Failure Criteria in Fibre Reinforced Polymer Composites :

Can any of the Predictive Theories be Trusted ?

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Peter Soden (University of Manchester, UK)

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NAFEMS World Congress, Boston, 23rd-26th May 2011

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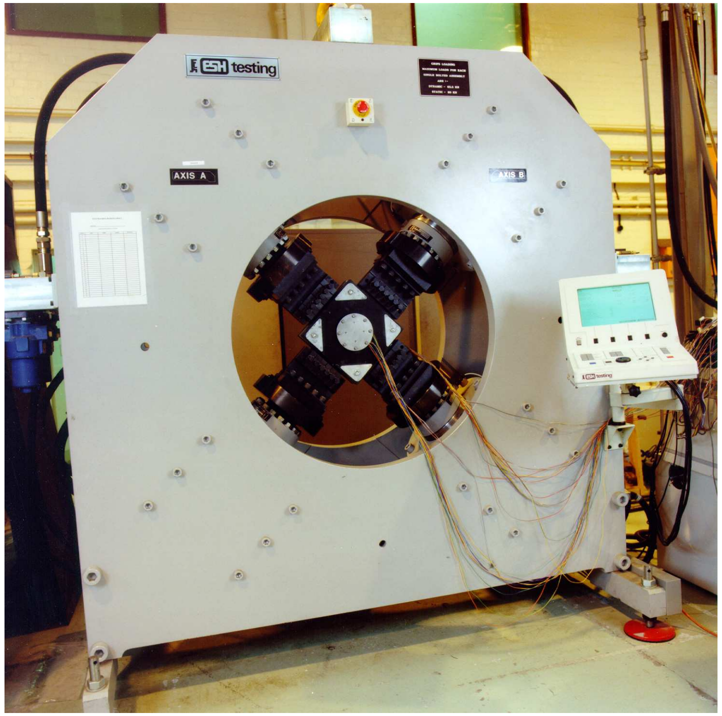
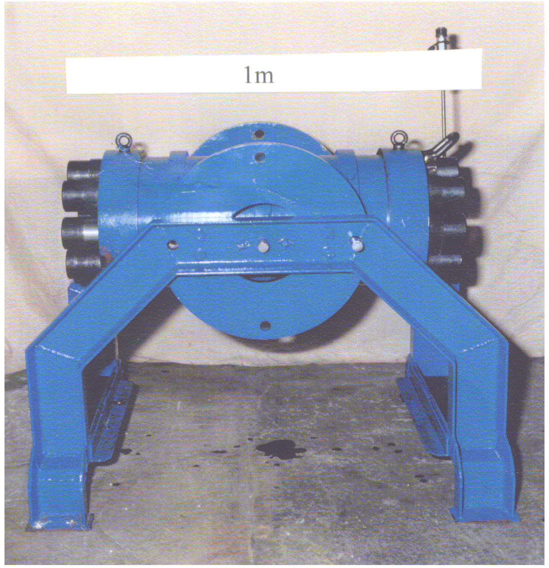
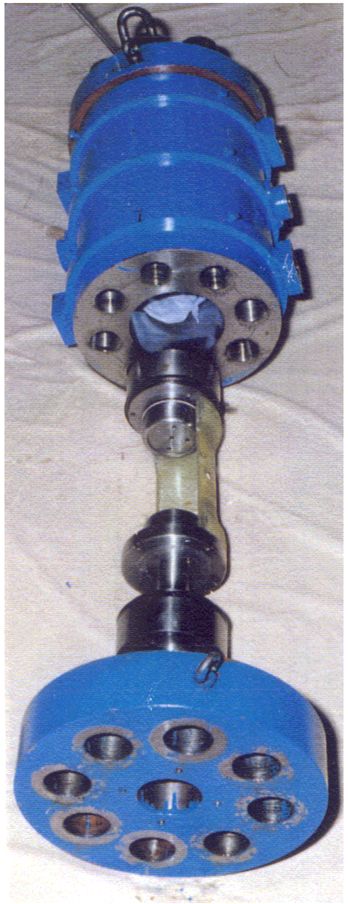
1. Background



Cruciform Biaxial Test Rig



Cylindrical Biaxial Test Rig



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1. Background - **'Experts Meeting' held at St Albans (UK) in 1991**

Title :-

'Failure of Polymeric Composites and Structures:
Mechanisms and Criteria for the Prediction of Performance'

- Meeting organised by the UK Science & Engineering Research Council together with the UK Institution of Mechanical Engineers.
- Expert delegates invited from many countries.
- The meeting took the form of a series of formal presentations interspersed with informal discussion groups.

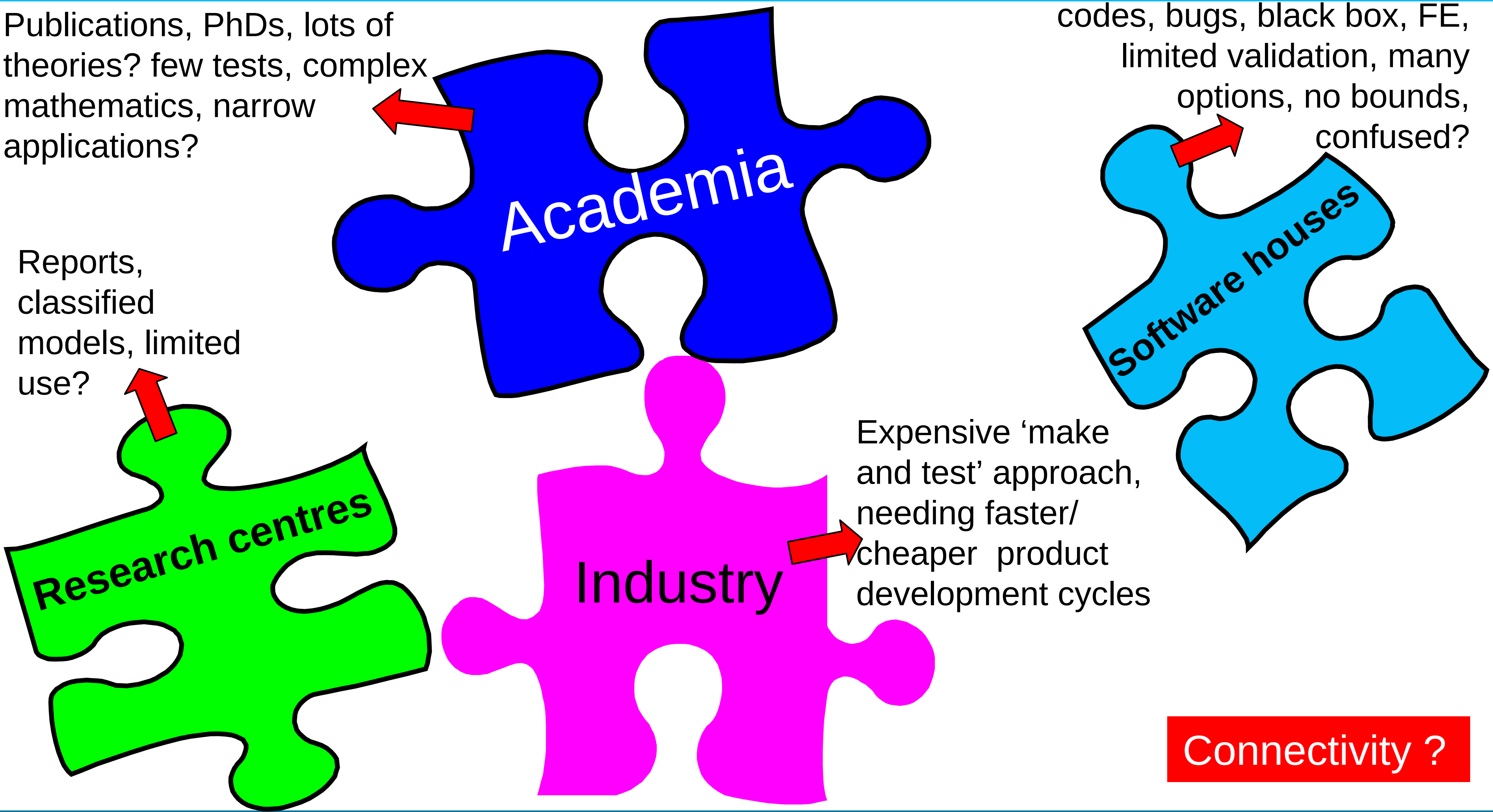
1. Background - **Major issues facing the composites community**

Publications, PhDs, lots of theories? few tests, complex mathematics, narrow applications?

codes, bugs, black box, FE, limited validation, many options, no bounds, confused?

Reports, classified models, limited use?

Expensive 'make and test' approach, needing faster/ cheaper product development cycles



Connectivity ?

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1. Background - **Key Findings from the 'Experts Meeting'**

There is no universal definition for what constitutes 'failure' of a composite structure.

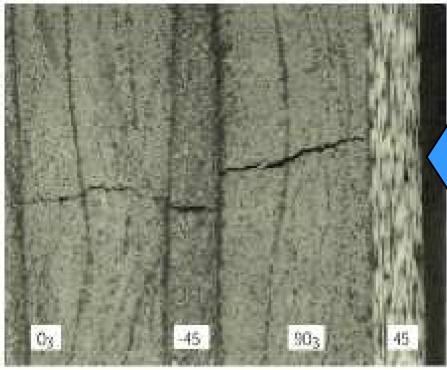
None of the current predictive failure theories were considered to be credible for use in practical engineering applications.

1. Background - **Key Findings from the ‘Experts Meeting’**

There is no universal definition for what constitutes ‘failure’ of a composite structure.

One definition :-

‘Failure’ is the point beyond which the structure or component ceases to fulfil its function.



Failure of liquid hydrogen composite tank grounded protoflight test of hypersonic vehicle (X33) (NASA)

1. Background - **Key Findings from the 'Experts Meeting'**

None of the current predictive failure theories were considered to be credible for use in practical engineering applications.

A Grand Challenge:

How accurately can we predict the strength of an FRP laminate?

2. Concept For the World Wide Failure Exercises (WWFE)

Objective

- Establish a benchmark

Method

- Identify the leading failure theories for FRP laminates
- Test the general applicability of the theories across a range of problems
- Compare the theories against each other
- Compare the theories against experimental evidence
- Draw conclusions and recommend way forward

Closing the gap between the academic world and the design world

2. Concept For the World Wide Failure Exercises (WWFE)

1. What failure prediction theories are in use world-wide ?
2. How to ensure that ‘authorised’ versions of those theories are tested ?
3. How to ensure that a critical quantity of ‘authorised’ predictions are produced ?
4. What test problems do I pick to test the theories to their limits ?
5. Where do I get credible experimental data from ?
6. How do I ensure that those making the predictions use identical input data and provide output data (ie predictions) to a common format ?
7. How to maintain a level playing field
8. Which part of the elephant do I attack first ?

2. Concept For the World Wide Failure Exercises (WWFE)

I. Establish Framework

Consultation with leading experts

International Call for contribution of high quality multi-axial experimental data via conferences and journals

Selection of possible participants

Issue invitation letter and instructions to participants

Author agrees/declines to participate

Establish a list of participants

Selection of “test problems” where good quality experimental data exist

Assemble datapack 1:

Define test cases (Materials, Geometry, Loading), Define parameters to be predicted, and Issue Instructions to authors for Part A

2. Concept For the World Wide Failure Exercises (WWFE)

II: PART A

Issue datapack1 to participants

↓

Participant proceeds/withdraws

↓

Individual papers describing theory and containing "*blind*" theoretical prediction for specified cases

↓

Publish Part (A) in Composites Science and Technology COMPARISION OF *'BLIND'* THEORETICAL PREDICTIONS

2. Concept For the World Wide Failure Exercises (WWFE)

III: PART B

Assemble datapack 2:
Provide full set of experimental results for each case and describe the experiments
- Issue Instructions to authors for Part B

↓

Issue of datapack 2 to participants

↓

Individual papers describing (a) theoretical/experimental comparison, (b) Possible refinement to theory, (c) Reasons for differences and (d) Recommendation

↓

Publish Part B in Composites Science and Technology
HOW WELL CAN WE PREDICT FAILURE?

3. WWFE-I - Issues Tackled

All test cases featured laminates assembled from continuous fibre reinforced unidirectional laminae subjected to 2D in-plane loading

- Use of micro-mechanics for prediction properties
- Prediction of the biaxial failure of a lamina in isolation
- Prediction of 2D modes of failure
- Prediction of the biaxial failure envelopes for a variety of laminates
- Matrix failure in tension, shear and compression
- Material non-linearity
- Post failure modelling under 2D stresses
- Prediction of fibre failure

3. WWFE-I - Participants

Contributor(s)	Organisation	Approach represented	Theory Designation
Chamis C C **Gotsis P K** **Minnetyan L**	NASA Lewis Cleveland USA	1) ICAN 2) CODSTRAN (micromechanics analyses)	Chamis (1) Chamis (2)
Eckold G C	AEA Technology Harwell UK	British Standard pressure vessel design codes	Eckold
Edge E C	British Aerospace Military Aircraft Division Warton UK	British Aerospace In-house design method	Edge
Hart-Smith L J	Douglas Products Division Longbeach USA	1) Generalised Tresca theory 2) Maximum strain theory	Hart-Smith (1) Hart-Smith (2)

3. WWFE-I - Participants

Contributor(s)	Organisation	Approach represented	Theory Designation
McCartney L N	National Physical Laboratory London UK	Physically based ‘Damage Mechanics’	McCartney
Puck A **Schürmann H**	Technische Hochchule Darmstadt Germany	Physically based 3-D phenomenological models	Puck
Rotem A	Faculty of Mechanical Engineering, Technion-Israel Institute of Technology Haifa Israel	Interactive matrix and fibre failure theory	Rotem
Sun C T **Tao J X**	Purdue University School of Aeronautics & Astronautics Indiana USA	Linear and non-linear analysis (non-linear is FE based)	Sun

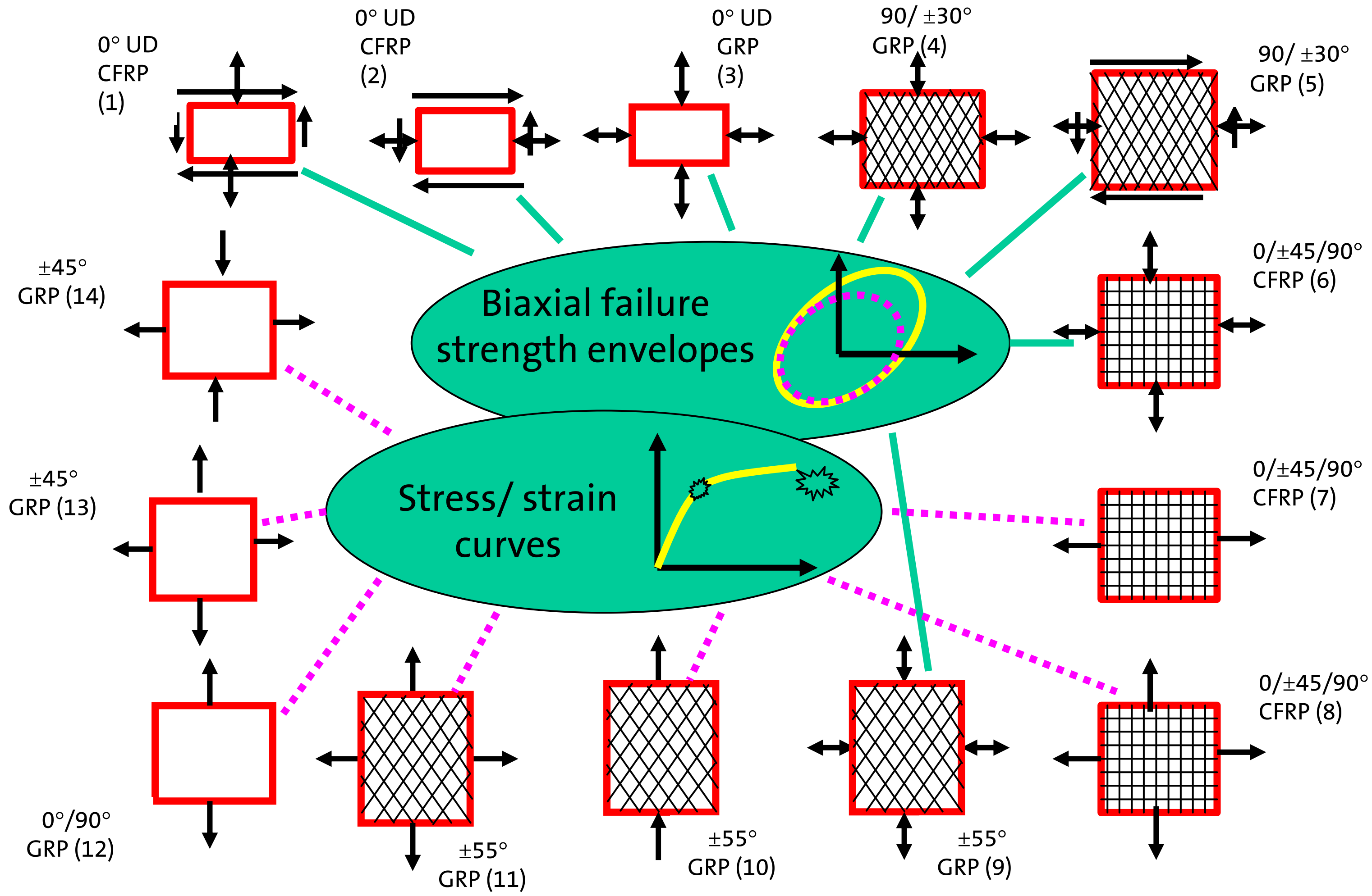
3. WWFE-I - Participants

Contributor(s)	Organisation	Approach represented	Theory Designation
Tsai S W **Liu K-S**	Aeronautics and Astronautics Dept Stanford University California USA	Interactive progressive quadratic failure criterion	Tsai
Wolfe W E **Butalia T S**	Department of Civil Engineering Ohio State University Ohio USA	Maximum strain energy method, due to Sandhu	Wolfe
Zinoviev P **Grigoriev S V** **Labedeva O V** **Tairova L R**	Institute of Composite Technologies Orevo Moskovkaya Russia	Development of Maximum stress theory	Zinoviev

3. WWFE-I - Participants

Contributor(s)/	Organisation	Approach represented	Theory Designation
L J Hart-Smith	Boeing, USA	10% rule theory	Hart-Smith (3)
R Cuntze and A Freund	MAN Technologies Germany	Failure Mode Concept (Puck+ probabilistics)	Cuntze
T Bogetti , C Hoppel , V Harik , J Newill , B Burns	U.S. Army Research Laboratory;	Maximum strain theory (3-D formulation)	Bogetti
S J Mayes and A C Hansen	Naval Surface Warfare Center, West Bethesda Alfred University	Multi-continuum theory (Micro-mechanics based FE theory)	Mayes
Z-M Huang	Tongi University, Shanghai, China	Bridging model (Micromechanics+plasticity)	Huang

3. WWFE-I - Test Cases for laminates and loading



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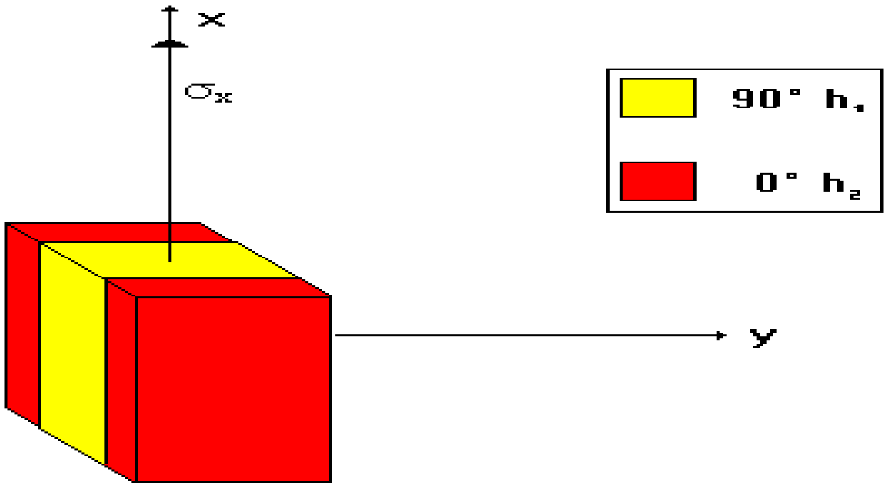
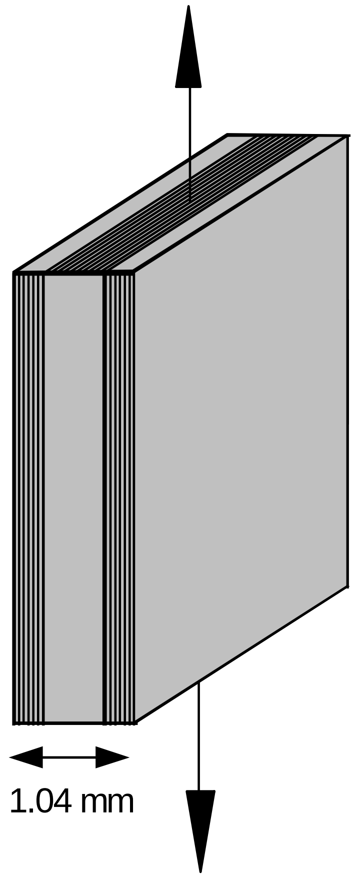
3. WWFE-I - Test Case 12 -- $(0/90)_S$ GRP, Uniaxial Tensile Loading

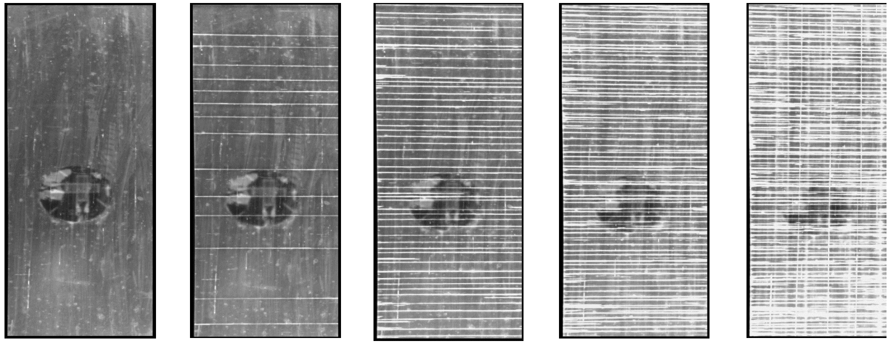




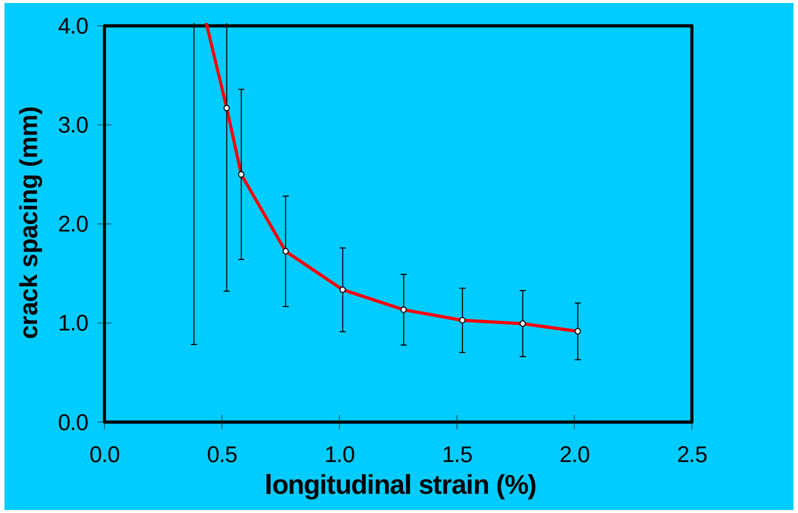
Schematic of the loading configuration of a (0/90)s cross ply laminate.

Note that the thickness of the laminate is 1.04 mm, h1 = 0.52mm and h2 = 0.26mm.

3. WWFE-I - Test Case 12 -- $(0/90)_S$ GRP, Uniaxial Tensile Loading



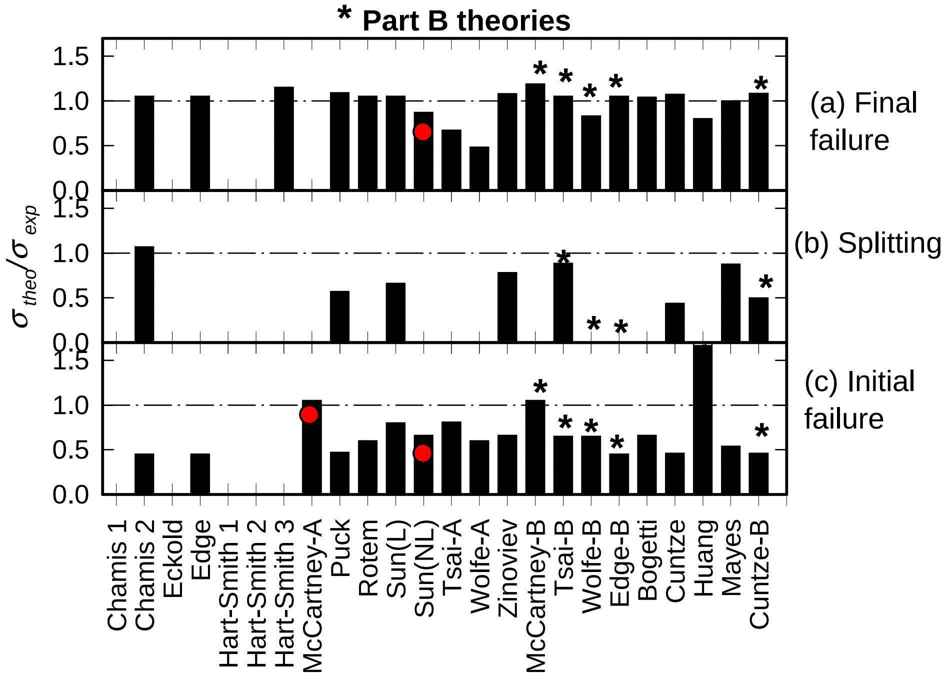
Crack development



Crack density versus strain

Test Case 12:

(0/90) GRP laminate under tension



Majority predicted only 2 modes?

Only 2 theories predicting crack density

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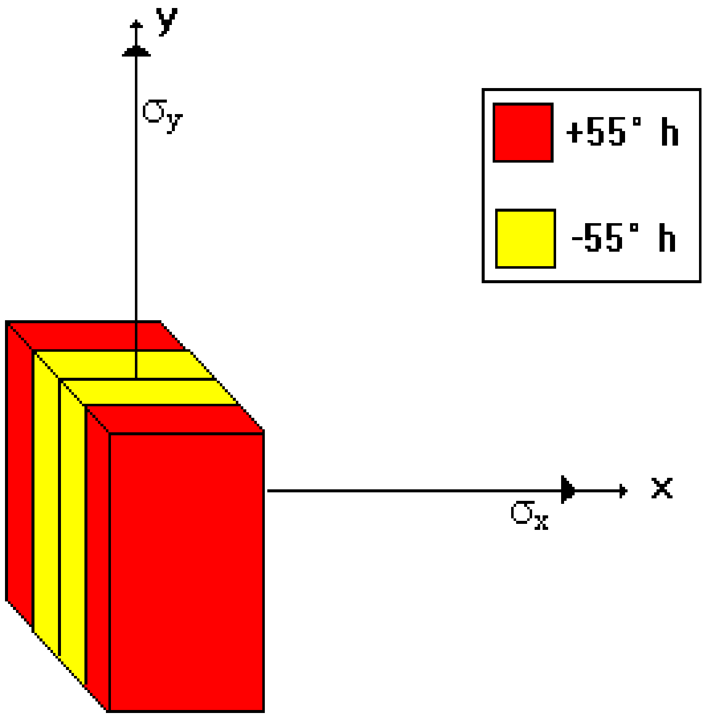
3. WWFE-I - Test Cases 9,10,11-- ±55° Glass/Epoxy

Biaxial Envelope & Stress / Strain Curves at (1y:0x) and (2y:1x) Ratio



Schematic of the loading configuration and lay-up of a ±55 angle ply laminate.

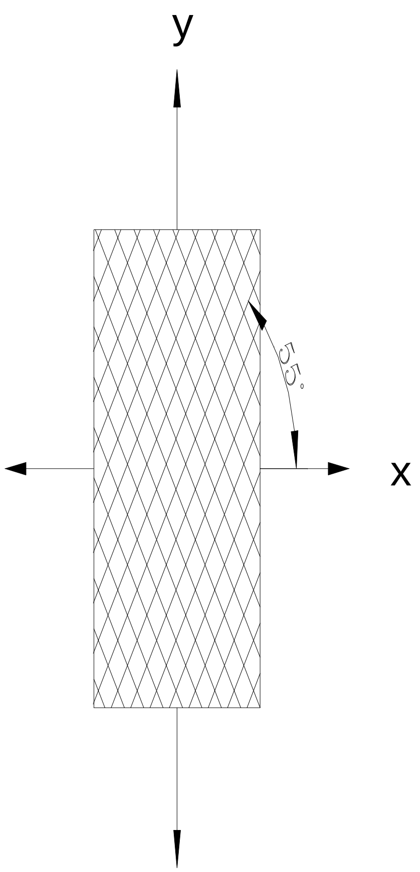
Note: the thickness of the laminate is 1mm where h = 0.25 mm.

3. WWFE-I - Test Cases 9,10,11-- ±55° Glass/Epoxy

Biaxial Envelope & Stress / Strain Curves at (1y:0x) and (2y:1x) Ratio

PROPERTY	VALUE
E_1 (GPa)	45.6
E_2 (GPa)	16.2
G_{12} (GPa)	5.83*
ν_{12}	0.278
ν_{23}	0.4
G_{1C} (Jm^{-2})	165
α_1 (10^{-6} °C^{-1})	8.6
α_2 (10^{-6} °C^{-1})	26.4
Stress Free Temperature (°C)	120

Properties of the E Glass / Epoxy System

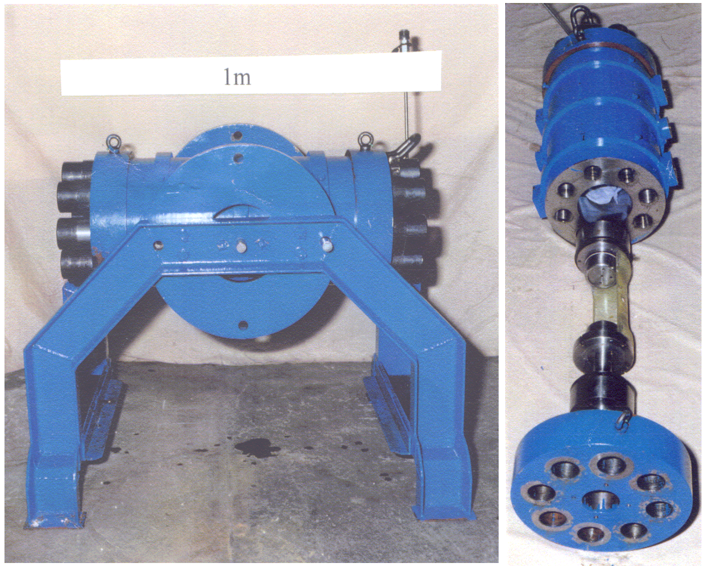


±55° Lay up and Loading Configuration

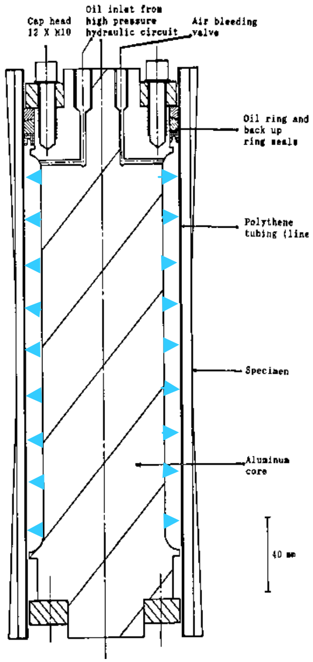
3. WWFE-I - Test Cases 9,10,11-- ±55° Glass/Epoxy

Biaxial Envelope & Stress / Strain Curves at (1y:0x) and (2y:1x) Ratio

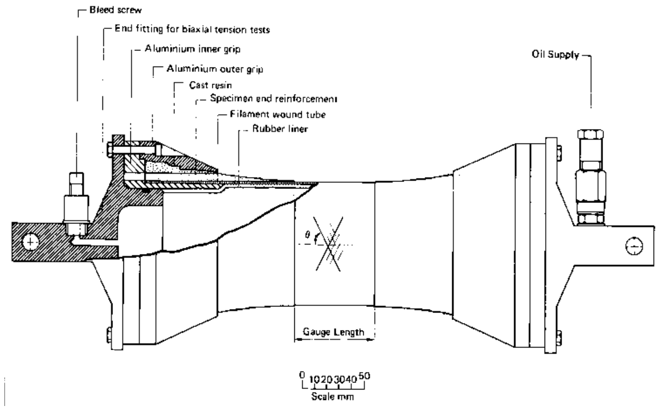
Test Facilities for generating Biaxial Failure Envelopes



Biaxial Compression Test Rig



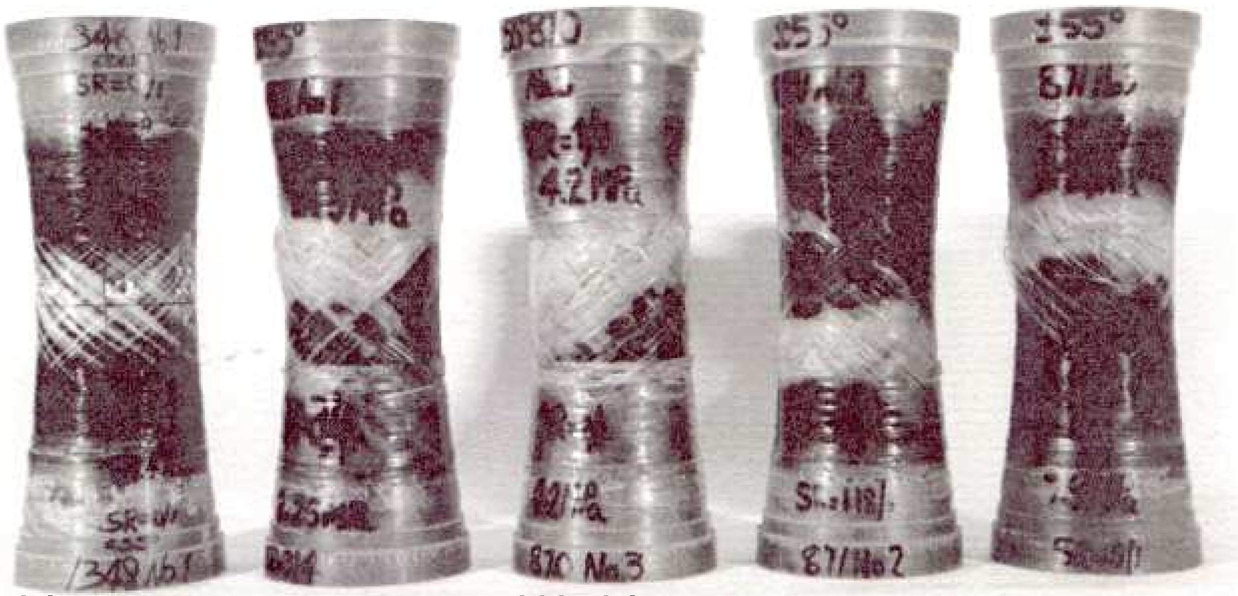
Uniaxial Hoop Tension Test Rig



Biaxial Tension Test Rig

3. WWFE-I - Test Cases 9,10,11-- ±55° Glass/Epoxy

Glass/Epoxy ±55° Biaxial Test Specimens



	Uniaxial Tension		Equi-biaxial Tension		
SR	0/1	0.75/1	1/1	1.18/1	13/1

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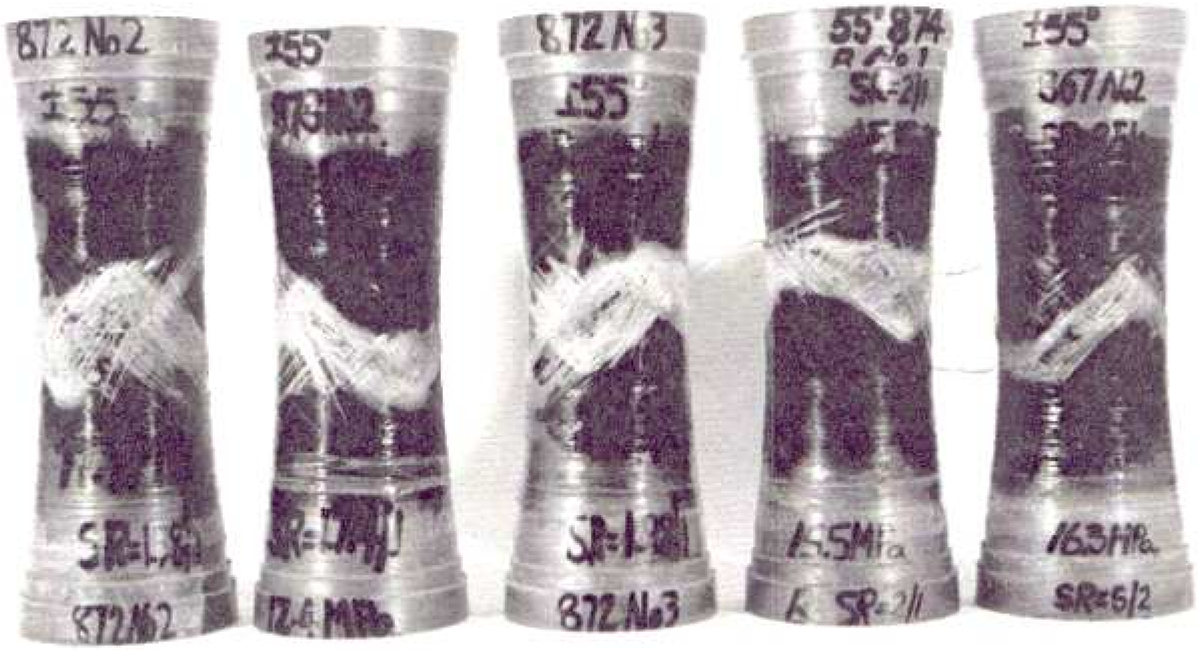
3. WWFE-I - Test Cases 9,10,11-- ±55° Glass/Epoxy

Glass/Epoxy ±55° Biaxial Test Specimens



The Netting Analysis Ratio

SR	1.58/1	1.714/1	1.98/1	2/1	2.5/1

3. WWFE-I - Test Cases 9,10,11-- ±55° Glass/Epoxy

Glass/Epoxy ±55° Biaxial Test Specimens

Moving Towards the Open Ended Burst Condition

SR	3/1	3.31/1	3.5/1	5.5/1	10.1

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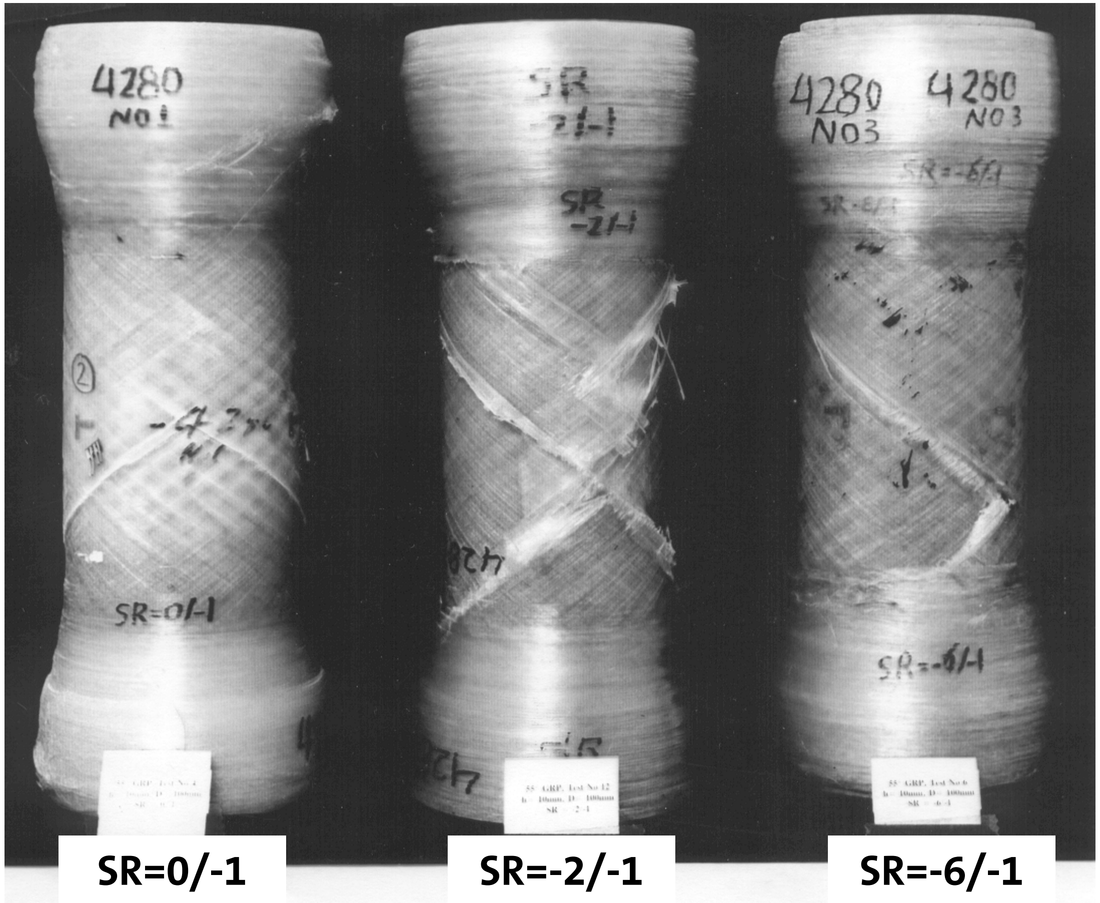
3. WWFE-I - Test Cases 9,10,11-- ±55° Glass/Epoxy

Glass/Epoxy ±55° Biaxial Compression Test Specimens



3. WWFE-I - Test Cases 9,10,11-- ±55° Glass/Epoxy

Experimental Procedure and Results

FEATURE	FAILURE STRESS σ_y (MPa)		
Stress Ratio (σ_x/σ_y)	1/0	2/1	-2/-1
Leakage Failure	386	280	None
Catastrophic Failure	595	736	-792

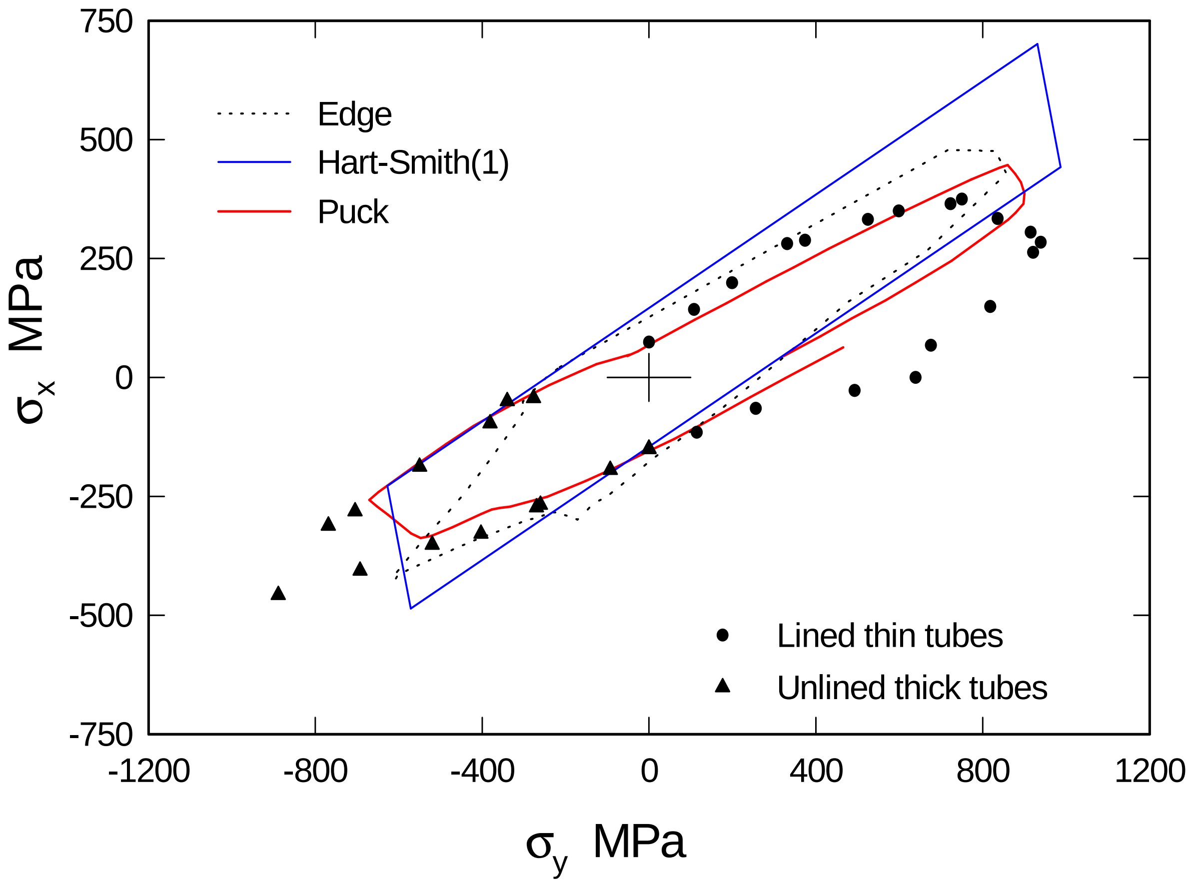
Tests were performed on both virgin and lined tubes

'Initial' failure was characterised by weeping of the test liquid through the tube wall

'Final' failure was signified by catastrophic rupture

- sometimes prefaced by significant damage and deformation well before the end point

3. WWFE-I - Test Case 9 -Failure Envelope for ±55° GRP Laminate (1)



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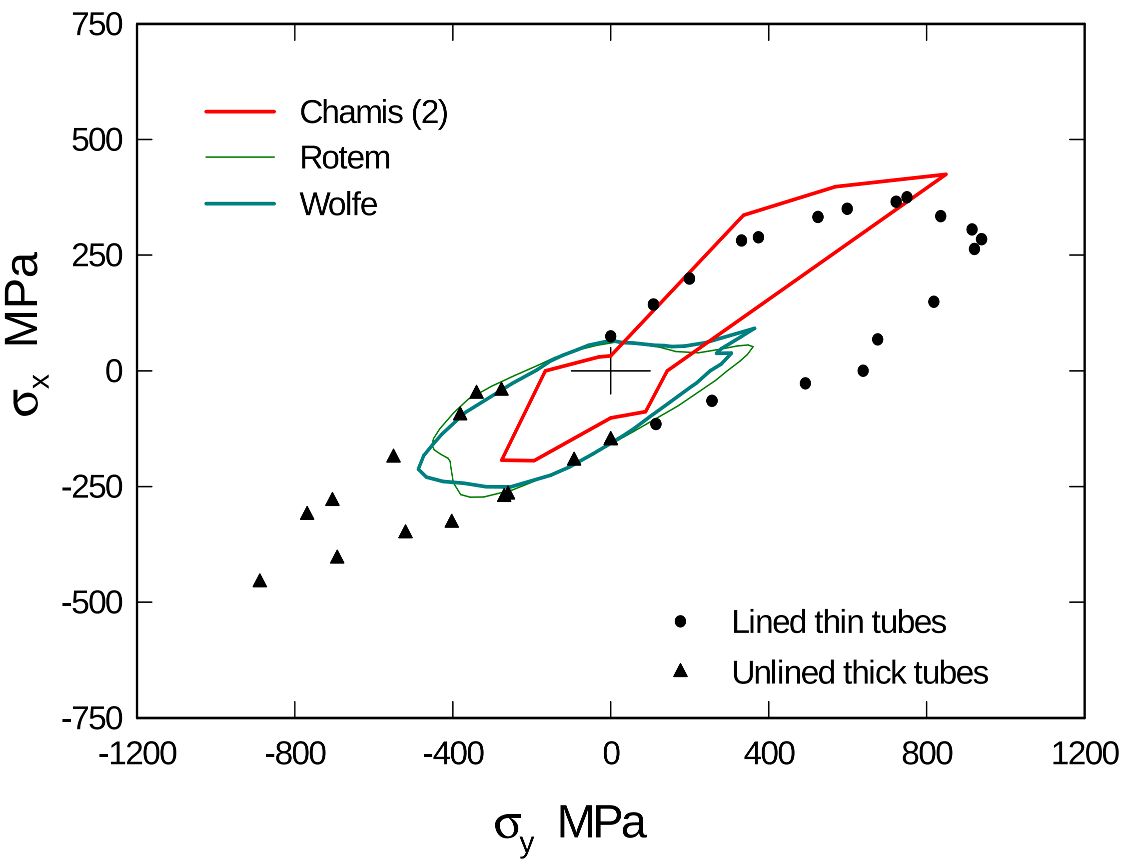
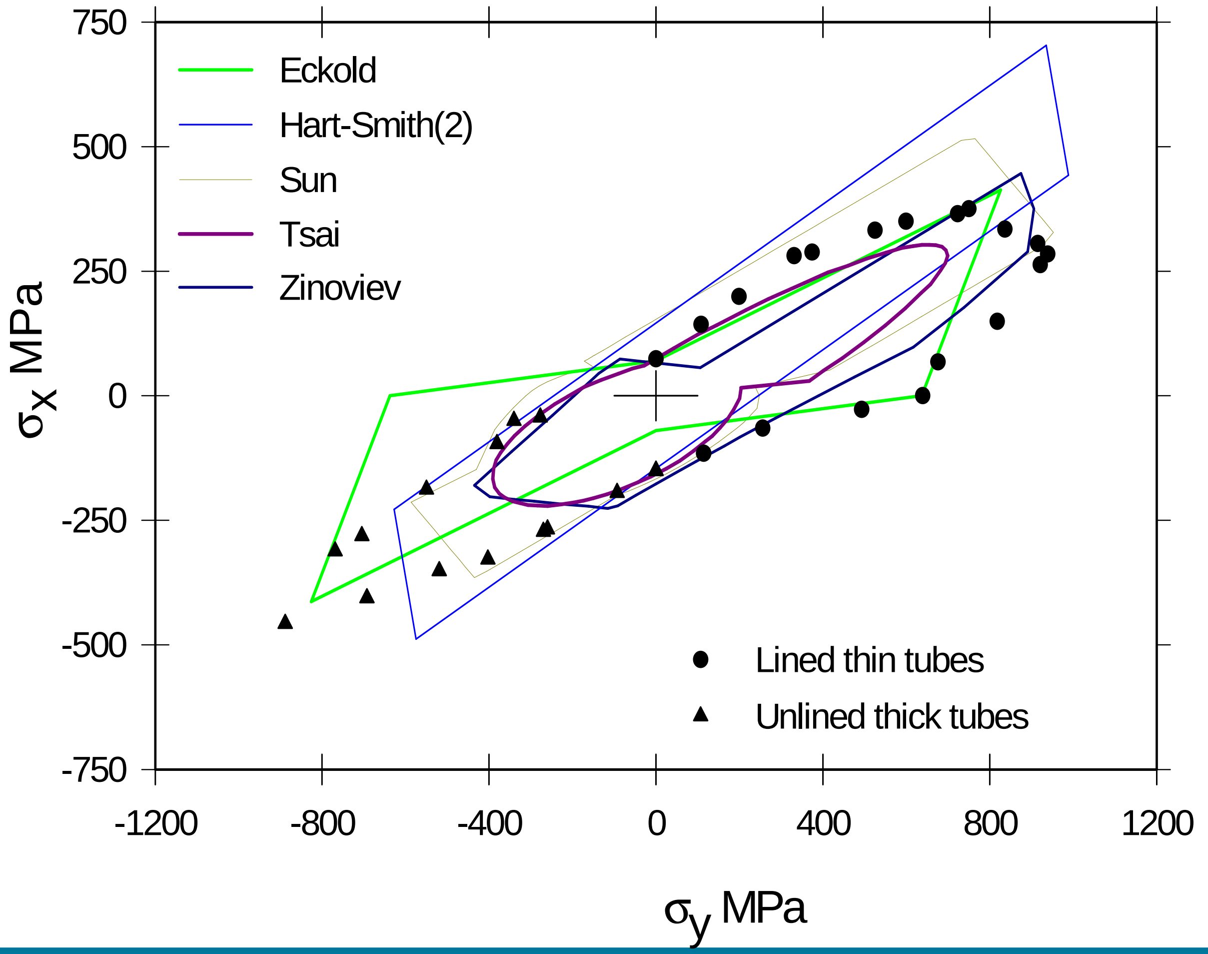


3. WWFE-I - Test Case 9 -Failure Envelope for ±55° GRP Laminate (1)



3. WWFE-I - Criteria used for ranking the WWFE theories (1)

Criterion 1: **Predicting the biaxial strength of a UD composite to within 10% of the experimental value**

Criterion 2: **Predicting the biaxial strength of multi-directional laminates to within 10% of the experimental value**

Criterion 3: **Predicting the deformation of multi-directional laminates to within 10% of the experimental value**

Criterion 4: **Predicting the general features exhibited in the experimental results**

3. WWFE-I - Ranking Criteria

- Accuracy within ± 10 %
- Accuracy within ± (>10<50)%
- Accuracy greater than ± 50%

Predicting the Biaxial Strength of a Unidirectional Composite

CHAMIS-2	ECKOLD	EDGE	HART-SMITH1	HART-SMITH2	MCCARTENY	PUCK	ROTEM	SUN(L)	Sun(NL)	TSAI	WOLFE	ZINOVIEV	Stress-ratio	Test case
1	1	1	1	1		1	1	1		1	1	1	SR =1/0	0 LAMINA UNDER SHEAR+TRANSVERSE
1	1	1	1	1		1	1	1		1	1	1	SR =0/1	0 LAMINA UNDER SHEAR+TRANSVERSE
1	0.29	1	1	1		1	1	1		1	1	1	SR = -1/0	0 LAMINA UNDER SHEAR+TRANSVERSE
1.05	1.21	1.05	1.05	1.05			1.05	1.05		0.96		1.21	SR =0.35/1	0 LAMINA UNDER SHEAR+TRANSVERSE
0.6	0.55	0.63	0.63	0.63			0.6	0.6		0.76		0.63	SR =-0.73/1	0 LAMINA UNDER SHEAR+TRANSVERSE
1		1	1	1		1	1	1		1	1	1	SR =1/0	0 LAMINA UNDER SHEAR+LONGITUDINAL
1		1	1	1		1	1	1		1	1	1	SR =-1/0	0 LAMINA UNDER SHEAR+LONGITUDINAL
1		1	1	1		1	1	1		1	1	1	SR =0/1	0 LAMINA UNDER SHEAR+LONGITUDINAL
0.778		1.05	1.05	1.05		0.92	1.05	1.05		0.831	0.92	1.05	SR =20.7/1	0 LAMINA UNDER SHEAR+LONGITUDINAL
0.65		0.71	0.71	0.71		0.71	0.76	0.71		0.71	0.76	0.71	SR =7.2/1	0 LAMINA UNDER SHEAR+LONGITUDINAL
1.02		0.84	1.3	1.3		1.16	1.3	1.3		0.98	1.18	1.3	SR =-13.6/1	0 LAMINA UNDER SHEAR+LONGITUDINAL
0.87	0.67	1.13	1.05	0.84		1.1	1.125	1.125		0.955	0.77	1.125	SR =18.8/-1	0 LAMINA UNDER LONG. +TRANS.
0.9	0.45	1.54	1.36	0.845		1.34	1.2	1.54		0.99	0.88	1.54	SR =9.3/-1	0 LAMINA UNDER LONG. +TRANS.
0.91	0.33	1.2	1.2	0.84		1.17	1.08	1.195		0.96	0.95	1.195	SR =4.23/-1	0 LAMINA UNDER LONG. +TRANS.
1	1.6	1	1	0.505		1	1	1		1	0.45	1	SR =-1/0	0 LAMINA UNDER LONG. +TRANS.
1	1	1	1	1		1	1	1		1	0.83	1	SR =1:0	0 LAMINA UNDER LONG. +TRANS.
1	0.28	1	1	1		1	1	1		1	1	1	SR =0:-1	0 LAMINA UNDER LONG. +TRANS.

Accuracy within ± 10 %
Accuracy within ± (>10<50)%
Accuracy greater than ± 50%

3. WWFE-I - Ranking Criteria

Predicting the Ultimate Strength of Multidirectional Laminates

NO	CHAMIS-2	ECKOLD	EDGE	HART-SMITH1	HART-SMITH2	McCartney	PUCK	ROTEM	SUN(L)	Sun(NL)	TSAI	WOLFE	ZINOVIEV	Stress Ratio	Test case
1	0.225	--	0.62	0.74	0.737	n	0.85	0.675	0.809	n	0.531	0.32	0.656	SR = -2.3/1	30/90 UNDER SHEAR+DIRECT STRESSES
2	0.393	--	1.01	1.08	1.08	n	0.91	0.436	0.927	n	0.535	0.21	0.818	SR = 1/1	30/90 UNDER SHEAR+DIRECT STRESSES
3	0.336	--	0.83	1	0.974	n	1.11	0.449	0.967	n	0.613	0.38	0.914	SR = 0/1	30/90 UNDER SHEAR+DIRECT STRESSES
4	0.814	1.94	0.67	1.15	1.18	n	0.84	0.734	1.222	n	0.534	0.53	0.608	SR = -1/0	30/90 UNDER SHEAR+DIRECT STRESSES
5	0.371	1.16	0.6	0.89	0.89	n	0.9	0.528	0.733	n	0.444	0.45	0.87	SR = 1/0	30/90 UNDER SHEAR+DIRECT STRESSES
6	0.41	1.09	1.34	1.43	1.43	n	1.23	0.238	1.318	n	0.909	1.02	1.272	SR = 1/2.86	30/90 UNDER DIRECT STRESSES
7	0.183	1.03	1.2	1.43	1.53	n	1.06	0.55	1.06	n	0.55	0.43	0.916	SR = 1/-1.44	30/90 UNDER DIRECT STRESSES
8	1.4	2.83	1.69	2.25	2.25	n	1.84	1.81	2.11	n	1.71	1.88	1.2	SR = -1/-2.3	30/90 UNDER DIRECT STRESSES
9	0.808	0.59	0.84	1.31	1.342	n	0.91	0.194	0.963	n	0.883	0.19	0.937	SR = 1/1	30/90 UNDER DIRECT STRESSES
10	0.842	1.75	1.82	1.35	1.35	n	2.06	1.69	1.771	n	1.49	1.07	1.824	SR = -1/0	30/90 UNDER DIRECT STRESSES
11	0.67	0.69	0.78	1.09	1.04	n	0.78	0.672	0.938	n	0.765	0.45	0.814	SR = 1/0	30/90 UNDER DIRECT STRESSES
12	--	--	1.61	1.59	1.506	n	1.56	1.641	1.614	n	1.401	1.24	1.614	SR = -1/0	0/90/45 UNDER DIRECT STRESSES
13	--	--	1.49	1.31	1.463	n	1.49	1.034	1.358	n	0.928	0.59	1.534	SR = 1/-1	0/90/45 UNDER DIRECT STRESSES
14	--	--	2.65	2.78	2.814	n	2.76	2.757	2.65	n	4.153	2.41	2.727	SR = -1/-1	0/90/45 UNDER DIRECT STRESSES
15	0.9	--	0.9	0.92	0.939	--	0.97	0.373	0.98	0.98	0.875	0.82	0.963	SR = 2/1	0/90/45 UNDER DIRECT STRESSES
16	0.496	--	0.92	0.92	0.941	--	0.98	0.766	0.94	0.94	0.863	0.72	1.013	SR = 1/0	0/90/45 UNDER DIRECT STRESSES
17	0.47	1.02	1.86	2.1	2.15		1	0.96	2.25	n	1.1	0.96	0.97	SR = 0/1	55 UNDER DIRECT STRESSES
18	0.76	0.74	1.9	1.82	1.92		0.76	0.405	1.74	n	0.85	0.41	0.44	SR = 0.75/1	55 UNDER DIRECT STRESSES
19	1.3	0.53	1.2	2.16	2.24		0.62	0.205	1.43	n	0.62	0.21	0.204	SR = 1.3/1	55 UNDER DIRECT STRESSES
20	0.292	0.79	0.48	0.53	0.544	--	0.64	0.163	0.886	n	0.65	0.19	0.91	SR = 3.3/1	55 UNDER DIRECT STRESSES
21	0.694	0.47	1.16	0.97	0.972	--	1.02	1.027	1.111	n	1.055	1.03	1.19	SR = 0/-1	55 UNDER DIRECT STRESSES
22	0.239	0.99	0.49	0.73	0.723	--	0.72	0.485	0.642	n	0.461	0.55	0.484	SR = -2/-1	55 UNDER DIRECT STRESSES
23	1.154	1.11	1.24	1.33	1.327	--	1.19	0.173	1.076	1.08	0.815	0.15	1.196	SR = 2/1	55 UNDER DIRECT STRESSES
24	0.24	1.08	0.45	0.43	0.426	--	0.57	0.479	0.417	0.42	0.336	0.43	0.655	SR = 1/0	55 UNDER DIRECT STRESSES
25	1.356	--	1.28	--	--	0.8	1.28	0.179	1.275	1.31	0.826	0.14	1.315	SR = 1/1	45 UNDER sr=1/1
26	0.539	0.61	3.17				0.78	0.924	0.771	0.78	0.771	0.77	0.952	SR = 1/-1	45 UNDER SR=1/-1
27	1.054	--	1.05	--	--	0.8	1.1	1.051	1.051	0.81	0.673	0.48	1.084	SR = 1/0	0/90 UNDER SR=1/0

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	Accuracy within ± 10 %
	Accuracy within ± (>10<50)%
	Accuracy greater than ± 50%

3. WWFE-I - Ranking Criteria

Predicting the Deformation (Failure Strain & Strain Ratios) of Multi-Directional Laminates

NO	CHAMIS-2	ECKOLD	EDGE	HART-SMITH1	HART-SMITH2	MCCARTENY	PUCK	ROTEM	SUN(L)	Sun(NL)	TSAI	WOLFE	ZINOVIEV	Stress-ratio	Test case
1	0.932		1.24				1.23	2.688	0.909	1.35	1.249	1.09	1.3	sr=1/0	AXIAL STRAIN FOR 55 GRP UNDER SR=1/0
2	19.05		0.95				0.98	0.836	1	1.04	0.997	0.76	1.065	sr=1/0	HOOP STRAIN FOR 55 GRP UNDER SR=1/0
3	1.199		1.02				0.98	2.505	0.706	1.01	0.779	1.08	0.951	sr=1/0	STRAIN RATIO FOR 55 GRP UNDER SR=1/0
4	0.992		0.9				1.01		1.52	1.01	0.993	0.9	0.974	sr=2/1	AXIAL STRAIN FOR 55 GRP UNDER SR=2/1
5	0.959		0.88				0.99	0.482	1.018	0.89	0.942	0.83	0.986	sr=2/1	HOOP STRAIN FOR 55 GRP UNDER SR=2/1
6	0.965		0.97				0.98		0.668	1.1	0.949	0.97	1.011	sr=2/1	STRAIN RATIO FOR 55 GRP UNDER SR=2/1
7	1.41/0.	0.06	1.34				0.41	0.198	0.122	0.2	0.08	0.21	0.378	sr=1/0	HOOP STRAIN FOR 0/90/45 CFRP UNDER SR=1/0
8	-0.03		1.35				-0.3	-0.14	-0.056	-0.14	-0.04	-0.1	-0.302	sr=1/0	AXIAL STRAIN FOR 0/90/45 CFRP UNDER SR=1/0
9	0.475	0.47	0.81				0.82	0.696	0.46	0.7	0.536	0.71	0.799	sr=1/0	STRAIN RATIO FOR 0/90/45 CFRP UNDER SR=1/0
10	1.32	0.2	1.69				0.14	1.512	0.884	1.42	0.864	0.13	1.116	sr=2/1	HOOP STRAIN FOR 0/90/45 CFRP UNDER SR=2/1
11	0.306	0.12	-0.3				0.33	0.023	0.655	0.22	0.31	0.02	0.66	sr=2/1	AXIAL STRAIN FOR 0/90/45 CFRP UNDER SR=2/1
12	0.229		-0.17				0.23	0.143	0.736	0.15	0.359	0.15	0.596	sr=2/1	STRAIN RATIO FOR 0/90/45 CFRP UNDER SR=2/1
13	0.77	0.19	1.02			0.77	1.06	1.04	1.062	0.84	0.616	0.46	1.033	sr=1/0	AXIAL STRAIN FOR 0/90 GRP UNDER SR=1/0
14	2.404	0.8	1.63			1.26	0.2	6.232	-0.4	2.8	1.032	0.7	0.896	sr=1/0	TRANS. STRAIN FOR 0/90 GRP UNDER SR=1/0
15	3.118	3.15	1.6			1.64	0.18	5.976	0.376	3.35	1.685	1.9	0.866	sr=1/0	POISSON'S RATIO FOR 0/90 GRP UNDER SR=1/0
16	6.743	0.2	1.13			0.6	1.16	0.091	1.131	1.31	0.712	0.09	1.123	sr=1/1	HOOP STRAIN FOR 45 GRP UNDER SR=1/1
17	7.663	0.23	1.29			0.68	1.32	0.103	1.285	1.49	0.809	0.1	1.276	sr=1/1	AXIAL STRAIN FOR 45 GRP UNDER SR=1/1
18	1.136	1.14	1.14			1.14	1.14	1.136	1.136	1.14	1.136	1.14	1.136	sr=1/1	STRAIN RATIO FOR 45 GRP UNDER SR=1/1
19	-0.04	-0.04	1.34				-0.2	-0.15	-0.056	-0.18	-0.06	-0.2	-0.776	sr=1/-1	AXIAL STRAIN FOR 45 GRP UNDER SR=1/-1
20	0.044	0.05	1.52				0.27	0.159	0.064	0.2	0.064	0.2	0.82	sr=1/-1	HOOP STRAIN FOR 45 GRP UNDER SR=1/-1

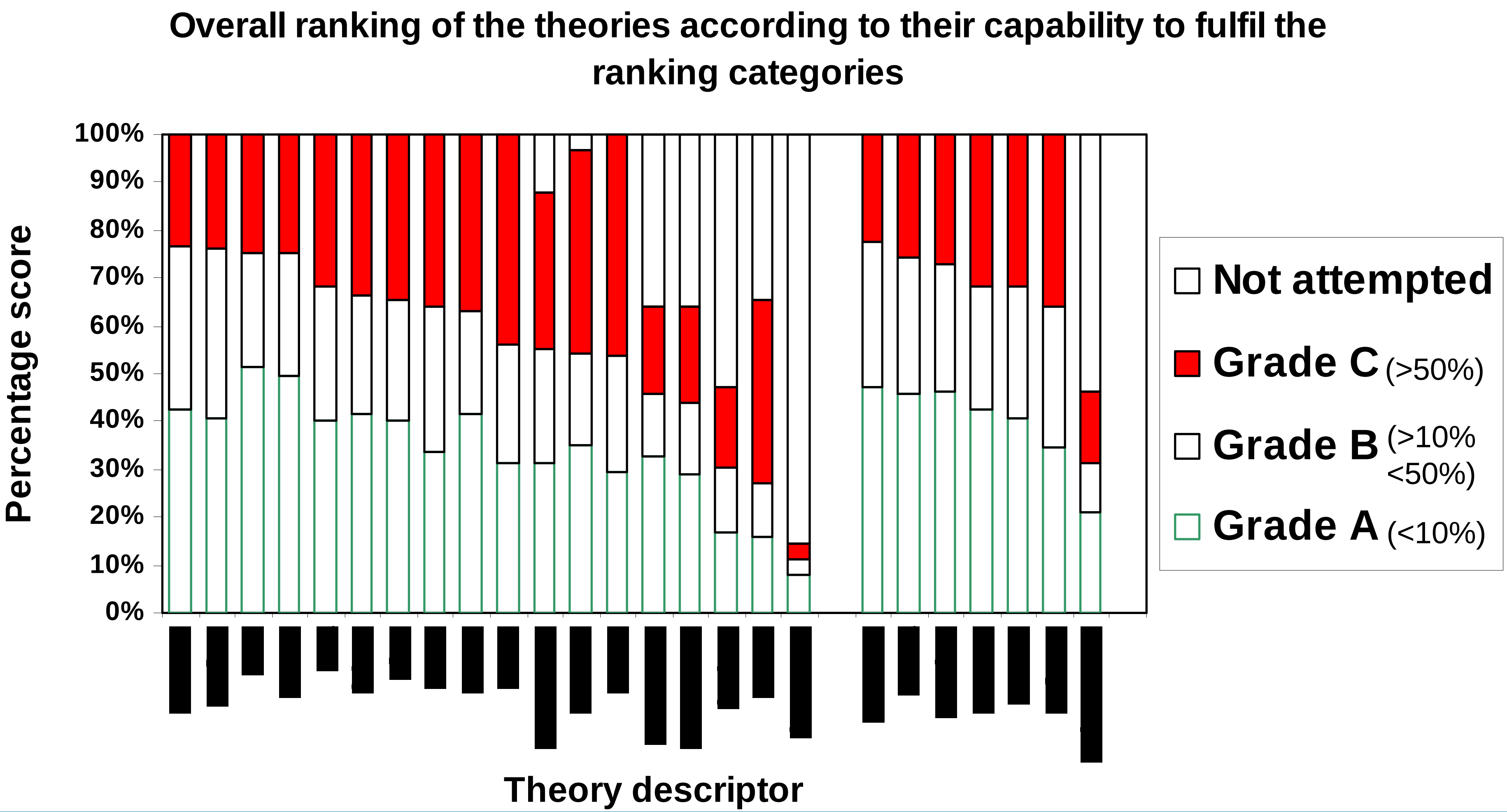
	Accuracy within ± 10 %
	Accuracy within ± (>10<50)%
	Accuracy greater than ± 50%

3. WWFE-I - Ranking Criteria

Predicting the Initial Failure in Multi-Directional Laminates

NO	CHAMIS-2	ECKOLD	EDGE	HART-SMITH1	HART-SMITH2	MCCARTENY	PUCK	ROTEM	SUN(L)	Sun(NL)	TSAI	WOLFE	ZINOVIEV	Test Case No.	Test case
1	0.97	0.98	0.93			0.97	1.01	1.09	0.97	0.97	1.04	0.98	0.97	12	Initial modulus or slope for 0/90 grp under SR =1/0
2	1.14	1.08	0.98			1.07	1.39	1.42	1.13	1.07	1.35	1.01	1.08	12	Poisson's Ratio for 0/90 grp under SR =1/0
3		1.32	0.45			1.05	0.47	0.6	0.8	0.66	0.81	0.65	0.66	12	Failure stress of 0/90 grp under SR =1/0
4		1.33	0.46			1.05	0.46	0.54	0.693	0.66	0.757	0.67	0.66	12	Failure strain in loading direction for 0/90 grp
5		3.03	0.92			1.67	0.82	1	1.14		1.417	1.17	1.14	13	Failure stress at initial cracking for 45 grp under SR =1/1
6	0.038		0.09				0.43	0.575	0.389		0.45	0.55	0.603	7	initial failure stress for 0/90/45 cfrp under SR =1/0
10	0.033		0.08				0.37	0.511	0.347		0.444	0.55	0.54	8	initial failure stress for 0/90/45 cfrp under SR =2/1
7	0.103	0.11	0.18				0.2	0.186	0.282		0.262	0.39	0.324	9	Unlined Failure stress for 55 grp at SR=5.5:1
8	0.095	0.16	0.14				0.16	0.163	0.251		0.272	0.25	0.248	9	Unlined Failure stress from 55 grp at SR=3:1
9	0.326	0.63	0.41				0.51	0.51	0.739		0.78	0.65	0.65	9	Unlined Failure stress for 55 grp at SR=0.75:1
11	0.308	0.17	0.69				0.85	0.534	0.642	0.65	0.518	0.66	0.516	10	Unlined Failure stress from 55 grp under SR =1/0
12	0.532	0.52	0.91				0.92	0.779	0.515	0.79	0.599	0.76	0.894	10	Poisson's ratio at leakage for 55grp under SR =1/0
13	-0.06	-0.06	-0.57				-0.8	-0.31	-0.126	-0.32	-0.1	-0.3	-0.68	10	Axial strain of unlined specimens from 55 grp under SR =1/0
14	0.112	0.11	0.63				0.83	0.4	0.245	0.4	0.165	0.42	0.761	10	Hoop strain of unlined specimens from 55 grp under SR =1/0
15	0.161	0.59	0.25				0.31	0.336	0.432	0.43	0.464	0.4	0.4	11	Unlined Failure stress from 55 grp under SR =2/1

3. WWFE-I - Ranking Criteria



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3. WWFE-1 - Achievements

- **Provided designers with guidelines on accuracy and bounds of applicability for the current failure theories.**
- Brought together the thoughts & experience of key members of world community, traditionally at odds, to advance the science
- Altered the philosophies of renowned theoreticians about the definition of failure, creating a greater insight

3. WWFE-1 - Achievements

- Resulted in improvements to theories by identifying weaknesses
  - 50% of theories were modified.
  - 40 year old, widely adopted theories were modified for the first time.
  - the modified theories now being embedded in numerical software packages

- Highlighted gaps in theoretical &experimental understanding for the community to focus on

3. WWFE-1 - Publications

Expert Meeting 1992

Exercise launched

Originators of failure theories/Designers & Software houses, invited

Call made for 'good test data'

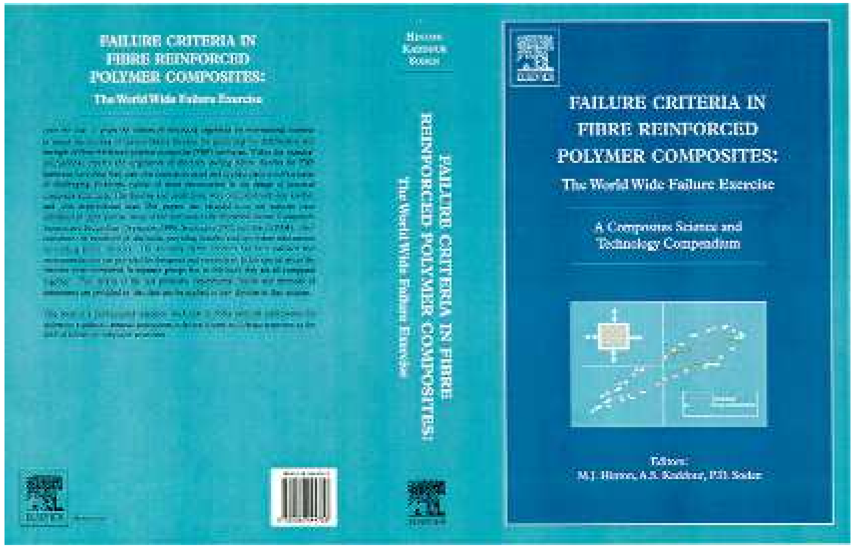
14 Challenging problems identified

19 best known failure criteria evaluated

3 International Journal Special Editions produced

Book Published By Elsevier 2004

Hinton, Kaddour, Soden



2004

2002

1998

3. WWFE-1 - Gaps that have been identified (1)

- Applicability of composite failure criteria to isotropic materials
- Effects of pressure on shear strength and deformation of UD lamina
- Failure of unidirectional lamina (UD) under hydrostatic pressure
- Effect of through-thickness stress on biaxial failure of UD lamina
- Effects of 3D stresses on the failure of multi-directional laminates
- Deformation of laminates under hydrostatic pressure
- 3D elastic constants of multidirectional laminates
- Effects of lay-up on through-thickness strength of laminates
- Failure under combined through-thickness and shear of laminates

Failure Under 3-D Stress States

3. WWFE-1 - Gaps that have been identified (2)

- Damage initiation and evolution
- Matrix cracks initiation and crack density evolution
- Delamination initiation and propagation
- Effects of ply thickness, constraints
- Effects of ply stacking sequence
- Cracking under thermal loading
- Monotonic loading, unloading and reloading
- Failure at stress concentration (e.g. open hole)
- Statistical and probabilistic nature of failure
- Leakage prediction

Failure of Damaged Laminates

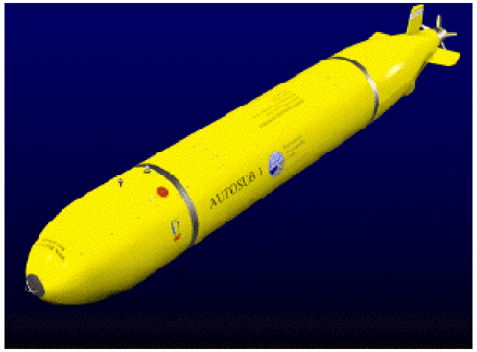
3. WWFE-1 - Gaps that have been identified (3)

The Second World-Wide Failure Exercise (WWFE-II)

Benchmarking of failure criteria under tri-axial stresses for fibre-reinforced polymer composites

Courtesy of Vestas Wind System

Rotor blades are thick at the root?

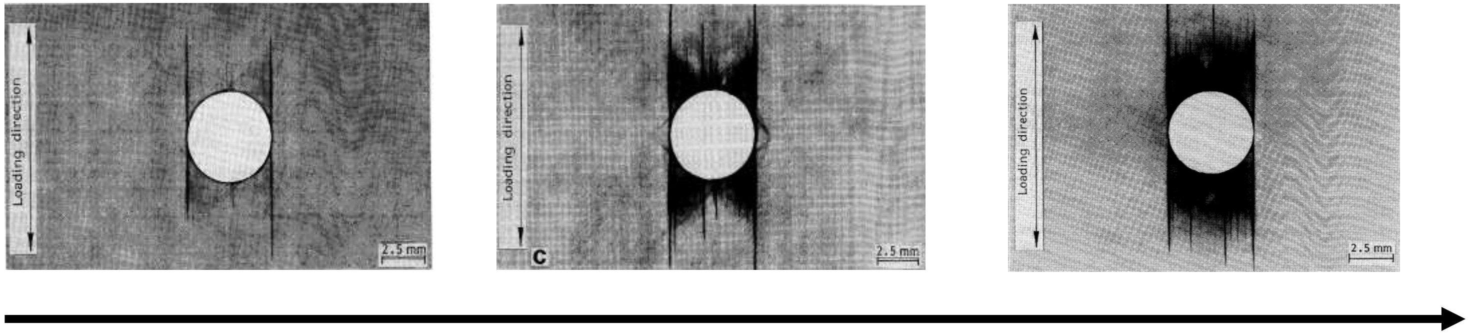


Deep-water application require increased thickness to avoid collapse?

3. WWFE-1 - Gaps that have been identified (4)

The Third World-Wide Failure Exercise (WWFE-III)

Damage, fracture and continuum mechanics theories for fibre-reinforced polymer composites



Compression-compression fatigue (+/-45/0_2)s CFRP, (Soutis et al).

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4. WWFE-II - A Quick Look

The Second World-Wide Failure Exercise (WWFE-II)

Benchmarking of failure criteria under tri-axial stresses for fibre-reinforced polymer composites

4. WWFE-II - Contributors to WWFE-2 (from the 60 groups invited)

	Group/name	Country	Organisation	Method/ failure criteria
1	Bogetti, Staniszewski, Burns, Hoppel, Gillespie and Tierney	USA	U.S. Army Research Laboratory	Maximum strain failure criterion
2	Carrere / Maire	France	ONERA	Chaboche's anisotropic damage
3	Cuntze	Germany	Germany	Failure Mode Concept (FMC)
4	Nelson, Hansen, Mayes	USA	Wyoming University	Multi-continuum micro-mechanics theory
5	Huang	China	Tongi University	Generalised max stress/bridging model
6	Kress	Switzerland	ETZ Zurich (Switzerland)	Hashin's theory
7	Deuschle and Kroeplin	Germany	Stuttgart university	Puck's phenomenological failure criteria
8	Pinho/Robinson/ Camanho	UK/UK/ Portugal	Imperial College/Imperial College/ University of Porto/ NASA	Improved failure criterion
9	Rotem	Israel	Technion University	Interactive matrix and fibre failure theory
10	Tsai and Ha	USA	Stanford University/ South Korea	Tsai's interactive failure theory
11	Wolfe, Butalia, Zand and Schoeppner	USA	Ohio State University, AFRL, Wright-Patterson, AFB, Ohio (USA)	Maximum strain energy failure theory
12	Ye	UK	Leeds University	Christensen's theory

Red colour: Contributors to WWFE-1

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4. WWFE-II - Progress to date

Stage	Activities	Status
1-Establish Framework	•Consultation with leading experts •Call for contribution of high quality experimental data •Selection of participants •Issue invitation letter •Participant agrees/declines •Establish participants list •Selection of "test cases" •Define Materials properties •Parameters to be predicted •Assemble Data-Pack 1	Completed
2-PART (A): Blind theoretical predictions	•Issue Data-Pack 1 and Instructions •Participant proceeds/withdraws •Establish participants list •Submission of Part A papers: (*blind* theoretical prediction) •Stringent reviewing of papers •Publish Part (A)	Completed
3-PART (B): Comparison with Test data	•Issue Data-Pack 2 and Instructions •Submission of Part B papers: Comparison with experiments	Completed
	•Stringent reviewing of papers •Publish Part (B)	Remaining

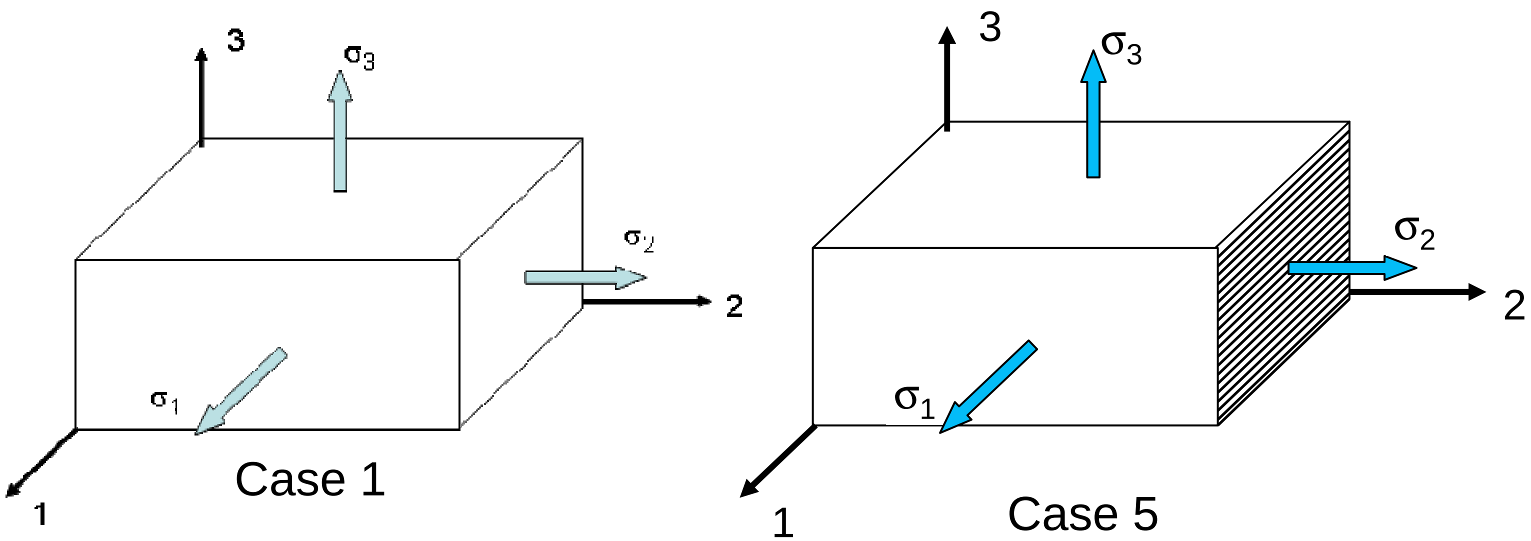
4. WWFE-II - A Quick Look (Test Cases 1 and 5)

- Test Case 1 deals with an isotropic material (Epoxy resin) subjected to a range of triaxial stress states.
- Test Case 5 is concerned with a unidirectional laminate (a U/D Glass/Epoxy) subjected to the same conditions.
- The two Cases are interrelated insofar as the epoxy polymer material studied in Case 1 is the same resin matrix used in making the E-glass/epoxy composite laminate in Test Case 5.

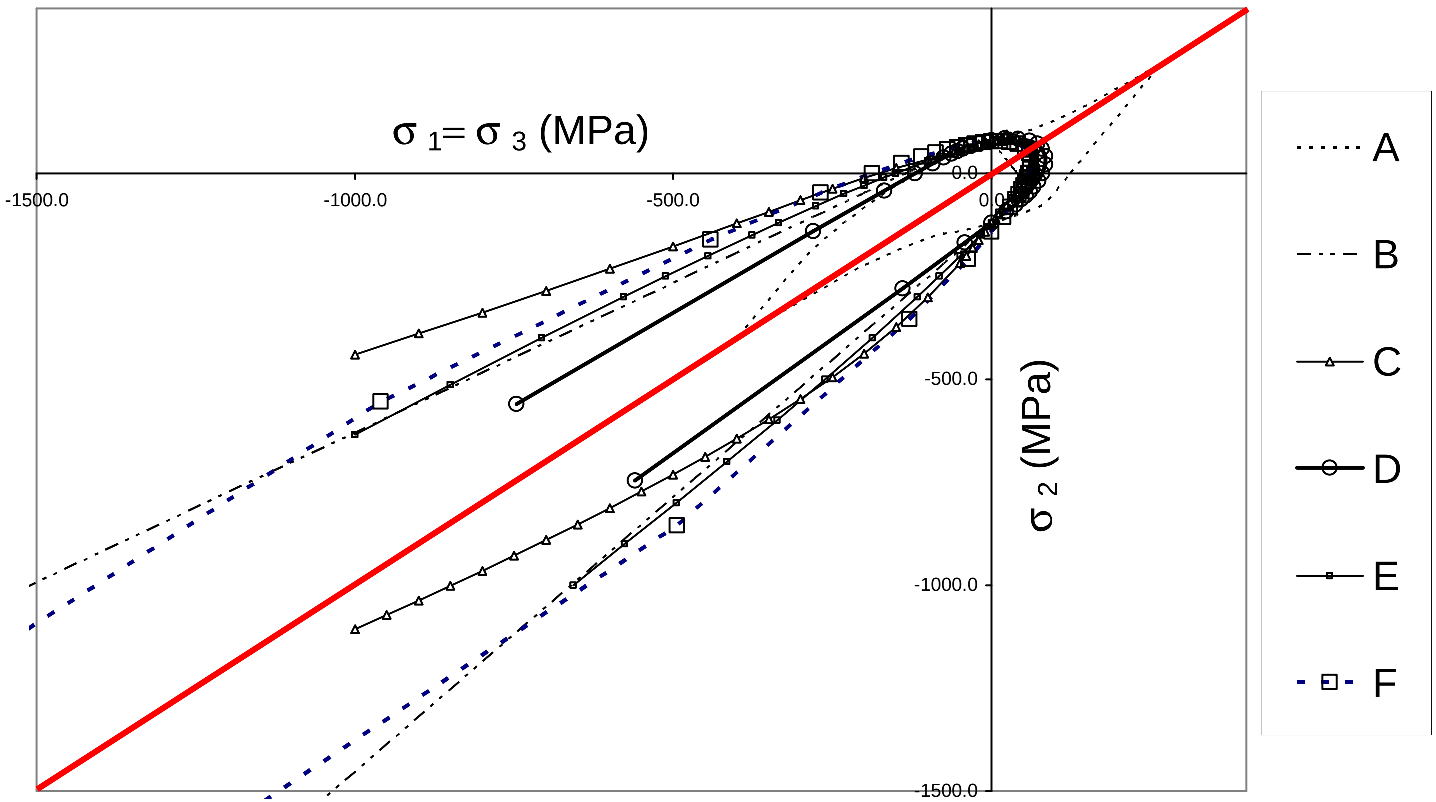
Treatment of material isotropy/anisotropy and material heterogeneity

4. WWFE-II - A Quick Look (Test Cases 1 and 5)

Test Case	Laminate lay-up	Material	Required predictions
1	Resin	MY750 epoxy	σ_2 versus σ_3 (σ_1 = σ_3) envelope
5	0°	E-glass/MY750	σ_2 versus σ_3 (σ_1= σ_3) envelope

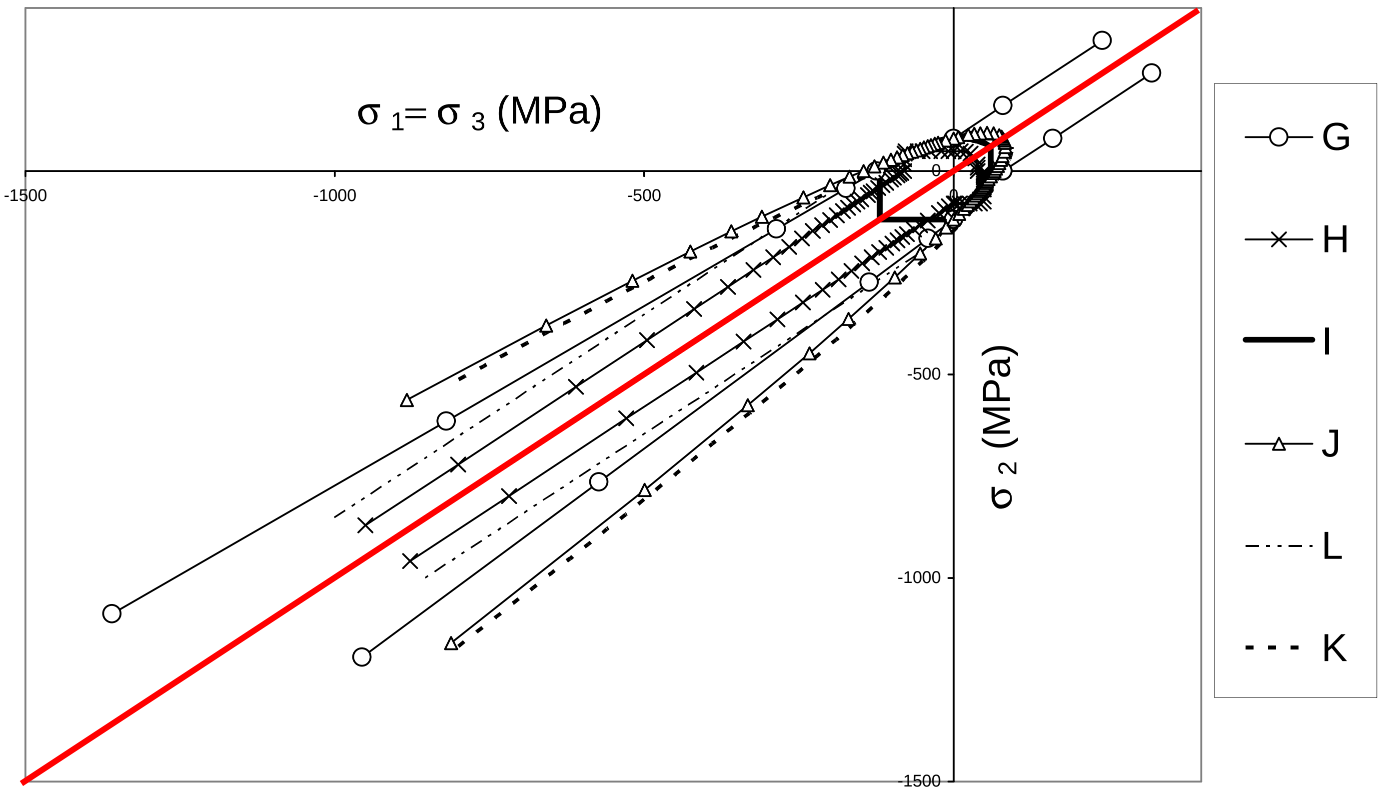


4. WWFE-II - Test Case 1 - Epoxy Resin (1/2)



5 open curves, 1 closed curve in compression – compression quadrant
All curves are closed in the tension-tension quadrant

4. WWFE-II - Test Case 1 - Epoxy Resin (1/2)



5 open curves, 1 closed curve in compression–compression quadrant
5 closed curves, 1 open curve in tension-tension quadrant

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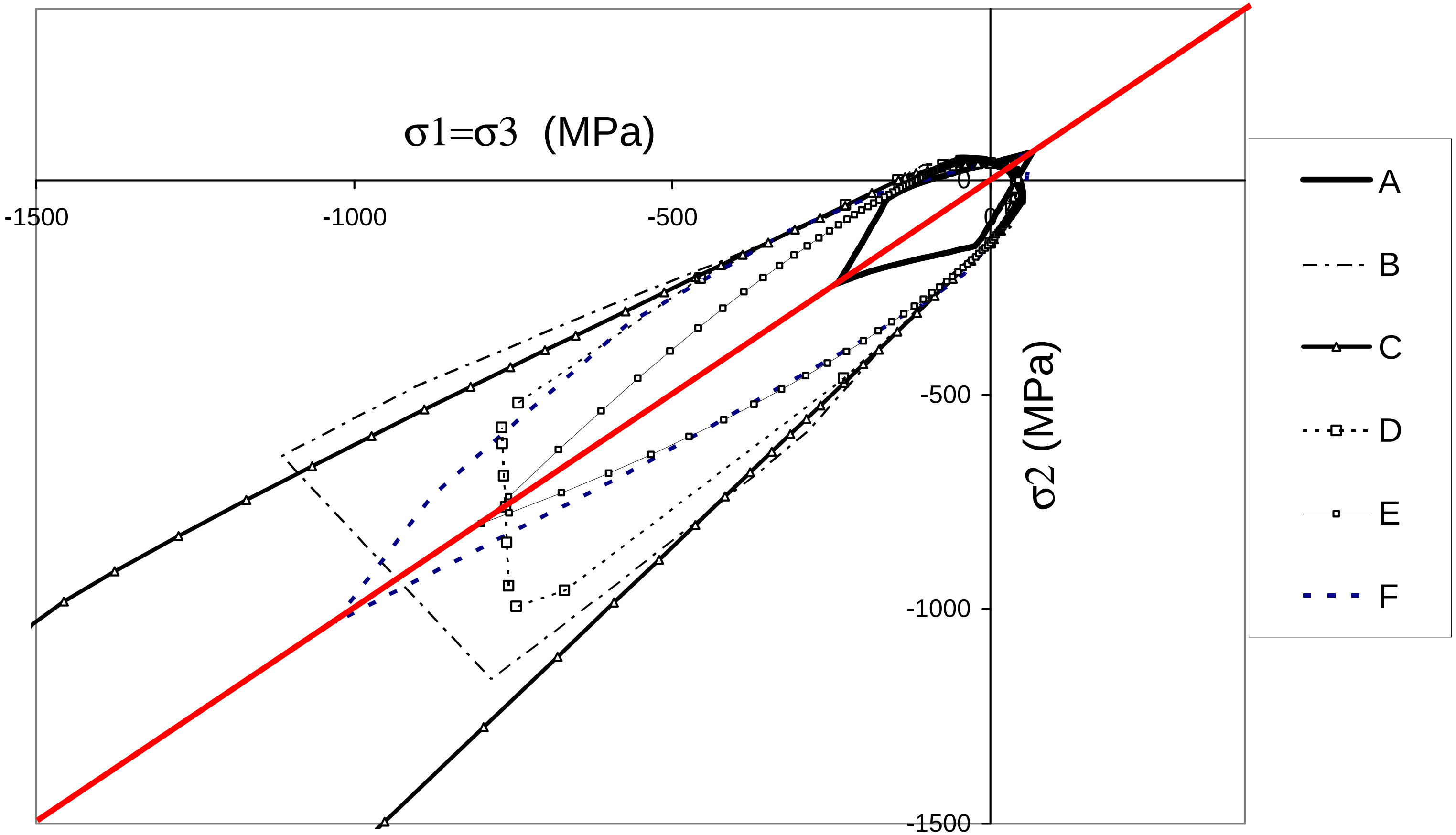
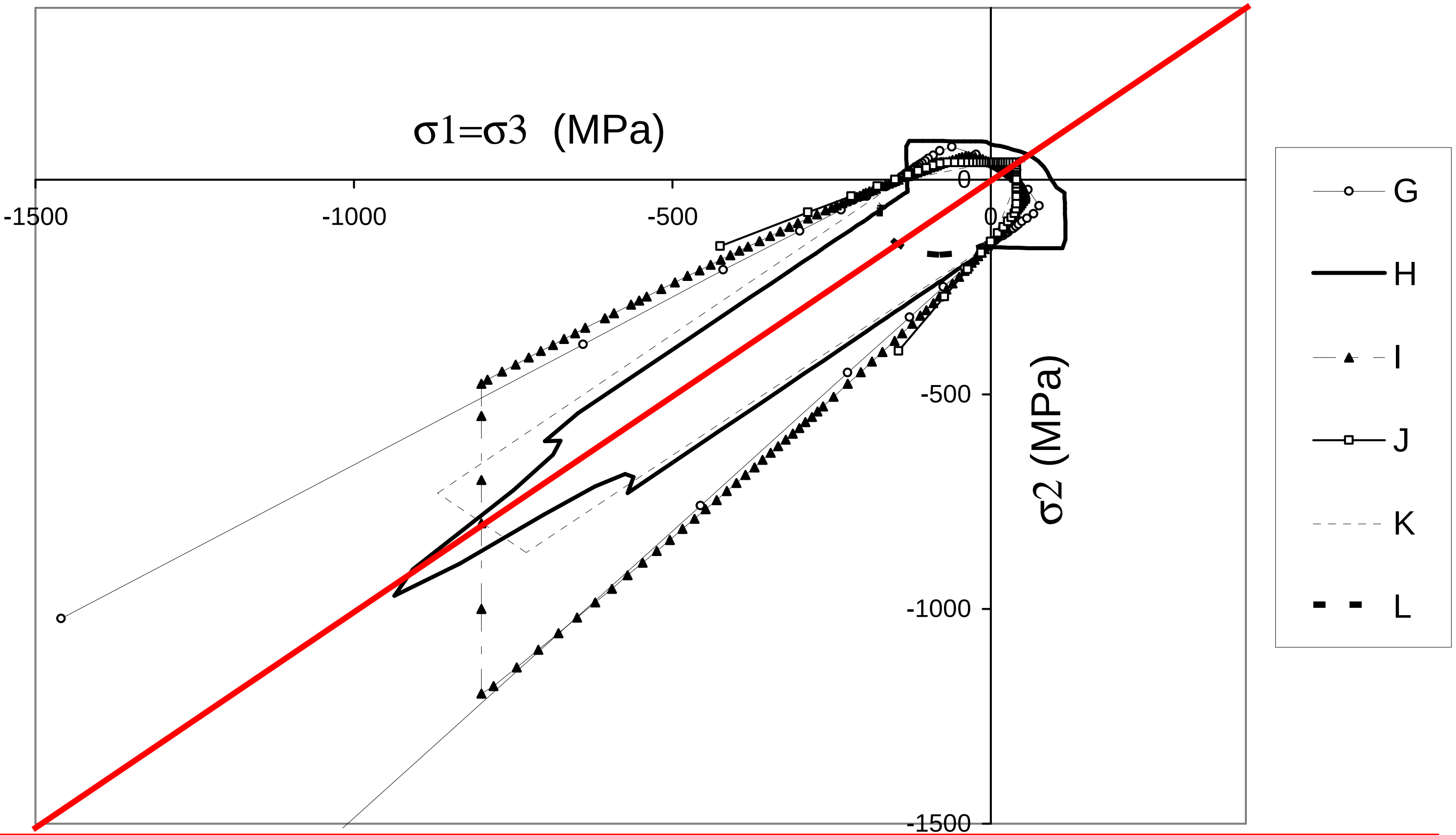
4. WWFE-II - Test Case 5 – U/D Glass/Epoxy



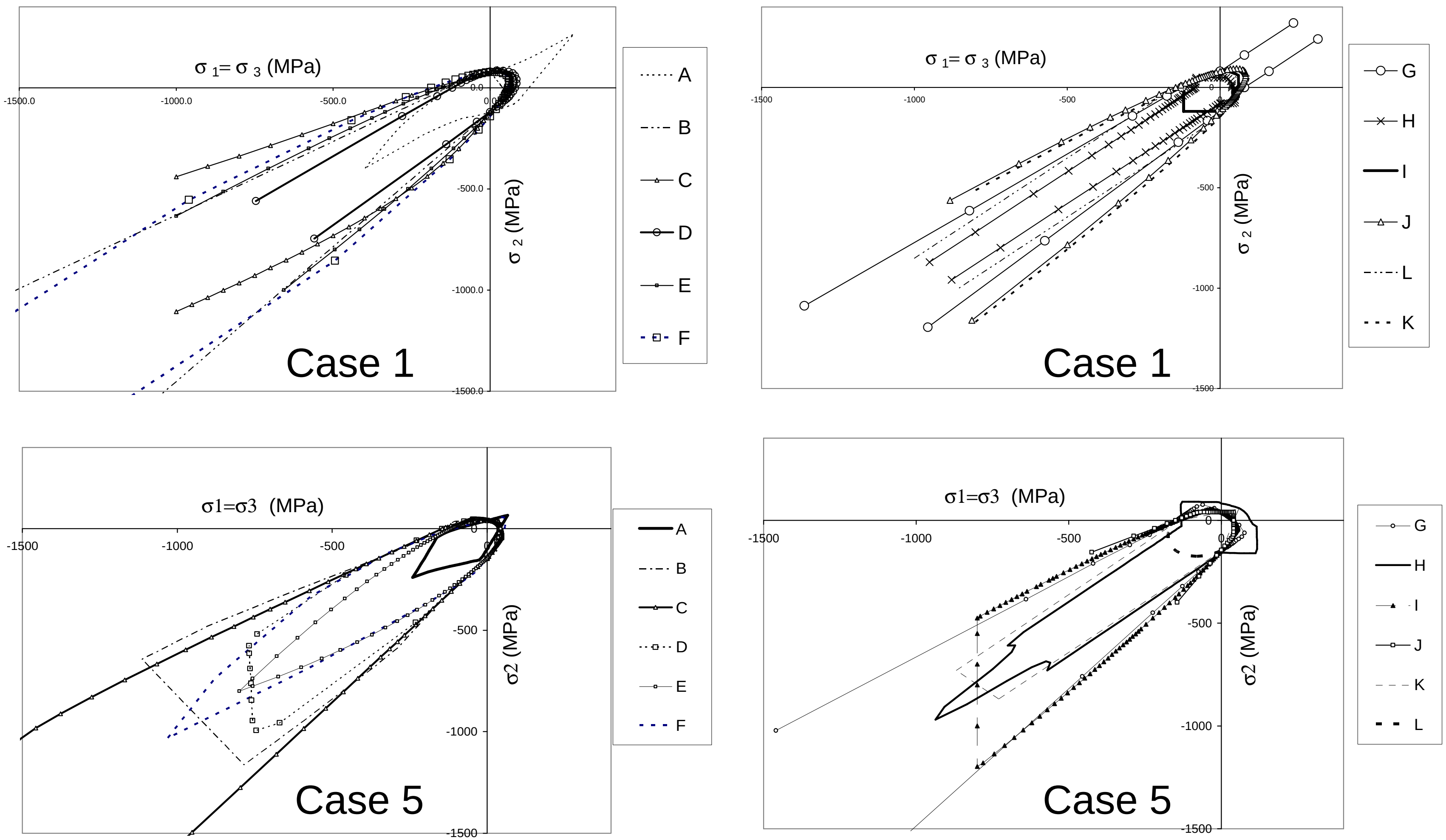
5 closed curves, 1 open curve in compression–compression quadrant
All curves are closed in the tension-tension quadrant

4. WWFE-II - Test Case 5 – U/D Glass/Epoxy



1 open curve, 5 closed curves in compression–compression quadrant
All curves are closed in the tension-tension quadrant

• WWFE-II - Comparison between Test Cases 1 (Epoxy) and Test Case 5 (U/D Glass/Epoxy)



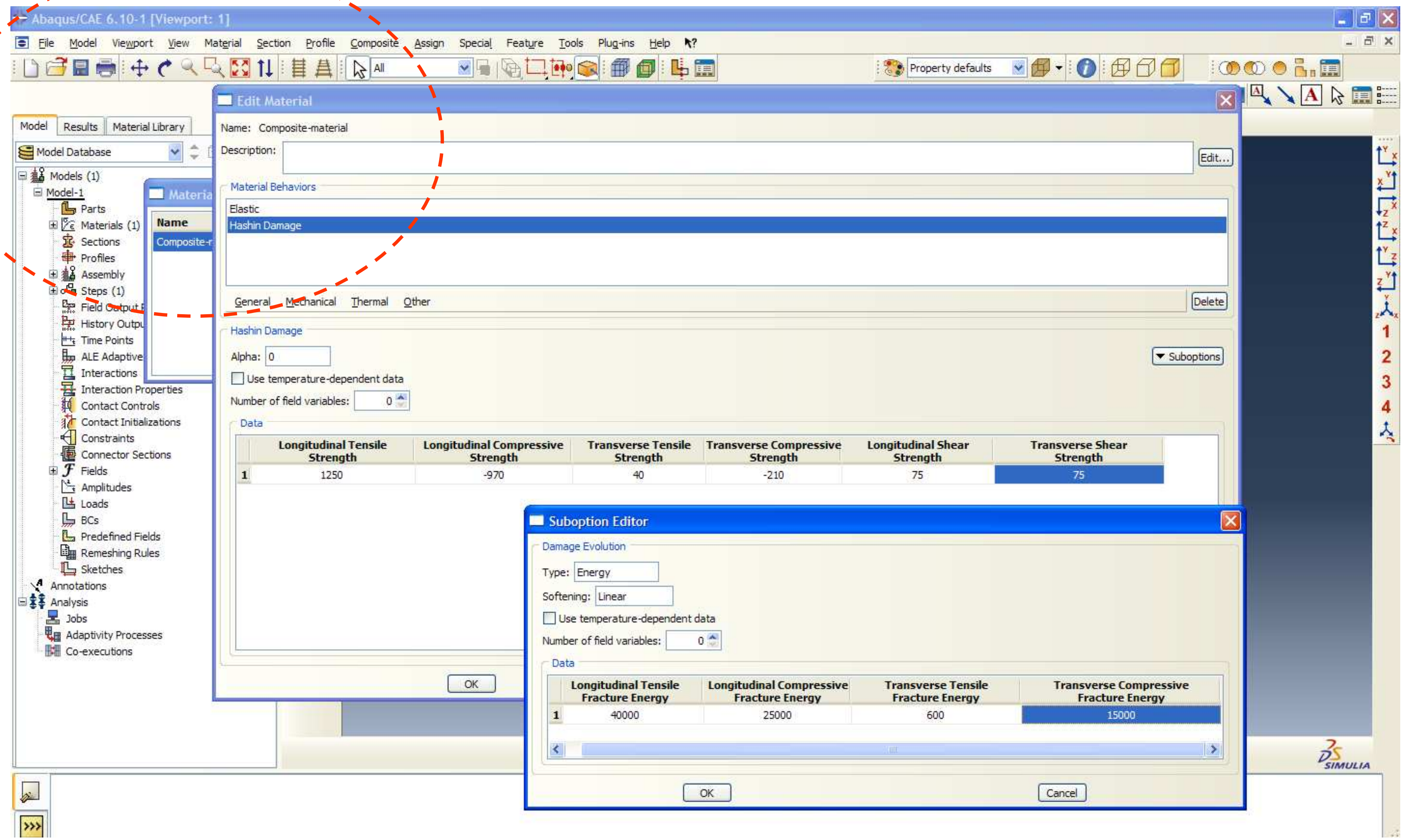
4. WWFE-II - Early Observations from Test Cases 1 and 5

- Most theoreticians (10 out of 12) employed separate equations to delineate between isotropic (Test Case 1) and heterogeneous (Test Case 2) materials.
- A conscious ‘operator intervention’ is required to make that selection (is that what designers want ?)
- There was significant diversity between the theoretical predictions for Test Cases 1 and 5
  - in terms of the shapes of the failure envelopes and
  - whether or not the envelopes should be open under hydrostatic compressive and/or tensile loading situations.
- The remaining Test Cases will undoubtedly provide further evidence of the resilience (or lack of) for the 12 theories

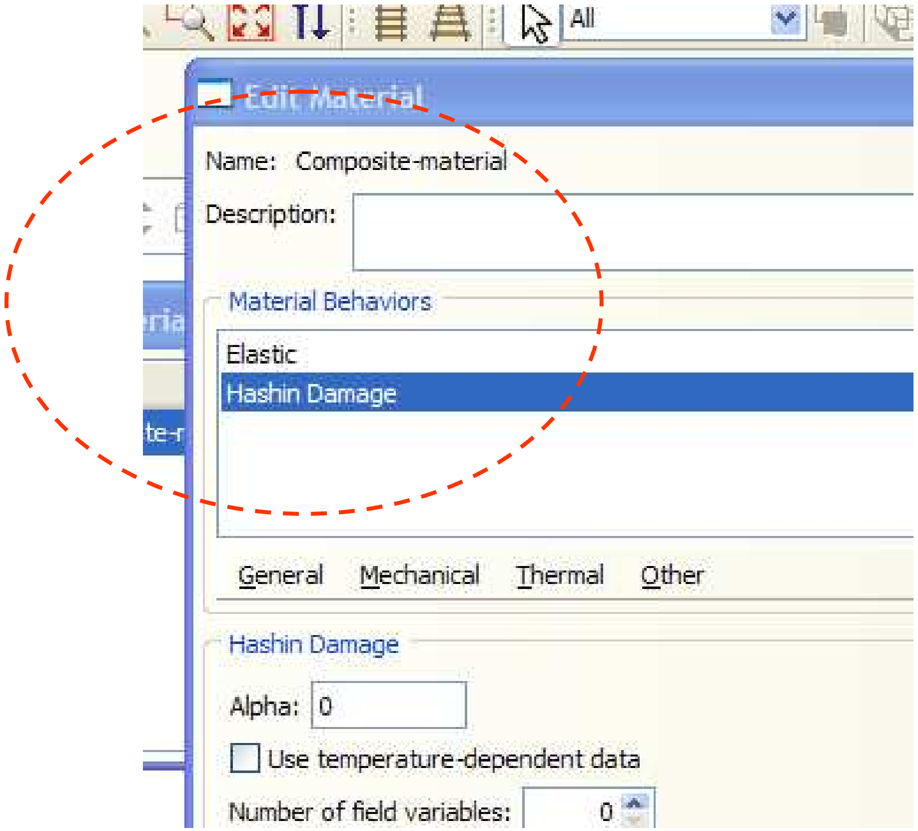
Watch this space for the next instalment !

5. Closing Remarks

5. Closing Remarks - Maintaining Awareness



5. Closing Remarks - Maintaining Awareness



5. Closing Remarks - Maintaining Awareness

Professor Hashin's reasoning for declining to participate in WWFE-I, is worth noting (quoting from his letter to the organisers) :-

"my only work in this subject relates to failure criteria of unidirectional fibre composites, not to laminates. ……..

……….I must say to you that I personally do not know how to predict the failure of a laminate (and furthermore, that I do not believe that anybody else does)".

5. Closing Remarks

- Use current predictive failure theories with caution
  (a look at the literature is recommended)

- If you think this is a mature domain - It isn't !

- High quality experimental data is required to validate many aspects of predictive failure theories

5. Closing Remarks

- The theories coded into current FE tools almost certainly differ from the original theory and from the original creator's intent.

- Continued effort is needed to bridge the gap between academia, industry and the software houses in this domain

Keep an eye for the output from WWFE-II and WWFE-III

5. Closing Remarks - Timelines for completing WWFE-II and WWFE-III

No	Activity	Anticipated date
1A	WWWF-II: Part A	Q3 2011
2A	WWFE-II: Part B	Q4 2011
3A	Book combining Part A and Part B	Q2 2012
1B	WWFE-III: Part A	Q4 2011
2B	WWFE-III: Part B	Q2 2012
3B	Book combining Part A and Part B	Q4 2012

5. Closing Remarks - Final Comment

The Organisers of the ‘World Wide Failure Exercises’ wish to thank all of the participating authors.

Due to their generous support, the Exercise has been made possible and a great opportunity created to make significant progress in this difficult area.

Thank you for your attention

Any Questions?