PROGRESSIVE FAILURE OF COMPOSITE BONDED JOINTS

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INTRODUCTION (1/2)

- The trend in aircraft structures is the progressive replacement of metallic materials with composites, because of its superior structural properties: higher stress allowables, better behaviour in fatigue and damage tolerance, less sensitivity to corrosion phenomena, etc.
- Airbus new A350 or Boeing B787 have over 50 % of their structure made up of composites. Fuel consumption reduction is around 20 %.
- **Bonded joints** in composites are typically used: stiffened panels (joint skin – stiffener), joints skin - ribs, skin – spar, etc. These joints are quite complicated to analyze even for a simple <u>static strength</u> prediction. <u>Progressive debonding</u> failure is particularly complicated to simulate.
- When developing an aircraft, it is necessary to carry out numerous tests at various levels (coupons, details, stiffened panels, components, etc.) for validation of simulation tools, and for airworthiness certification.

INTRODUCTION (2/2)

- Many ongoing research activities aim to find reliable and accurate simulation techniques for bonded joints. Two theories are commonly used:
  - **Virtual crack closure technique** (VCCT): belongs to Linear Fracture Mechanics, requires the calculation of the strain energy release rates (SERR) in a pre-damaged structure. It can predict debondings or delaminations growth.
  - **Cohesive zone** (CZ): belongs to damage mechanics. It is advantageous in the sense that no pre-damage is required, also the theory predicts not only damage growth, but damage onset as well.
- INTA (spanish research centre for aerospace) works in an internal R+D project in finding robust FEM simulation methodologies for **bonded structures**. This project is carried out at various levels (coupons, details, subcomponents), for the moment we are working at coupon level.
- The work presented in this paper corresponds to DCB coupons using paste adhesive Epibond 1590, and comprises detailed CZ FEM simulations, experimental tests, and a quite detailed correlation Simulations - Tests.

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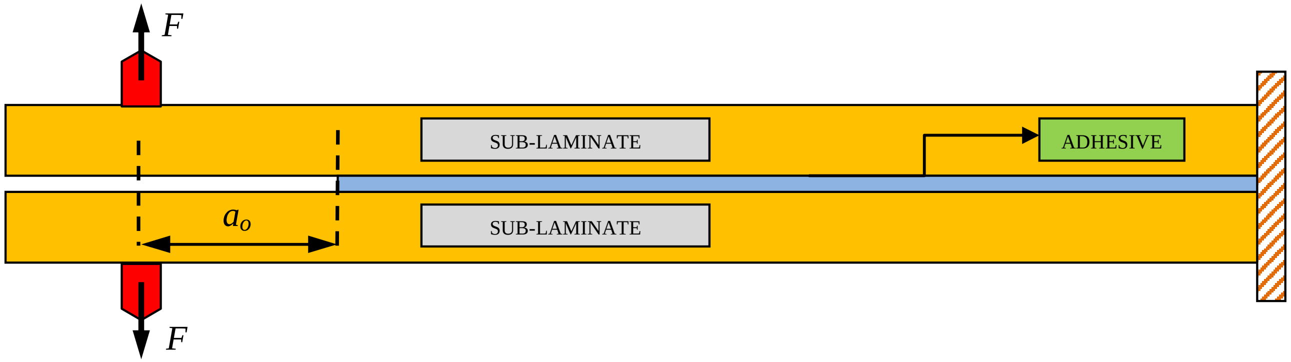
DCB Coupon: Test Method for **Mode I** Interlaminar Fracture Toughness

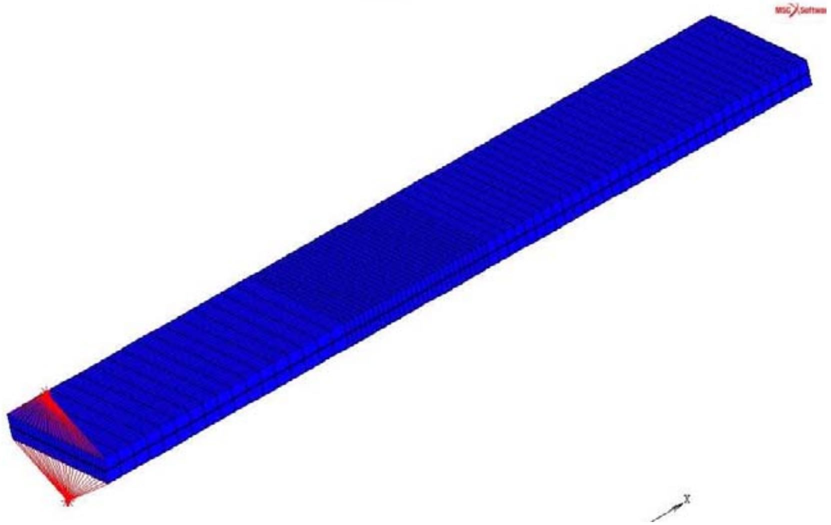
Double Cantilever Beam (DCB) coupons are used to characterize experimentally the fracture toughness of composites or adhesives, working in mode I (tension mode): G_{IC}.



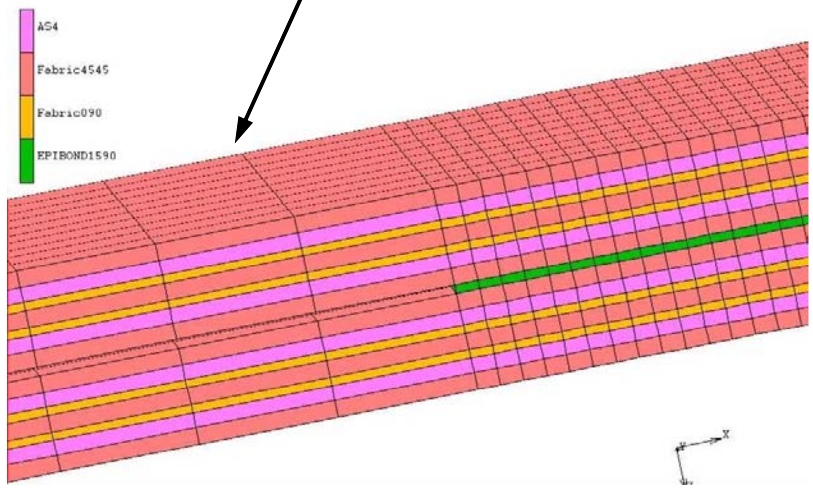
- Progressive debonding (growth) takes place in the coupon mid-plane.
- During tests the curve load-displacement is recorded, sometimes the physical crack length a is also monitored by optical methods.
- Normative is ASTM 5528-01, written originally to characterize fracture toughness of resins, it can be used to characterize adhesives as well.

DCB COUPON FEM MODELLING

- Coupon dimensions: length 150 mm, wideness 25 mm, initial debond a_o 51 mm.
- Materials: AS fibre and 8552 epoxy resin, volume fibre is 60 %. Adhesive is paste Epibond 1590, typically used in repairs. In the FEM the adhesive thickness is considered constant (0,2 mm).



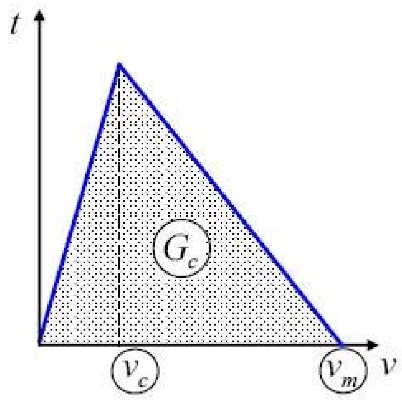
Lay-up: $[\pm 45_2, 90_2, 0/90, \pm 45_2]_S$



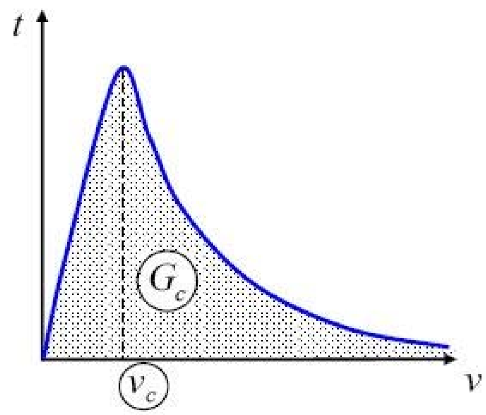
FEM is prepared with Patran, Mentat (to model adhesive CZ elements), and Marc (solver). Two types of elements were tested: composite solids, and homogenous solid elements. Considerable convergence problems were found using composite solids, so homogenous solid elements were used.

COHESIVE ZONE (CZ) ELEMENTS (1/2)

- Basic idea of CZ dates from early 60s, Dugdale and others introduced models avoiding the unrealistic infinite stresses at crack tip characteristic of the Stress Intensity Factors (SIF) approach.
- CZ elements are interface elements: traction vector t includes one normal component (mode I), and two tangentials (modes II and III). Its mechanical behaviour follow a phenomenological separation law t = f (υ), being υ the vector of nodal separations (3 components).



Bi-linear law



Exponential law

Most usual **separation laws** are **bi-linear** (fragile materials), **exponential**, and **combined linear - exponential**. Area enveloped by the curve is material fracture toughness G_C.

COHESIVE ZONE (CZ) ELEMENTS (2/2)

- Cohesive law considers a high non-linear behaviour: the first part of the curve is linear and reversible. When separation in the element exceeds the critical value υ_c, the element has been partially damaged and the behaviour is irreversible.
- If the deformation in the element is high enough ($\upsilon = \upsilon_m$) the FEM solver de-activates the element, this way the advance or growth of debonding in the structure is simulated.
- The exponential law was finally selected for our FEM because in the one hand is more adequate to model ductile materials, and in the other hand because FEM convergence is easier.
- A typical inconvenient of CZ FEMs is how to account for mixed-mode analysis. This is not our case, adhesive in a DCB coupon work only in Mode *I*.

MESH DEPENDENCY (1/3)

- It is know that CZ FEMs are mesh dependent (results depend of the mesh size).
- Several researchers are working on this, the usual approach is to adapt material allowables (maximum peeling stress in problems related to mode *I*) function of the mesh size.
- The work presented in this paper use a relatively complex theory based in energy considerations, considering Dugdale model for transverse stresses around a crack tip in a plastic material, and CZ FEM stresses based in Irwin/Bazant model:

Cohesive zone length: adhesive length along coupon longitudinal axis irreversibly damaged

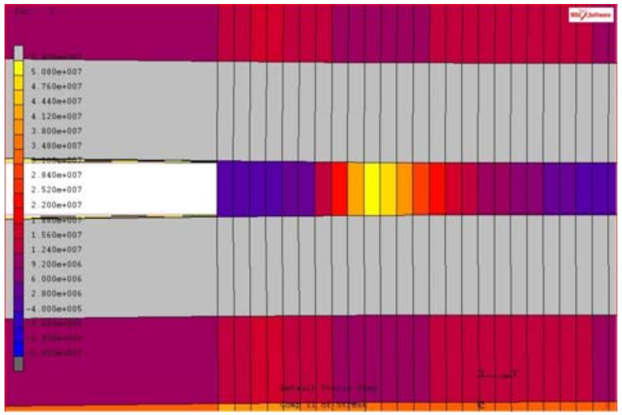
Sub-laminate elasticity modulus in transverse direction (direction 3)

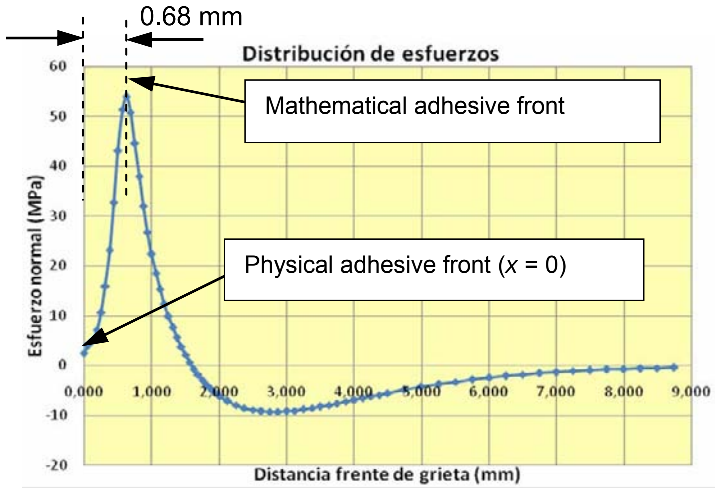
$$l_{CZ} = M \frac{E_{33} G_{IC}}{\sigma_o^2}$$

σ_o: adhesive allowable at transverse tension (peeling), t value of CZ element curve

MESH DEPENDENCY (2/3)

- To verify the theory, and the value for M a very detailed FEM was produced: mesh size of only 62.5 μm (FEM not suitable for progressive damage monitoring). The analysis is made applying a load that makes that the first element of the adhesive to be almost completely damaged (transmits almost no stress), although there is no de-bonding propagation.





- M value according to the FEM is 0.862, very close to Rice theory ($9\pi/32 \approx 0.88$).

MESH DEPENDENCY (3/3)

- When using a FEM with coarser mesh, l_{CZ} (Cohesive Zone length) will not be accurately predicted by the FEM.
- However there is a relation between the CZ length calculated by the FEM l_{CZ}* and the maximum stress in the adhesive σ_{max}*:

$$l_{CZ}^{*}(\sigma_{max}^{*})^{2} = ME_{33}G_{IC}$$

- So if σ_o (peeling allowable stress of CZ elements) is adapted function of l_{CZ}*, and mesh size is mesh size = l_{CZ}*/N_e (being N_e the number of adhesive elements within CZ length), it is expectable that FEM yields quite accurate results in terms of <u>global FEM behaviour</u>.

$$\sigma_o = \sqrt{\frac{ME_{33}G_{IC}}{N_e\left(mesh\ \ size\right)}}$$

General recommendation for N_e is between 3 and 10

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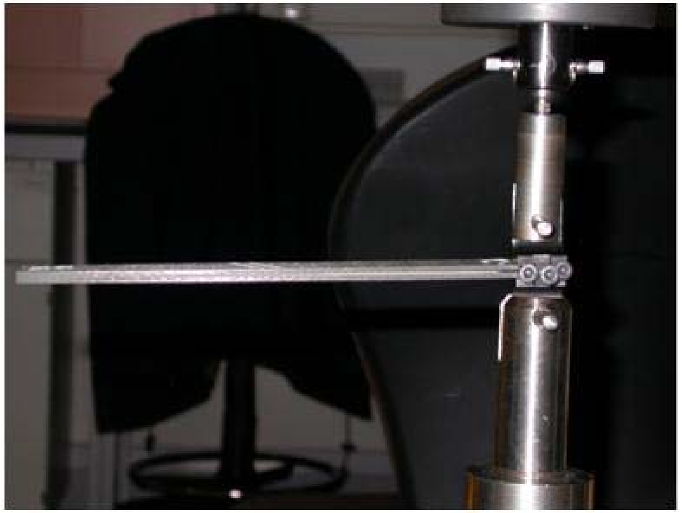
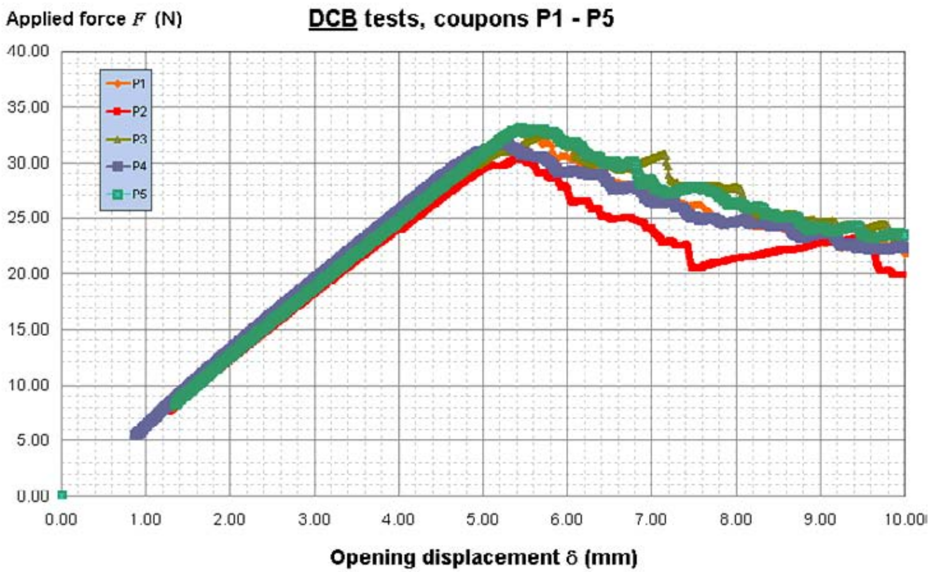
EXPERIMENTAL RESULTS (1/2)



DCB tests carried out at INTA



Experimental curves: load applied F (N) versus opening displacement δ (mm). Only coupon P2 behaves relatively different (attributed to poor surface preparation, or to an inadequate quality control of bonding process)

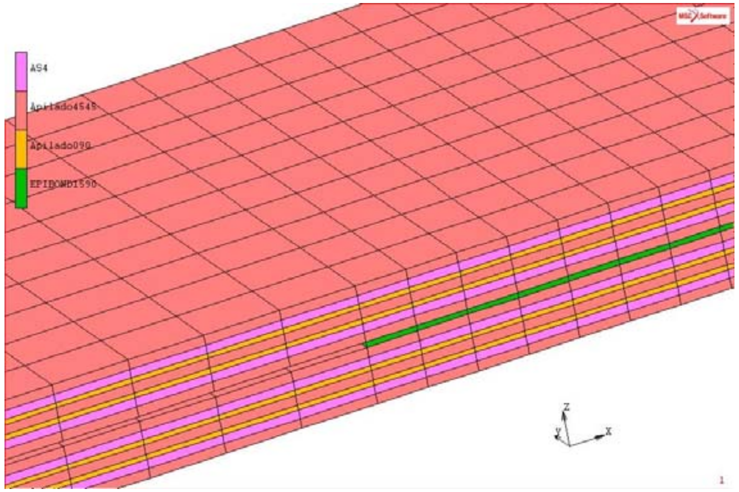
EXPERIMENTAL RESULTS (2/2)

- From these curves, by using the classical methods: modified beam theory (MBT), and compliance calibration method (CC) the adhesive Mode I Interlaminar Fracture Toughness G_{IC} is derived.
- For the FEMs, the value derived from CC method is used: G_{IC} = 211.7 J/m^2 (average value of the 5 coupons tested).

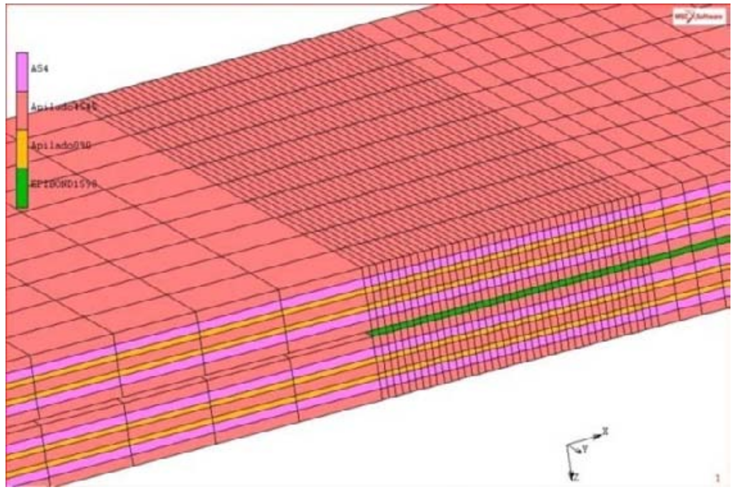
Coupon	Wide b (mm)	Thickness t (mm)	Crack length a (mm)	Compliance C (mm/N)	F_{max} (N)	Opening displacement δ for F_{max} (mm)	Slope n (Log C-Log a)	G_{IC} CC method (J/m^2)	G_{IC} MBT method (J/m^2)
P1	24.939	4.49	36	0.054	32.778	5.404	3.07	213.77	208.90
			41	0.081					
			46	0.111					
			51	0.162					
P2	25.051	4.554	36	0.055	30.517	5.448	3.21	208.87	195.20
			41	0.081					
			46	0.116					
			51	0.170					
P3	25.041	4.573	36	0.058	32.746	5.771	2.972	219.88	221.95
			41	0.084					
			46	0.118					
			51	0.162					
P4	24.907	4.626	36	0.058	31.956	5.283	2.926	194.43	199.35
			41	0.081					
			46	0.114					
			51	0.160					
P5	25.045	4.789	36	0.055	33.076	5.458	3.155	222.97	212.01
			41	0.081					
			46	0.118					
			51	0.163					
Average	**24.997**	**4.605**			**32.201**	**5.470**	**3.065**	**211.74**	**207.27**
σest	**0.068**	**0.113**			**1.036**	**0.181**	**0.119**	**11.23**	**10.59**

CORRELATION FEM SIMULATION - TESTS (1/3)

- 4 different FEMs were generated. Mesh sizes along longitudinal coupon axis in the debonding growth zone are 2 mm (total number of elements in the FEM 7480), 1 mm (8380 elements), 0.5 mm (9880 elements), and 0.25 mm (12880 elements).



DCB coupon FEM, mesh size 2 mm (7480 elements)



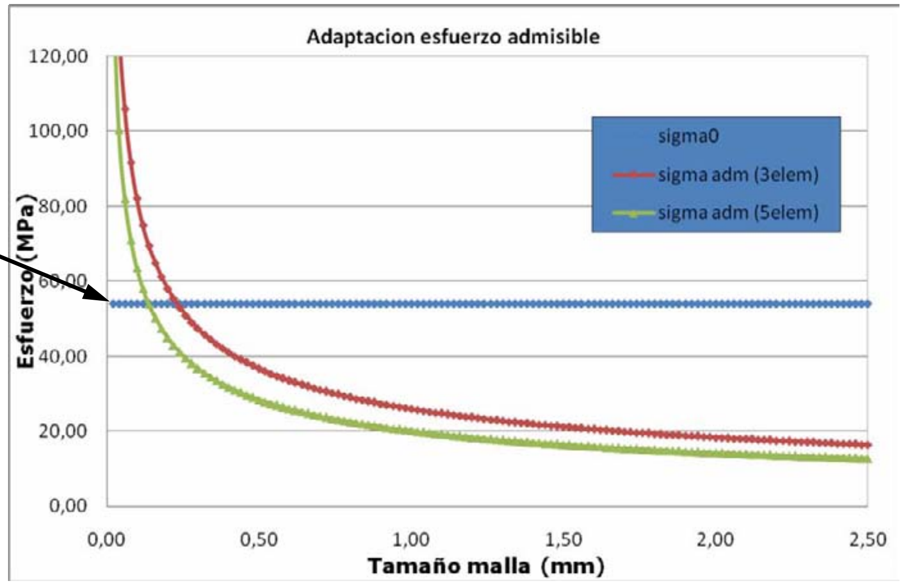
DCB coupon FEM, mesh size 0,25 mm (12880 elements)

- Solver used is Marc, analyses are static non-linear, results requested are <u>stresses in the adhesive</u> elements and <u>node displacements</u>.

CORRELATION FEM SIMULATION - TESTS (2/3)

- Maximum peeling stress σ_o is 54 MPa ("physical" adhesive allowable derived from manufacturer test data).
- σ_o (maximum value of CZ elements curve), is adapted function of the mesh size according to formula shown previously.
- N_e value: 3 and 5 (3 or 5 elements in the CZ length).

Physical **adhesive allowable** (peeling) σ_o = 54 MPa



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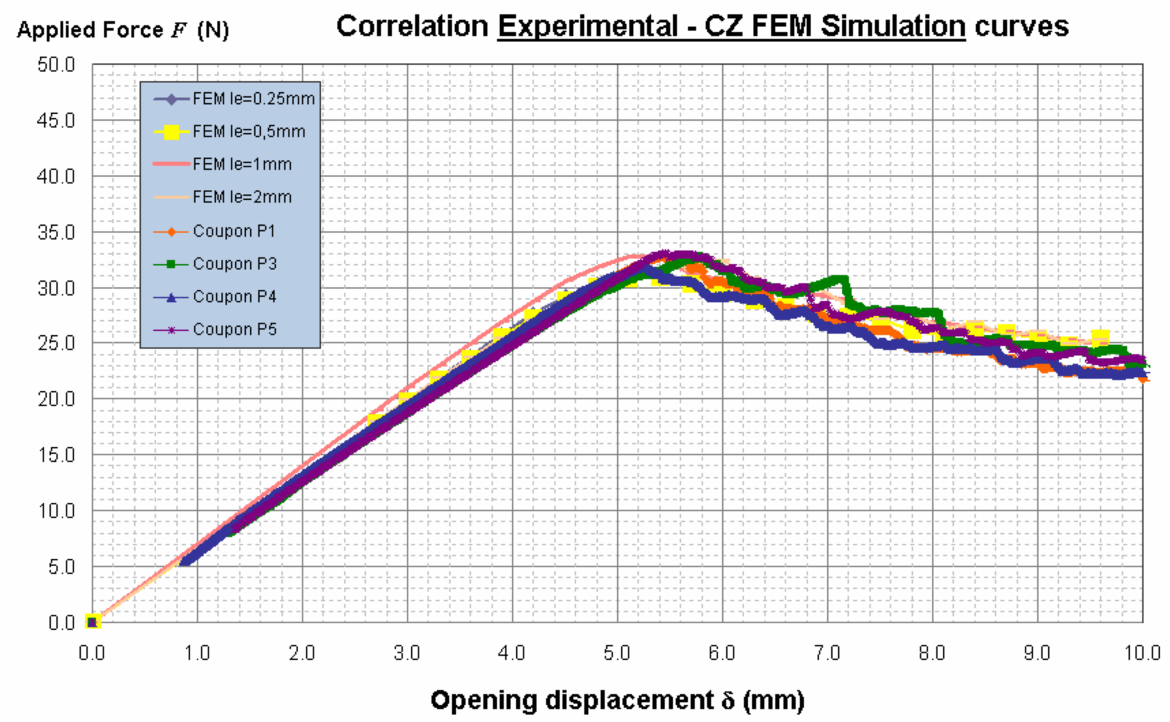
CORRELATION FEM SIMULATION - TESTS (3/3)

- Comparison between experimental and CZ FEM simulation "load applied versus opening displacement" curves.

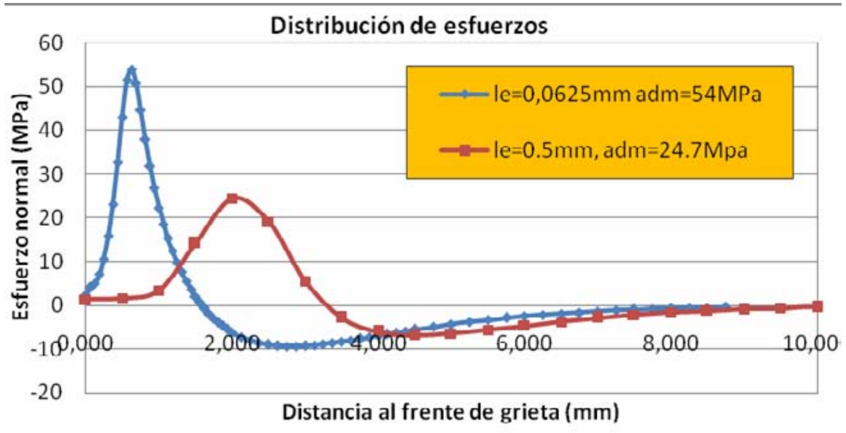


Experimental and **FEM predicted** curves are quite similar. Correlation is quite accurate in terms of initial curve slope, maximum load, and negative curve slope beyond maximum load.

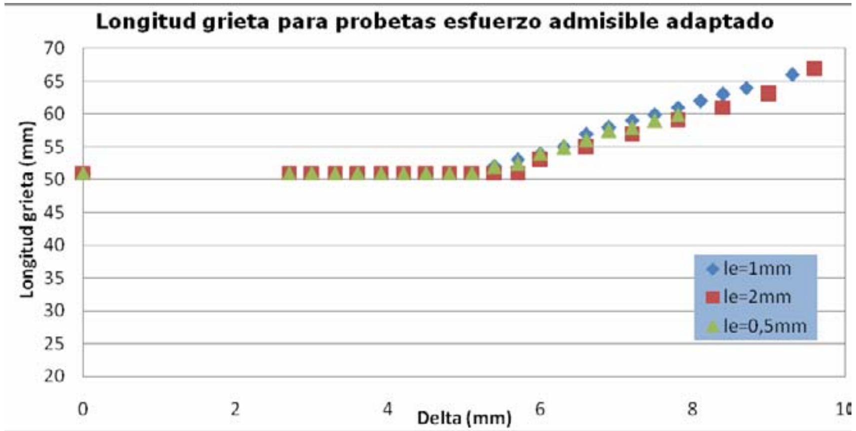
- CZ FEM methodology used seems adequate. Relatively coarse FEMs can be used to model progressive coupon debonding.

ANOTHER CZ FEM RESULTS

- Another results, <u>not comparable with experiments</u>, has been derived from CZ FEMs to verify its robust and coherent behaviour.



Peeling stress σ_3 for calibration FEM (mesh size 62.5 μm), and FEM of mesh size 0.5 mm. The methodology used makes that global FEM behaviour is similar for all mesh sizes, but “locally” the behaviour is different



Crack length (distance between the force application point and the node in the adhesive with null peeling stress), function of opening displacement. Curves shown are from FEMs with mesh sizes: 2 mm, 1 mm, and 0.5 mm.

CONCLUSIONS AND FUTURE WORK (1/2)

- A methodology to predict progressive debonding in structures by means of Cohesive Zone (CZ) FEM simulations has been explained.
- The methodology has been already used by several researchers, and has been applied to DCB coupons, that were tested at INTA (adhesive used is paste Epibond 1590).

- A summary of the work done:
  - CZ FEMs have been prepared by using classical software tools in the aeronautic industry: Patran, Mentat (to model adhesive CZ elements), and Marc (solver). Elements used are homogenous solid elements.
  - Different FEMs (different mesh sizes) have been used, the adhesive allowable peeling stress has been adapted function of mesh size. It has been found that FEM results are similar for all FEMs, so <u>mesh size dependence</u> problem can be solved.

CONCLUSIONS AND FUTURE WORK (2/2)

- Experimental tests were carried out on 5 DCB coupons, manufactured by pre-preg method with AS fibre and 8552 epoxy resin. For these coupons the curve "applied load – opening displacement" was obtained. Based in these curves, the adhesive fracture toughness in mode I G_{IC} was derived (<u>Compliance Calibration</u> method).
- The correlation between simulation and test curves was found to be quite accurate. All the relevant parameters: initial curve slope, maximum load, and negative curve slope beyond maximum load, were quite similar.

- Final conclusion is that results seem very promising, and the methodology used is adequate. Our intention is to continue the work Analysis of <u>progressive failure</u> of more complicated bonded structures including <u>mixed-mode</u> problems, for which right now there is no established methodology.

THANK YOU FOR YOUR ATTENTION