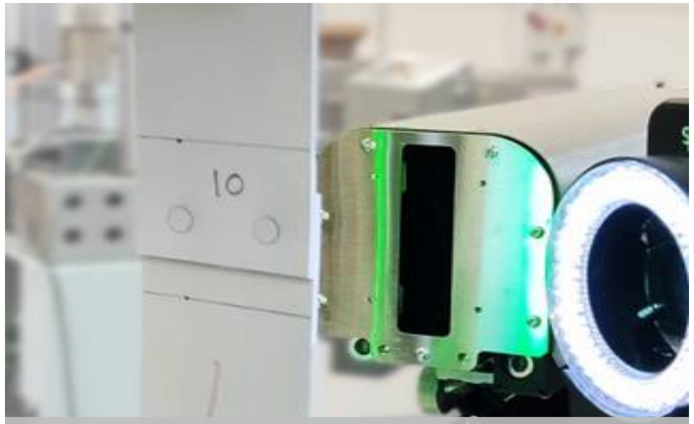
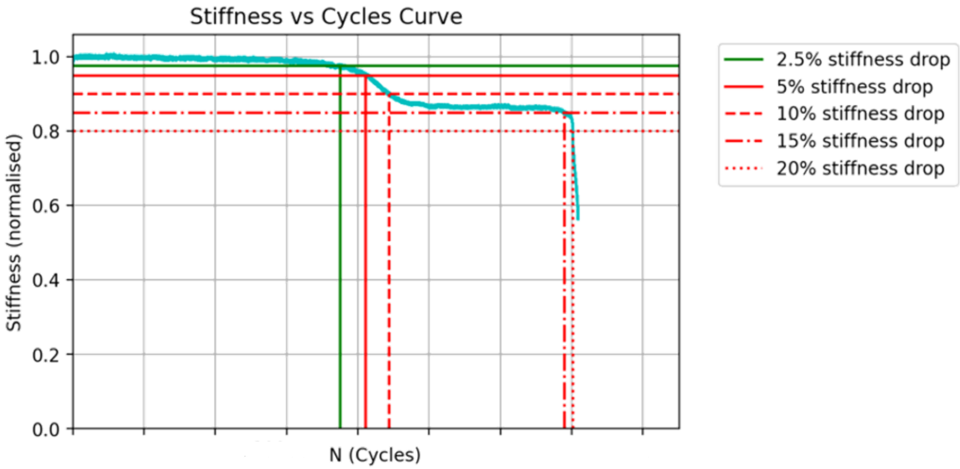


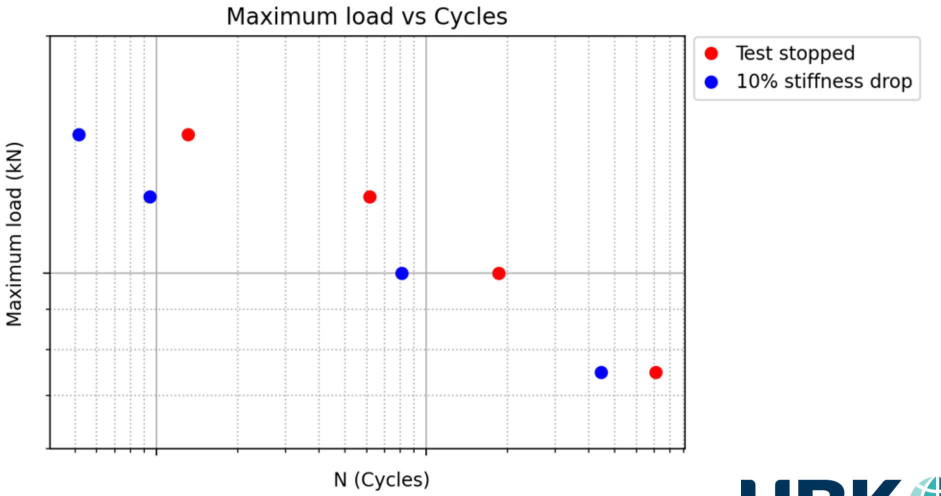
Image courtesy of NIO Performance Engineering Ltd

$$K(N) = \Delta F / \Delta u(N)$$

$$K_n(N) = \frac{K(N)}{K(N_0)} \cdot 100[\%]$$



- Possible failure criteria:
  - Specimen separation
  - Crack initiation
  - Stiffness drop
- The stiffness drop failure criterion is more flexible compared to the other two options, as it allows the definition of failure to be tailored to the needs/requirements of each company and/or application.
- Once the most appropriate failure criterion is chosen, it is possible to determine a series of load-life (LN) datapoints



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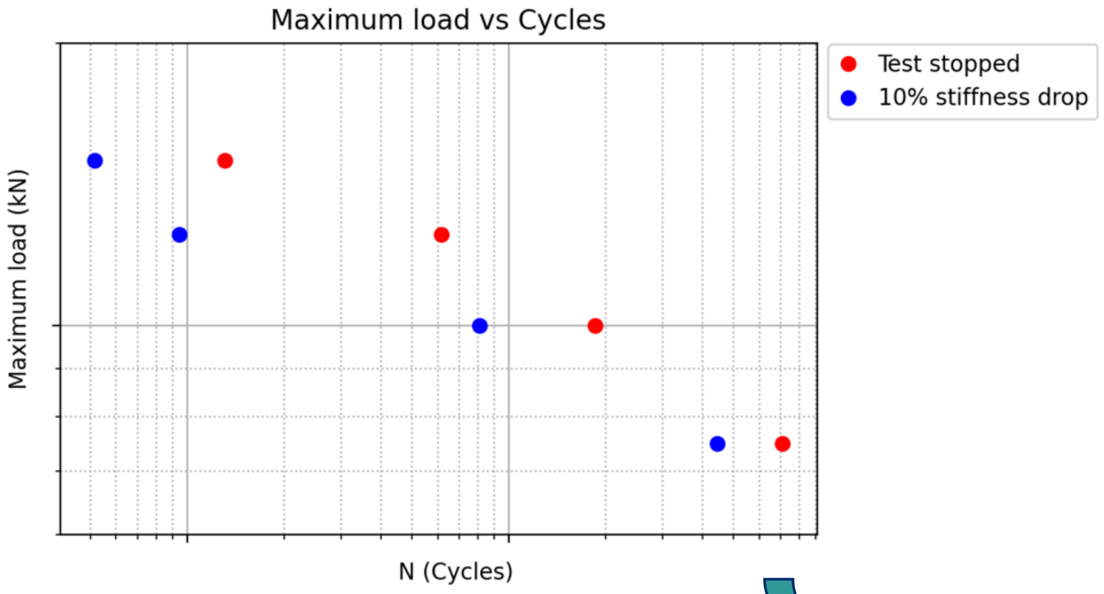
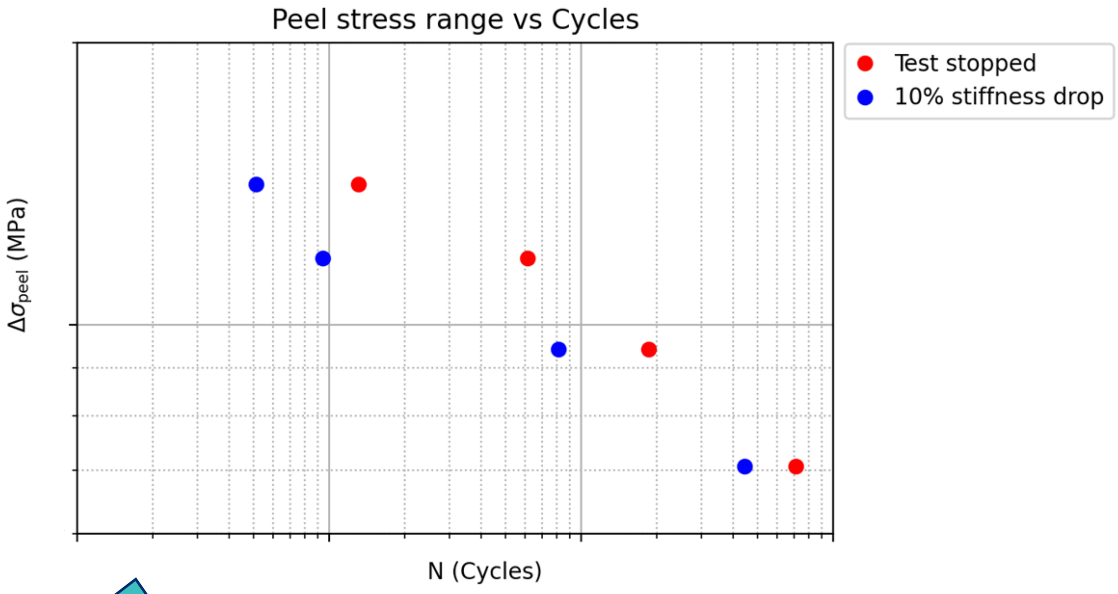
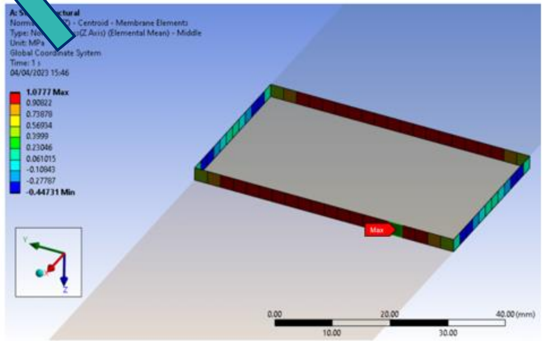
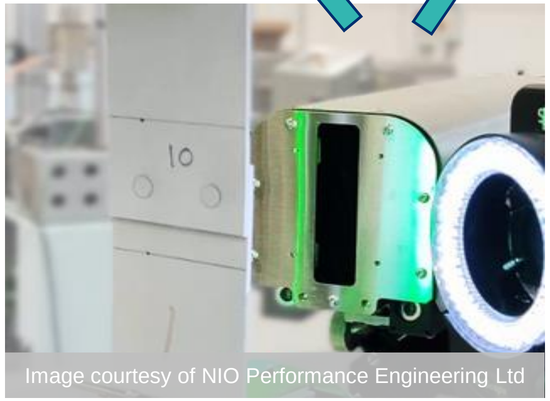
Fatigue parameters derivation through physical testing – Reverse engineering





$$\Delta\sigma_{peel} = \sigma_{peel\_\max\_unit\_load} \cdot \Delta F = \sigma_{peel\_\max\_unit\_load} \cdot F_{max} \cdot (1 - R)$$





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Conclusions

- A practical approach for the fatigue life estimation of adhesive and hybrid joints was presented.
- The proposed approach can be easily adopted by companies in the transportation industry, and it requires relatively limited changes to the typical FE modelling strategies used today, especially in the automotive industry.
- FE modelling guidelines to recover the peel stresses along the bond lines were proposed.
- The FE models obtained following the suggested guidelines are not computationally too onerous, have a good level of mesh insensitivity and do not require congruent meshes.
- A convergence study of the suggested FE modelling strategy showed that, the addition of the membrane shell elements, on the exposed faces of the solid elements, is a valid solution to recover the peel stresses from the solid elements in a reasonably mesh insensitive manner.
- The recovered peel stresses can be used as an input to perform fatigue analyses using the standard nCode DesignLife SN Analysis Engine.

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Conclusions

- The process to derive bespoke fatigue parameters of the adhesive joints through physical testing was also described and illustrated using real test data obtained as part of an extensive testing programme currently underway at HBK's 'Advanced Materials Characterisation & Testing' laboratory, in collaboration with NIO Performance Engineering Ltd.

- A further step would be to apply the proposed approach to full structures, such as vehicles body-in-white for further validation.

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Fatigue Design 2023 (FatDes 2023)

A practical methodology for the fatigue life estimation of adhesive joints

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Abstract

The use of adhesives in structural joints as an alternative to traditional joining techniques, such as welding and rivets, is becoming increasingly popular in the transportation industry, including (but not limited to) automotive and aerospace. This trend is driven especially by the increasing need and focus on greener ways of transportation and the consequent light weighting requirements. Furthermore, adhesives have the significant advantage, over traditional joining techniques, of allowing joining of dissimilar materials, including composites. Therefore, to optimise the design of adhesively bonded structures and reduce the risk of in-service fatigue failures, the transportation industry needs efficient, robust, and easy-to-use approaches for the modelling and fatigue life estimation of adhesively bonded joints.

This work presents a practical methodology for estimating the fatigue life of adhesively bonded joints that can be easily adopted by companies in the transportation industry. The proposed methodology includes Finite Element (FE) modelling guidelines to recover the required stresses along the bond lines, with limited changes to the typical FE modelling strategies currently used, especially in the automotive industry. It is proposed to model the adherends using shell elements and the adhesive layer with solid elements. The exposed edges of the adhesive are then wrapped with membrane shell elements used to extract the peel stresses. The solid elements and the shell elements are connected using 'bonded contacts' (or similar tools, depending on the FE software used). The proposed modelling guidelines provide FE models that are not computationally too onerous, with a good level of mesh insensitivity and that do not require congruent meshes. The peel stresses recovered from the FE model along the bond lines are then used as an input into nCode DesignLife to estimate the fatigue life of the bonded joints in the analysed structure. The fatigue life estimation is carried out using the standard nCode DesignLife SN analysis engine and bespoke SN curves obtained through testing of adhesively bonded specimens, representative of the joints in the production parts.

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Fatigue Design 2023 (FatDes 2023)

A pragmatic approach for the fatigue life estimation of hybrid joints

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[b]NIO Performance Engineering Ltd, Building 6 Begbroke Science Park, Woodstock Road, Begbroke Hill, OX5 1PF, United Kingdom

Abstract

The need for more environmentally sustainable ways of transportation and for a reduction in emissions and fuel consumption make lightweight structures essential. Together with the use of lightweight materials and design optimisation, the use of hybrid joints represents one way to reduce the weight of components and it is becoming increasingly popular in the transportation industry. The name 'hybrid joint' refers to a connection where adhesive bonding is used in conjunction with traditional joining techniques, such as spot welds and rivets with the aim of combining and exploiting the advantages of the individual joining techniques. To optimise the design of hybrid joints and minimise the risk of in-service fatigue failures, the transportation industry needs efficient, robust, and easy-to-use approaches for the modelling and fatigue life estimation of hybrid joints.

This work presents two practical methodologies for estimating the fatigue life of hybrid joints that can be easily adopted by companies in the transportation industry. The first methodology neglects the life given by the mechanical joints after failure of the adhesive (the joint is considered failed when the adhesive fails), while the second methodology considers the life of both the adhesive and the mechanical joints. In the first methodology, just one configuration would need to be analysed ('hybrid' joint or 'purely bonded' joint, if this simplification is considered reasonable). In the second methodology, instead, the analysis of two configurations would be required (the previous configuration followed by a configuration where only the mechanical fasteners are considered). The second methodology would produce more realistic fatigue life estimations compared to the first methodology, but it would be more onerous both in terms of modelling and computationally. For both methodologies, FE modelling guidelines to recover the required stresses are suggested. These guidelines require limited changes to the typical FE modelling strategies currently used, especially in the automotive industry. Furthermore, the proposed modelling guidelines provide FE models that are not computationally too onerous, reasonably mesh insensitive and that do not require congruent meshes. The relevant stresses recovered from the FE model are then used as an input into nCode DesignLife to estimate the fatigue life of the hybrid joints in the analysed structure. The fatigue life estimation is carried out using standard Stress-Life (SN) based nCode DesignLife analysis engines and bespoke SN curves obtained through testing of hybrid joint specimens, representative of the joints in the production parts.

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Bagni C., et al. "**A practical methodology for the fatigue life estimation of adhesive joints**". Structural Integrity Procedia, Elsevier, 2023.

Bagni C., et al. "**A pragmatic approach for the fatigue life estimation of hybrid joints**". Structural Integrity Procedia, Elsevier, 2023.

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Thank You

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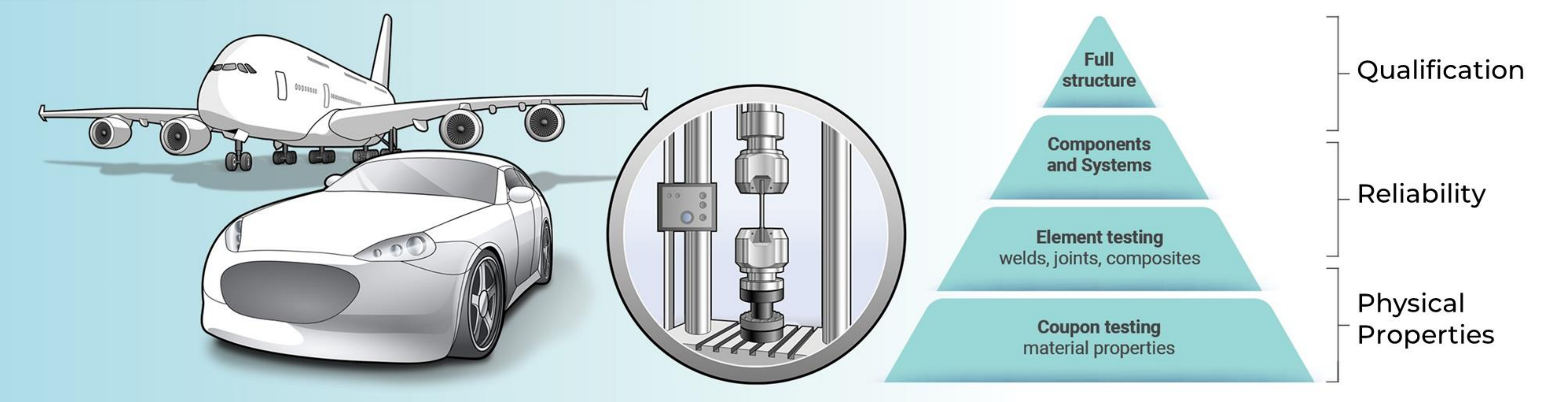

2023 HBK Technology Days

21 November 2023

Image courtesy of NIO Performance Engineering Ltd

- **A practical approach for the fatigue life estimation of adhesive and hybrid joints**

Dr. Cristian Bagni,
Technologist of Fatigue and Fracture, HBK