

# Mixed-Mode I+II Fracture Characterization Of Bonded Joints Using A Multi-Mode Apparatus

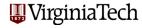
Caracterización de la fractura de juntas adhesivas en modo mixto I+II utilizando un aparato para mezcla de modos.

F.J.P. Chaves | L.F.M. da Silva | M.F.M. de Moura | D. Dillard









# motivation

motivación







predecir la tenacidad de la estructura

joint mechanical behavior



comportamiento mecánico de la unión

strain energy release rate in mode I, mode II and mixed-mode I+ II



tasa de liberación de energía de fractura en modo I, modo II y modo mixto (I+II)

esquema

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problem
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problema problem definition definición del problema problem components componentes del problema

data collection recopilación de datos data analysis

análisis de los datos creativity creatividad

> materials & technology materiales y tecnología experimenting

experimentar model

modelo

verification

verificación

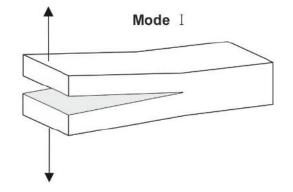
technical drawing

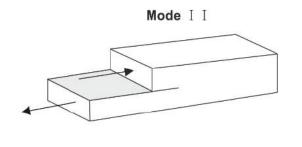
dibujo técnico

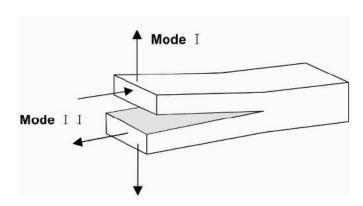
solution solución

# problem definition

# definición del problema







determination of the strain energy release rate in mode I, mode II and mixed mode I + II

determinar la tasa de liberación de energía de fractura en modo I, modo II y modo mixto I+II

Test name	Test scheme	Global Mixity, Ψ (Degree)
Asymmetric Double Cantilever Beam (ADCB)		≈ 0 - 34°
Single Leg Bending (SLB)	<b>V</b>	≈ 41°
Crack Lap Shear (CLS)	<b>4</b>	≈ 49°
Asymmetric Tapered Double Cantilever Beam (ATDCB)	<b>♦ •</b> • • • • • • • • • • • • • • • • •	≈ 20°
Mixed Mode Bending (MMB)		$\Psi$ = $f(c)$
Spelt Loading Jig (SPELT)	F, δ  S <sub>2</sub> S <sub>1</sub> L <sub>1</sub> (2L-L <sub>1</sub> )  α  α  οσοροσοσοσοσοσοσοσοσοσοσοσοσοσοσοσοσοσ	$\Psi = f(S_1, S_2, S_3, S_4)$

# problem components

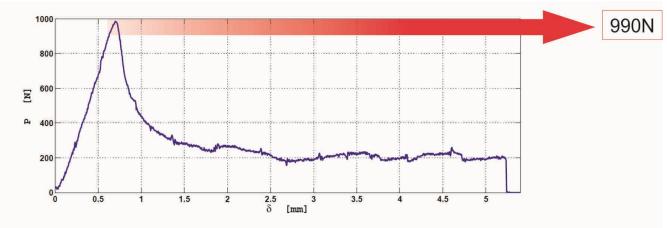
componentes del problema

$$\psi = \arctan\left(\sqrt{G_{\rm II}/G_{\rm I}}\right)$$

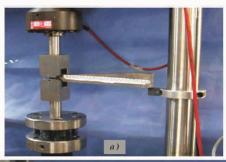
# data analysis

# recopilación de datos

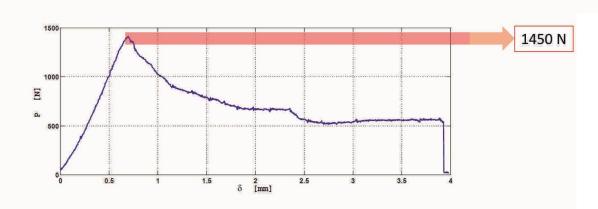




ADCB (P-δ) Load Displacement curve





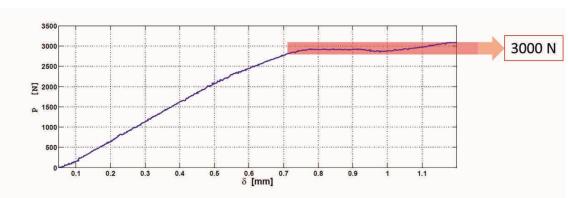


ATDCB (P-δ) Load Displacement curve

recopilación de datos

data analysis

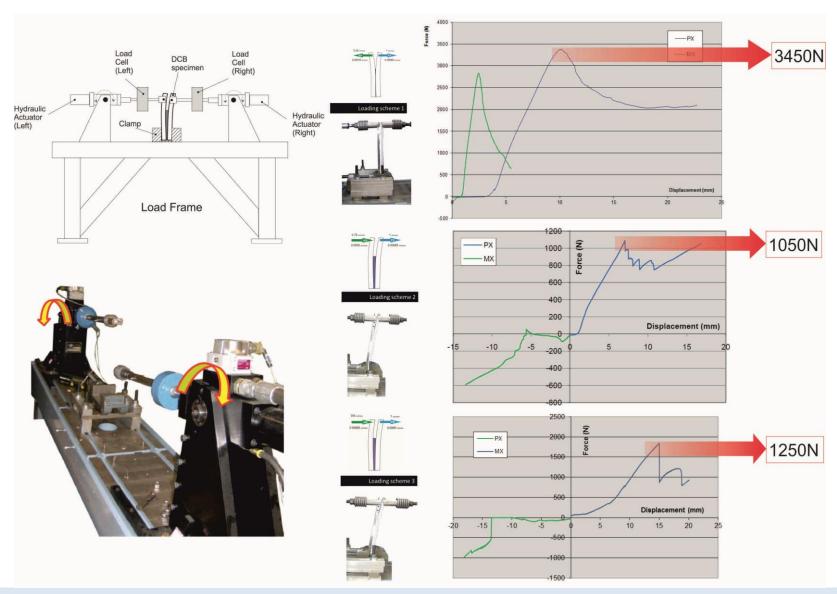




SLB (P- $\delta$ ) Load Displacement curve

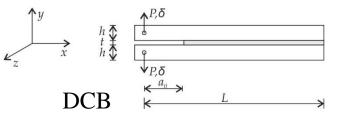
# data analysis

# recopilación de datos

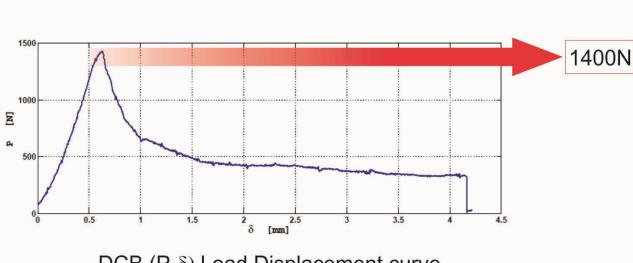


análisis de los datos

recopilación de datos

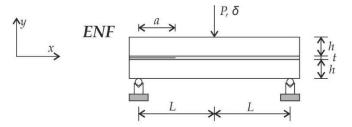


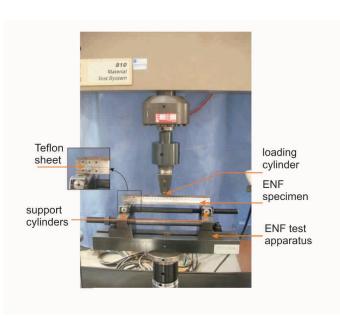


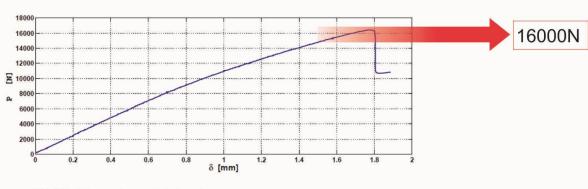


# recopilación de datos

# data analysis



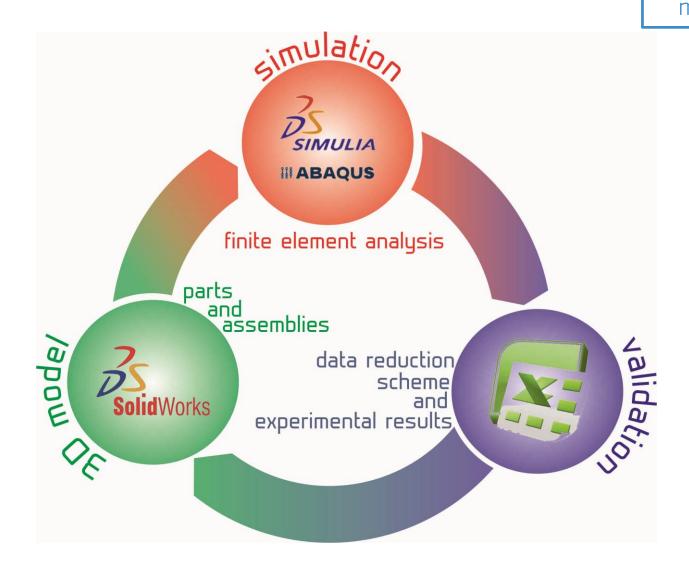




ENF (P-δ) Load Displacement curve

## materials and technology

materiales y tecnología



model

modelo

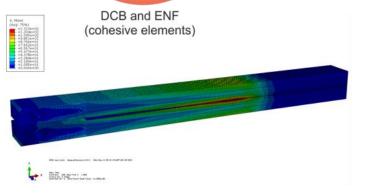
creativity

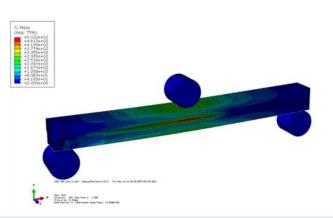
creatividad

modelo

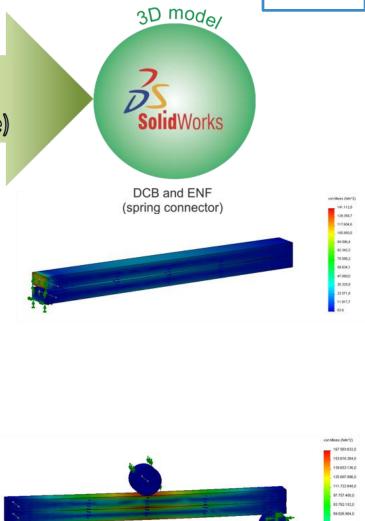
# Simulia III ABAQUS

# tunning (springs) puesta a punto (muelle)









41 895 404 8

modelo – ABAQUS®

#### bi-linear traction separation law

Ley triangular de daño cohesivo  $G_c$ 

#### cohesive law damage parameters

parámetros para la ley de daño cohesivo

Quads Damage			
Nominal Stress Normal-tension	21.64 Mpa		
Nominal Stress 1st direction	17.9 MPa		
Nominal Stress 2 <sup>nd</sup> direction	17.9 MPa		
Damage Evolution			
Normal Fracture Energy	0.43 N/m		
Shear Fract. Energy 1st Direction	4.7 N/m		
Shear Fract. Energy 2nd Direction	4.7 N/m		

#### DCB problem size in ABAQUS ®

dimensiones del modelo DCB en ABAQUS ®

Number of nodes	100624
Number of nodes defined by user	100624
Number of elements	87750
Number of elements defined by user	87750
Number of variables in the model	301872

#### ENF problem size in ABAQUS ®

dimensiones del modelo ENF en ABAQUS ®

Number of nodes	92199
Number of nodes defined by user	86547
Number of elements	79380
Number of elements defined by user	76551
Internal nodes generated by program	5652
Internal elem. generated for contact	2826
Number of variables in the model	268128

modelo - Solidworks®



#### Solidworks ® mesh characteristics

#### propiedades de la malla en Solidworks ®

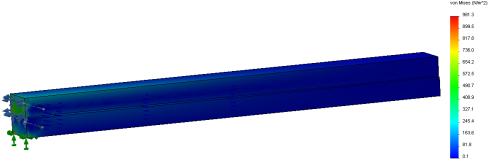
Mesh type	Solid Mesh
Mesher Used:	Curvature based mesh
Jacobian points	4 Points
Max. element size	7.21293 mm
Min. element size	1.44259 mm
Mesh Quality	High



modelo – Solidworks®



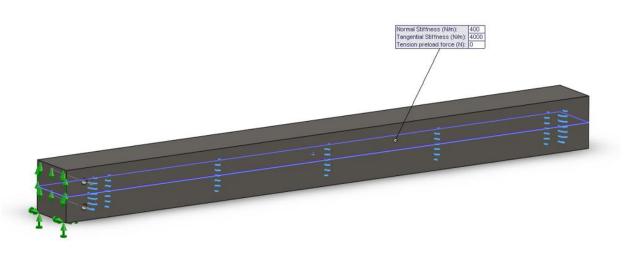
DCB and ENF (spring connector)



### DCB problem size in Solidworks ®

dimensiones del problema DCB en Solidworks ®

Total Nodes	24264
Total Elements	14980
Maximum Aspect Ratio	4.1124
% of elements with Aspect Ratio < 3	99.4
% of elements with Aspect Ratio > 10	0
% of distorted elements (Jacobian)	0

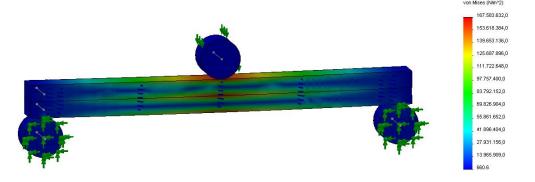




modelo – Solidworks®



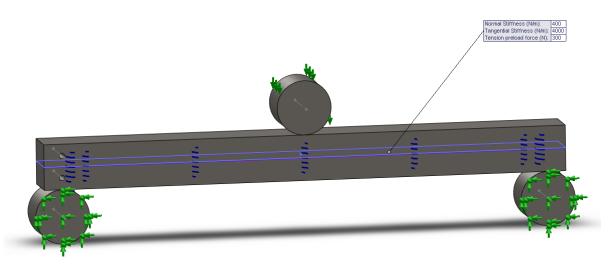
DCB and ENF (spring connector)



### ENF problem size in Solidworks ®

#### dimensiones del problema ENF en Solidworks ®

Total Nodes	17909
Total Elements	10478
Maximum Aspect Ratio	4.0217
% of elements with Aspect Ratio < 3	97.7
% of elements with Aspect Ratio > 10	0
% of distorted elements (Jacobian)	0



# materials and technology

materiales y tecnología

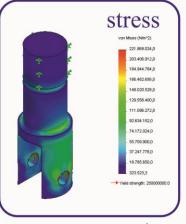
### Steel properties used for substrates and Jig base

propiedades de acero utilizado para sustratos y base del aparato

AISI P20				
Hardness (HB)	290/330			
Yield Stress (MPa)	640			
Ultimate Fracture Stress (MPa)	993			
DIN CK 45				
Hardness (HB)	170			
Yield Stress (MPa)	323			
Ultimate Fracture Stress (MPa)	578			

materiales y tecnología

modelo – Solidworks®



displacement

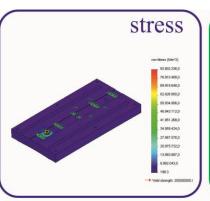
URES (rm)

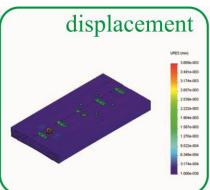
1 140-601
9-516-602
7-798-602
6-856-602
7-798-602
6-856-602
1-7398-602
1-7398-602
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1-7398-602
1-7398-603
1-000-600

tensión

desplazamiento

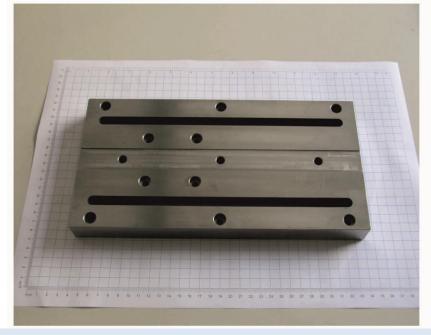






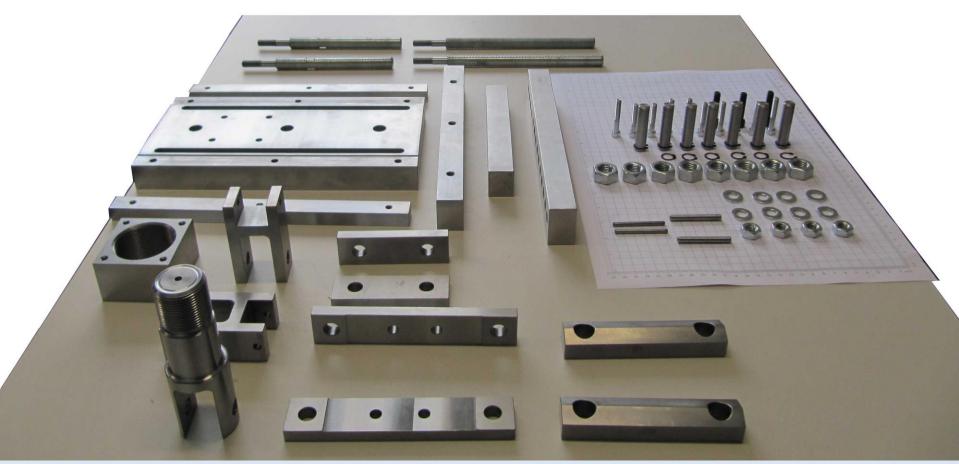
tensión

desplazamiento



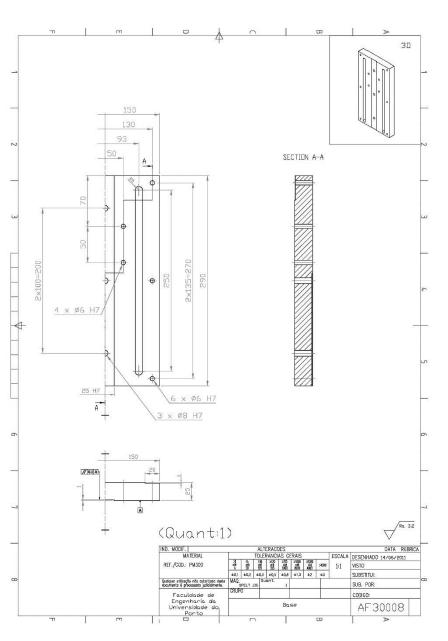
# materials and technology

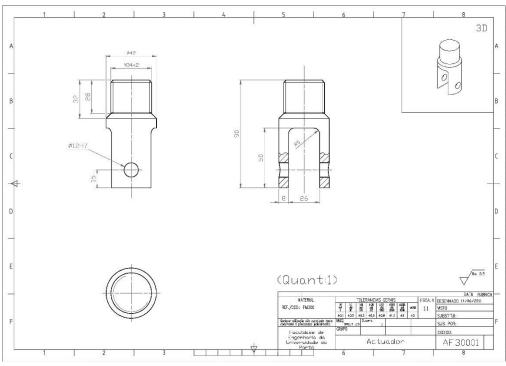
materiales y tecnología



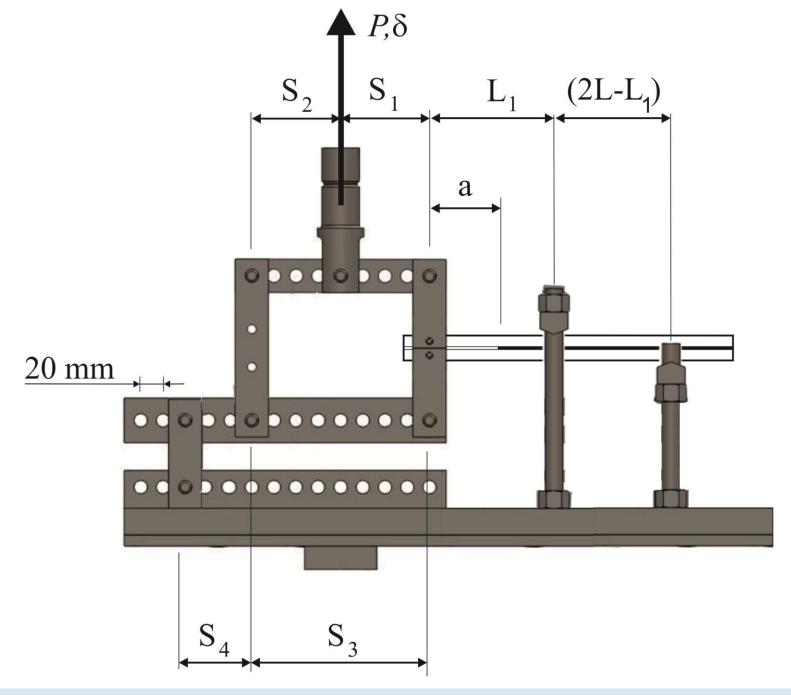
# technical drawing

dibujo técnico

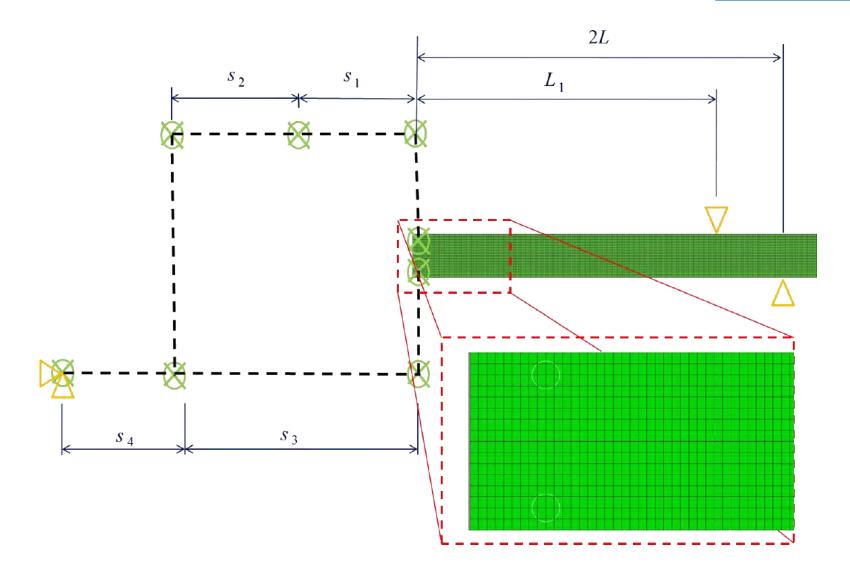




modelo



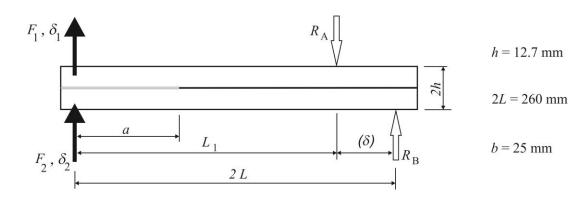
modelo – ABAQUS®



# modelo – ABAQUS®

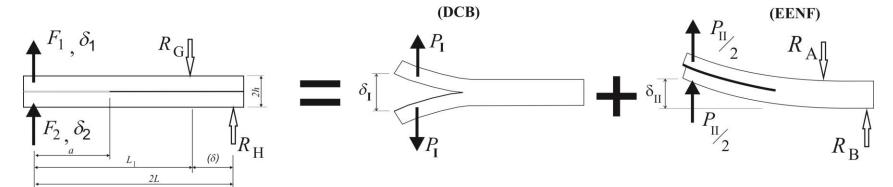
### loading scheme

#### diagrama de fuerzas



#### mode separation

#### separación de modos

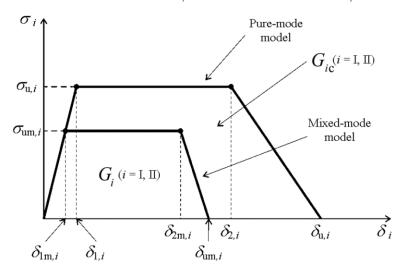


verification

modelo – ABAQUS®

#### trapezoidal traction separation law

#### ley de daño cohesivo trapezoidal



#### cohesive law damage parameters

#### parámetros para la ley de daño cohesivo

Elastic pr	roperties	Cohesive properties					
(Ste	eel)	(Adhesive)					
E	G	$\sigma_{\!\!\! \mathrm{u,I}}$	$\delta_{2,\mathrm{I}}$	$\delta_{2,\mathrm{II}}$			
(GPa)	(GPa)	(MPa)	(MPa)	(N/mm)	(N/mm)	(mm)	(mm)
210	80.77	23	23	0.6	1.2	0.0187	0.2062

# Different scenarios used for the fracture envelope calculation

Diferentes escenarios utilizados para el cálculo de la envolvente de fractura

	Jig arrangement					
Scenarios	<i>s</i> <sub>1</sub> (mm)	s <sub>2</sub> (mm)	s <sub>3</sub> (mm)	s <sub>4</sub> (mm)		
P1	100	40	140	<b>-</b> 60		
P2	120	40	160	-120		
P3	40	120	160	40		
P4	60	80	140	60		
P5	60	80	140	120		
P6	40	40	80	100		
P7	100	40	140	80		

# Obtained from the Obtained from LVDTs attached **Universal Testing** Geometry & Material inputs to each specimen beam Machine load displacements $S_1, S_2, S_3, S_4$ $\delta_1$ , $\delta_2$ $F_1 = F \frac{s_2}{s_3}$ ; $F_2 = F \frac{s_1 s_4}{s_3 (s_3 + s_4)}$ $P_1 = \frac{F_1 - F_2}{2}$ ; $P_{II} = F_1 + F_2$ equivalent crack length $a_{\rm el} = \frac{1}{6\alpha} A - \frac{2\beta}{A}$ $a_{\text{ell}} = \left[ \left( C_{\text{II}} - \frac{6LL_{1}}{5BhG(2L - L_{1})} \right) \frac{2Bh^{3}E}{3} - \frac{2LL_{1}^{2}}{3} \right]^{1/3}$

data analysis

análisis de los datos

Chaves et al., Engineering Fracture Mechanics. 2013, Vol. 107, pp.38-47

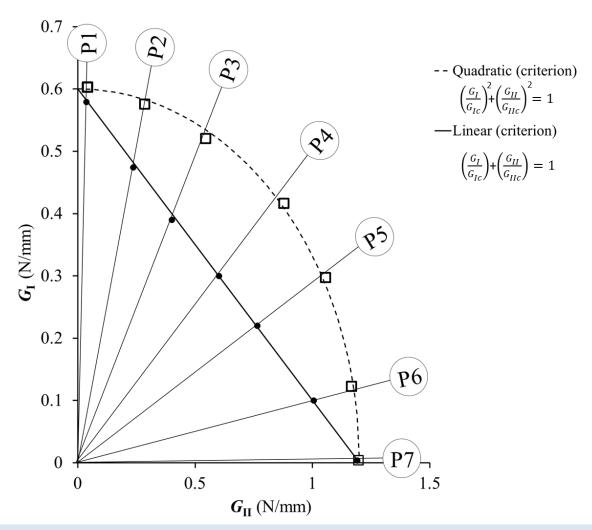
Mode I

 $G_{\rm II} = \frac{9P_{\rm II}^2 a_{\rm eII}^2}{4B^2 h^3 E}$ 

Mode II

#### Fracture envelope for the seven scenarios considering the linear ( • ) and quadratic ( •) criteria.

Envolvente de fractura para los siete escenarios considerando el criterio linear (•) y cuadrático (•).



solución

# UPIN UNIVERSIDADE DO PORTO INOVAÇÃO

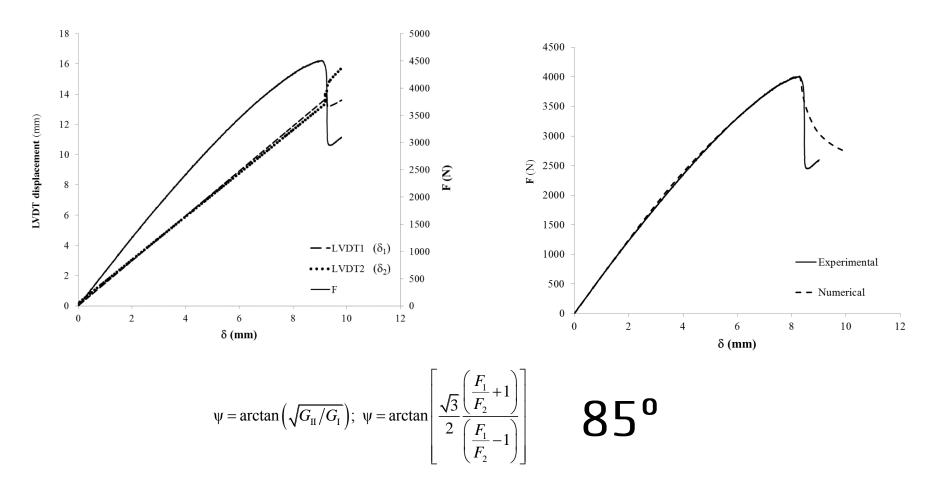


patent pending

pendiente de patente

#### Load vs. Displacement curves for a $\psi = 85^{\circ}$ combination

#### Curva de Carga vs. Desplazamiento para la combinación $\psi = 85^{\circ}$



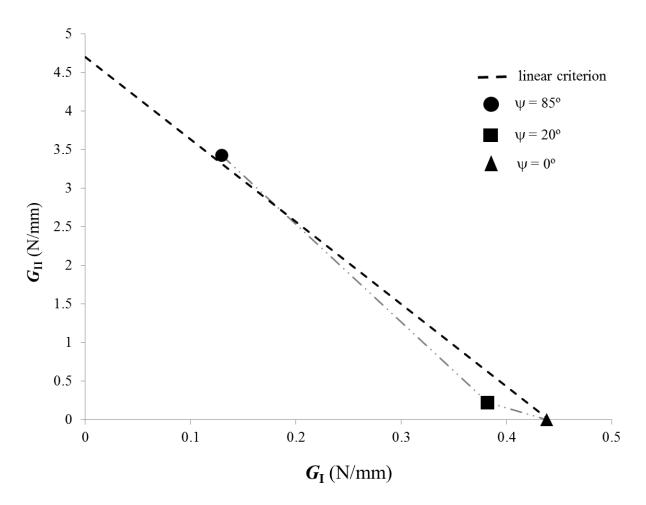
experimentar

# verification

verificación

#### Fracture envelope for three experiments

Envolvente de fractura para tres experimentos.



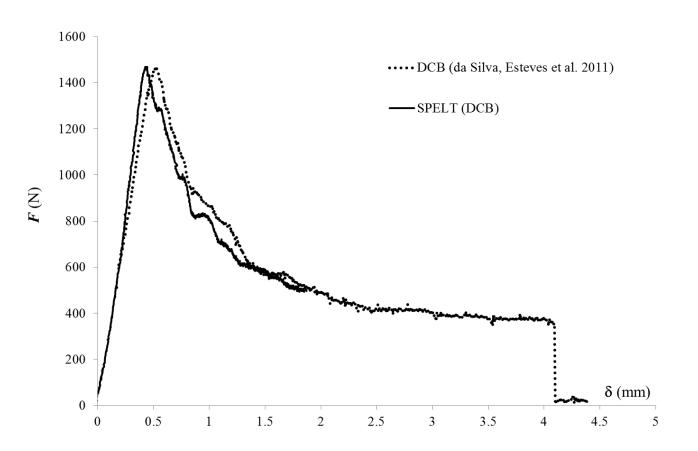
experimentar

verification

verificación

#### Load vs. Displacement curve for "classical" DCB and SPELT DCB

Curva de Carga vs. Desplazamiento para el DCB "clásico" y el DCB con SPELT



the development of the testing apparatus benefited of a design methodology based in numerical simulation using Finite Element Analysis

El desarrollo del aparato de prueba para la evaluación de la fractura en modo mixto I + II de las uniones adhesivas ha beneficiado de una metodología de diseño basada en simulación numérica usando análisis de elementos finitos.

conclusiones

conclusions

validation prior to manufacture, avoided errors and allowed optimization of materials and parts geometry

Esta metodología permite la validación antes de la fabricación, evitando errores y también permite la optimización de los materiales y la geometría de las piezas.

while at simulation stage a data reduction scheme that improves the efficiency of the test was also developed benefitting of the same design methodology

Mientras recorría la etapa de simulación también se ha desarrollado un esquema para tratamiento de datos que mejora la eficiencia del experimento, beneficiando de la misma metodología de diseño.

this data reduction scheme was first validated recurring to numerical results and later used to analyze experimental data with good results

Este esquema de tratamiento de datos primero se validó con los resultados numéricos y después con los resultados experimentales, reportando buenos resultados.

the apparatus was manufactured and used to obtain experimental results confirming its adequacy and novelty for the adhesive joints mixed-mode fracture evaluation, allowing to validate the data reduction scheme and obtain a full fracture envelope

El aparato fue fabricado y utilizado para obtener resultados experimentales que confirman su idoneidad y su novedad para la evaluación de modo mixto de las uniones adhesivas. Esto permitió validar el sistema de tratamiento de datos y obtener una envolvente de fractura completa.

#### acknowledgments

agradecimientos

the authors would like to thank "Fundação Luso-Americana para o Desenvolvimento" (FLAD) for the support through the project 314/06 2007 and Instituto de Engenharia Mecânica (IDMEC)



Los autores desean agradecer a la "Fundação Luso-Americana para o Desenvolvimento" (FLAD) por el apoyo a través del proyecto 314/06, 2007 y el Instituto de Ingeniería Mecánica (IDMEC).



we also like to acknowledge the support provided to Virginia Tech by the National Science Foundation (DMR NSF 0415840) in the development of the dual loading frame capable of facilitating mixed mode studies.



También nos gustaría agradecer el apoyo prestado a Virginia Tech por la Fundación Nacional de Ciencia (NSF DMR 0415840) en el desarrollo del *dual loading frame* capaz de facilitar los estudios de modo mixto.

agradecimientos

# thank you

gracias