ID-1608

COMPRESSION TESTING OF GLASS EPOXY NON-CRIMP FABRICS CONTAINING ELASTIC INSERTS

Dr Simon. E. Aramah [1] and Proff. Paul. J. Hogg [2]

[1] *Ford Motor Company, Product Development Europe, Dunton Technical Centre, UK*
[2] *Department of Materials, Queen Mary, University of London*

SUMMARY: A damage tolerance program is conducted in order to assess the effects of damage stiffness upon the residual strength of a Non-Crimp Fabric (NCF) loaded in compression. Reductions in damage stiffness are achieved by inserting homo-polymer materials (Nylon, Acrylic and PTFE) into an NCF compression test specimen. Mechanical test results show a decrease in compression strength with decreasing insert stiffness. Observations of specimen behaviour during testing reveal pseudo-CAI failure mechanisms. A predictive method for obtaining the residual strength for material containing impact damage is presented. Its development is based upon the Point and Average Stress Criterion as presented by Whitney and Nuismer [4]. The predictive method shows good agreement with the experimental data and reflects the trend observed of decreasing residual strength with decreasing damage stiffness.

KEYWORDS: Compression Testing, Non-Crimp Fabric, Elastic Insert, Impact Damage, Stress Fracture Criterion

INTRODUCTION

Polymer composites are prone to significant performance loss when subjected to impact damage. The greatest performance loss is observed when the structure (or specimen) is subjected to compressive loading. Reductions in strength of up to 50% have been observed (Cantwell and Morton) [1]. It is hypothesised that the reduction in compression strength after impact damage (CAI) is via the reduction in the stiffness properties of the impacted area. Thus an experimental program is conducted to prove this hypothesis.

MATERIALS/EXPERIMENTAL METHODS

A quasi-isotropic glass/epoxy Non-Crimp Fabric composite is used for the investigation. A non-crimped fabric is a “warp knitted” type fabric held together using a secondary fibre yarn knitted around the structural fibres, see fig. 1.

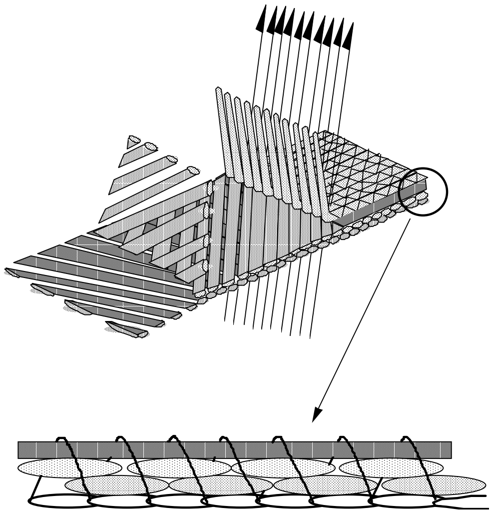

Fig. 1: A schematic diagram of the construction of a Non-Crimp-Fabric (NCF)

This type of fabric consists of reinforcement architecture that reduces fibre crimpage compared to that observed in a woven fabric (Crimpage is the undulation of the fibre tows caused by weaving fibre tows over one another). All laminates were constructed by hand lay-up with a fibre volume fraction (V_f) of 50%. The NCF is E-Glass based and was supplied by BTI-Europe. The fabric was impregnated with Shell Epikote 828-epoxy resin and Ciba-Geigy Araldite HY932 hardener mixed at a ratio of 3:1 by weight. All laminates were constructed with the following lay-up, see fig 2; $[(+45/90/-45/0)_2/(0/+45/90/-45)_2]$. This resulted in a laminate that was balanced but non-symmetric.

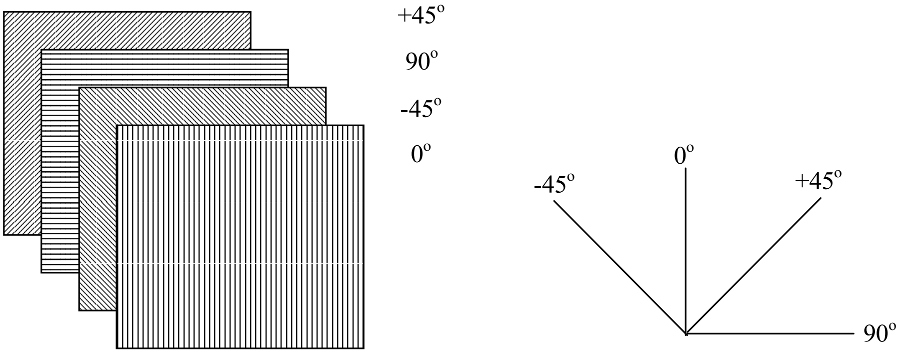

Fig 2: Illustration of lay-up sequence of a quasi-isotropic NCF

The dimensions of the damaged compression specimens are in accordance with the miniaturised Boeing test specimens developed by Hogg et al [2], they being 89 by 55mm. The specimens containing inserts were constructed by creating holes of various sizes in blank compression specimens via a milling machine, and then press fitting the inserts into these holes. The inserts themselves were created from rods of material, they being Nylon (30% Glass-fibre filled), Acrylic and PTFE. The insert sizes used were 10mm, 15mm, 20mm, 25mm, 30mm, plus diameters of 35mm and 40mm for the Acrylic inserts. The finished specimens are illustrated in fig 3.

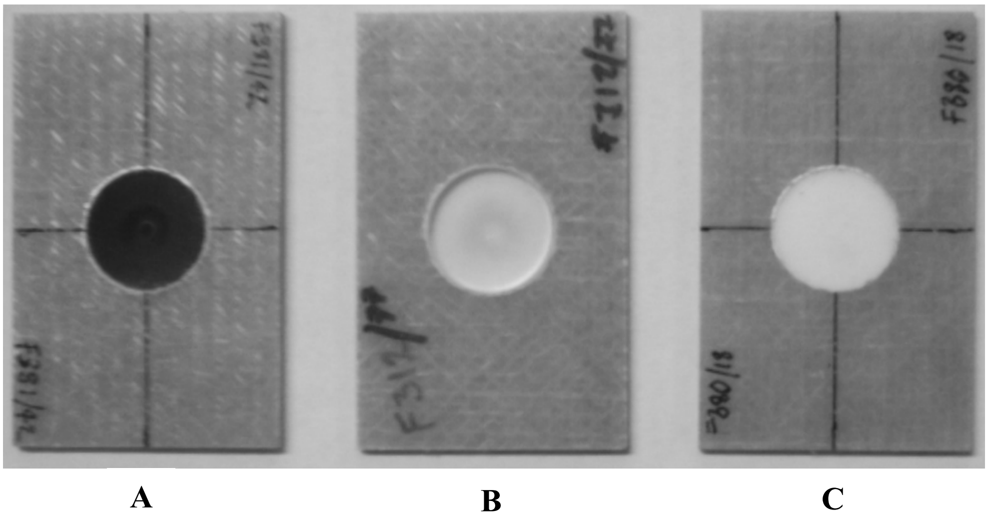

Fig. 3: Compression with insert specimens: (A) Nylon, (B) Acrylic, (C) PTFE

Impact damaged specimens received an impact via an instrumented drop weight impact machine. Incident impact energies of 4, 6, 8, 10 and 12 Joules were used. The compression tests for damaged specimens were conducted in accordance with the general procedure outlined in Hogg *et al* [2]. All tests were conducted using the miniaturised Boeing test fixture, see fig 4., in an Instron 1195 test machine with a load cell of 100KN and cross head speed of 1mm/min. Test data was acquired using a chart plotter. To obtain ultimate undamaged compression strength, mechanical tests were conducted in accordance with the ASTM test standard D3410 [3], using ITTRI type specimens.

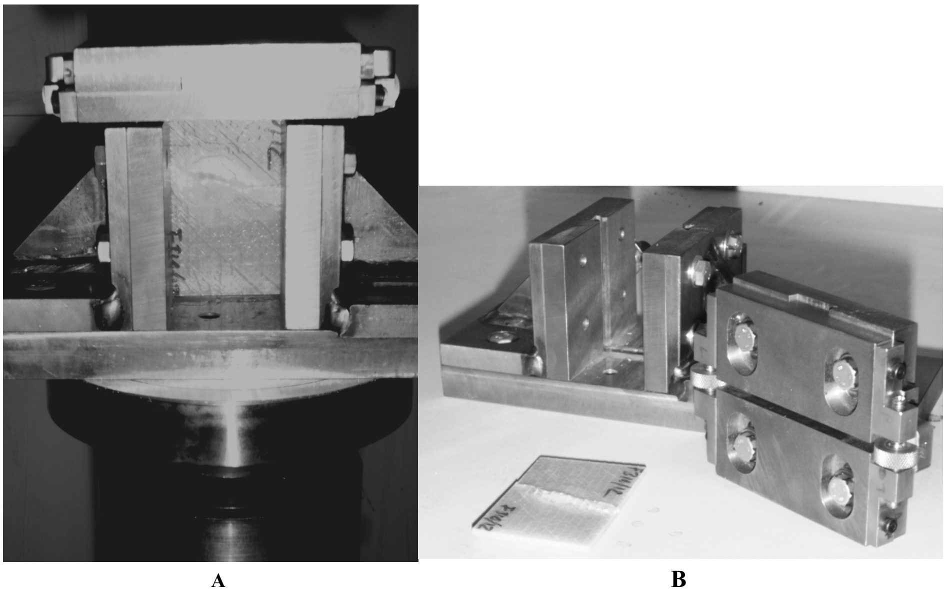

Fig 4: Miniaturised Boeing Compression After Impact Test Fixture; (A) In test position, (B) Exploded View

EXPERIMENTAL RESULTS

The results for undamaged, impact damaged (CAI) and specimens containing inserts (CWI) are tabulated in tables 1 to 3 respectively and are illustrated in fig. 5 below.

Table 1: Comparison of the results generated by the ASTM and Boeing miniature compression test methods

Test Type	**Compressive Strength**			**Compressive Modulus**		
	Mean (MPa)	SD	CV %	Mean (GPa)	SD	CV %
ASTM D3410	317.3	27.319	8.60	18.22	1.68	9.26
QMW Miniature	294.6	24.704	8.38	17.70	1.22	6.91

(11 specimens were used for the ASTM D3410 test and 6 for the QMW test)

Table 2: Compression after impact test results (CAI)

	Compressive Strength			**Impact Widths**		
Impact Energy (J)	Mean (MPa)	SD	CV %	Mean (mm)	SD	CV %
0	317.3	27.31	8.60	N/A	N/A	N/A
4	212.4	13.35	6.28	25.7	0.82	3.21
6	163.3	7.85	4.80	34.9	3.28	9.41
8	146.1	8.71	5.96	40.8	2.51	6.16
10	141.5	4.59	3.24	42.1	0.99	2.35
12	134.4	5.69	4.23	45.2	2.21	4.90

(6 specimens were used per impact energy)

Table 3: Compression with insert (CWI) test results

Insert Material	**Nylon (30% Glass fibre filled)**			**Acrylic**			**PTFE**		
Insert Stiffness (GPA)	**10**			**3.3**			**0.75**		
	Strength			**Strength**			**Strength**		
D (mm)	Mean (MPa)	SD	CV	Mean (MPa)	SD	CV	Mean (MPa)	SD	CV
0	317.3	27.31	8.60	317.3	27.31	8.60	317.3	27.31	8.60
10	230.3	6.22	2.70	217.0	7.61	3.50	216.8	8.21	3.79
15	196.3	9.49	4.83	187.0	6.49	3.47	176.1	8.31	4.72
20	183.5	13.32	7.26	172.2	6.14	3.56	158.2	8.48	5.36
25	166.1	9.40	5.66	136.5	5.54	4.05	139.4	3.83	2.75
30	149.0	5.90	3.96	121.3	6.45	5.32	113.5	4.77	4.20
35				106.9	5.44	5.09			
40				100.7	3.80	3.78			

Insert material and stiffness data provided by RS Services Ltd

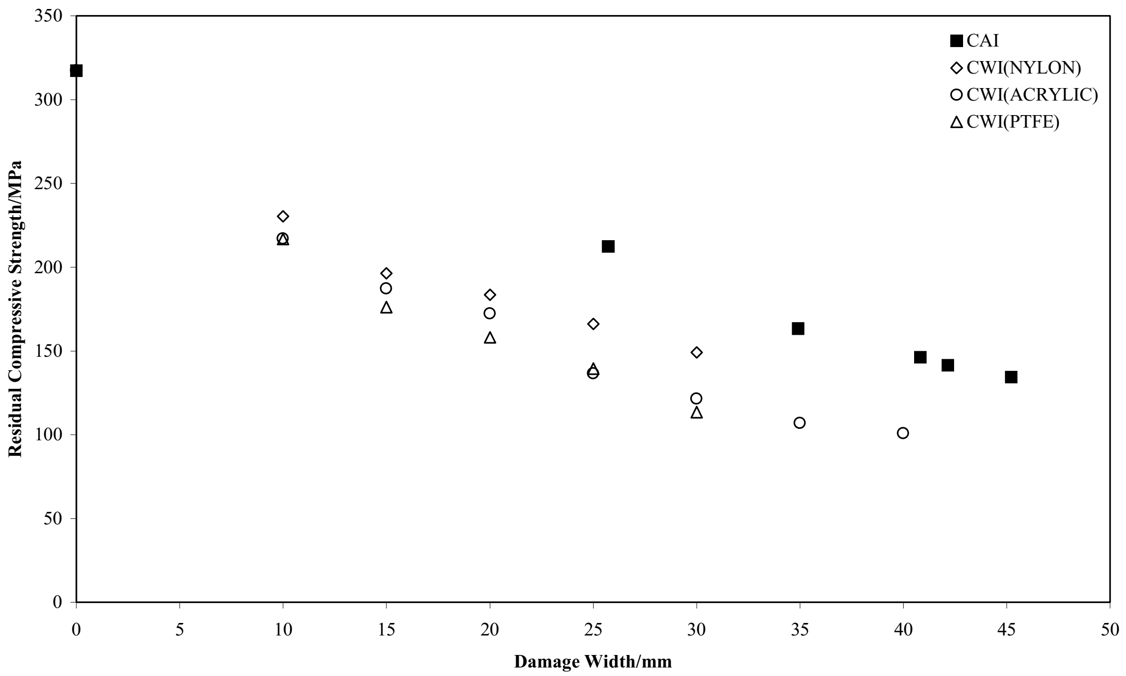

Fig. 5: An illustration of the effects of a local stiffness reduction on the compressive strength of a NCF composite

It can be seen that the retention of compressive strength increases with increasing insert stiffness, however, the difference between the strengths for the different inserts is relatively small. The results also show that impact damaged specimens retain a greater level of strength than specimens with inserts. This suggests that impact damage has a greater effective stiffness compared with that of the inserts.

It can be seen from fig. 5 that the reduction of strength with insert size is essentially linear for all insert types with the exception of the specimens containing Acrylic inserts. These specimens were tested with insert sizes greater than the 30mm used for Nylon and PTFE. At large insert sizes it seems that the retention of strength is reaching a plateau, probably due to the fact that the insert sizes are approaching the width of specimens, thus dominating the strength exhibited by the specimen.

EXPERIMENTAL OBSERVATIONS

All CWI specimens failed at the insert region, see fig 6., and for the smaller sized specimens (10-30mm) exhibited delamination and surface ply cracking progressing from the insert towards the edges of the specimen. However, the actual mode of failure differed between the three types of specimen.

The PTFE inserts displayed substantial buckling behaviour prior to failure. This became more apparent with increasing insert size. The insert behaved in a very ductile manner. The Acrylic inserts also displayed a tendency to buckle but because of their brittle nature, they tended to shatter or bow-out at failure. This tendency was observed for the largest insert sizes. The Nylon inserts also buckled and although being the stiffest of the three insert materials, they did not shatter at larger insert sizes. However, there was a greater tendency for these inserts to bow out for smaller insert sizes compared with that of the Acrylic inserts.

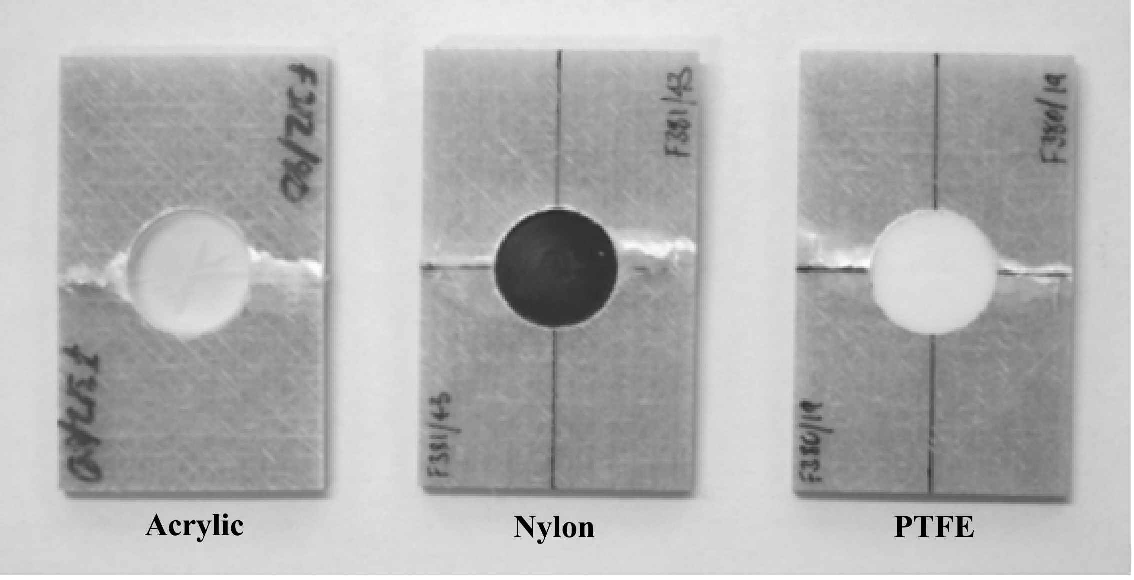

Fig 6.: Illustration of failed CWI test specimens

PREDICTIVE METHOD

Part of the overall damage tolerance program involved developing a method to predict the residual strength after impact damage for this material under in-plane loading conditions. This method, based upon Whitney and Nusimers [4] Stress Fracture Criterion (The Point Stress Criterion (PSC) and the Average Stress Criterion (ASC), relies upon the knowledge of three parameters; The stress distribution ahead of the impact damage area, which itself is idealised as an elastic insert, the stiffness of the damaged area and the undamaged strength of the material containing the impact damage. Predictions are made via a damage parameter, known as the characteristic length. This is thought to represent the length over which, flaw of a critical size exists ahead, of the impact damage, such that upon loading will cause failure. The difference between the two criteria being that for the PSC, failure occurs when the stress over the distance (represented by characteristic length, d_o) containing the flaw, is equal or greater than the failure strength of the undamaged material. Where as for the ASC, failure occurs when the *average* stress over length, a_o, is equal to or greater than the undamaged strength of the material.

The stiffness of the impact damage is obtained by a novel method. This involves mechanical testing of flexural specimens saturated by impact damage, and iterative scheme utilising classic laminate theory. From this the *average* modulus of the impact damage area was estimated to be 8.7GPa (A complete description of this method will be given in a comprehesive version of this paper).

The results of the application of this predictive method to the compression with inserts data is illustrated in figs 7 to 10. Values of the characteristic lengths used for predictions are tabulated in table 4.

Table 4: Values of characteristic length values for specimens containing impact damaged or elastic inclusions

Test Type	d_o/mm	a_o/mm
CWI(PTFE)	5	22
CWI(Acrylic)	N/A	4
CWI(Nylon)	N/A	6
CAI	N/A	8

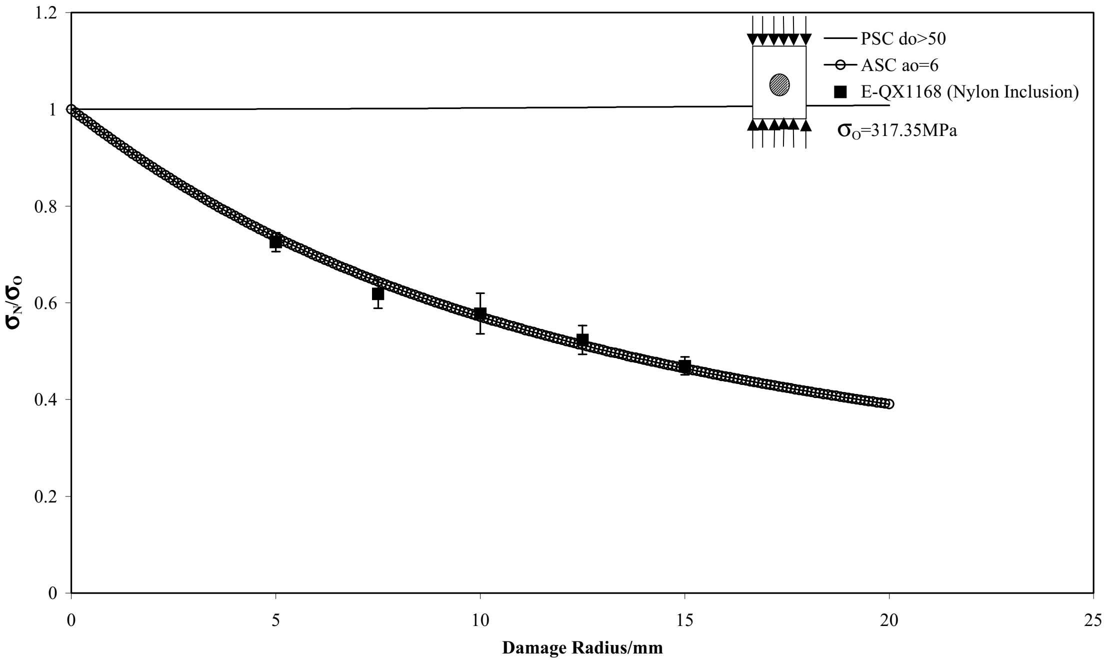

Fig 7: Comparison between experimental and predicted failure stresses for specimens containing a Nylon Inclusion loaded in uniaxial compression

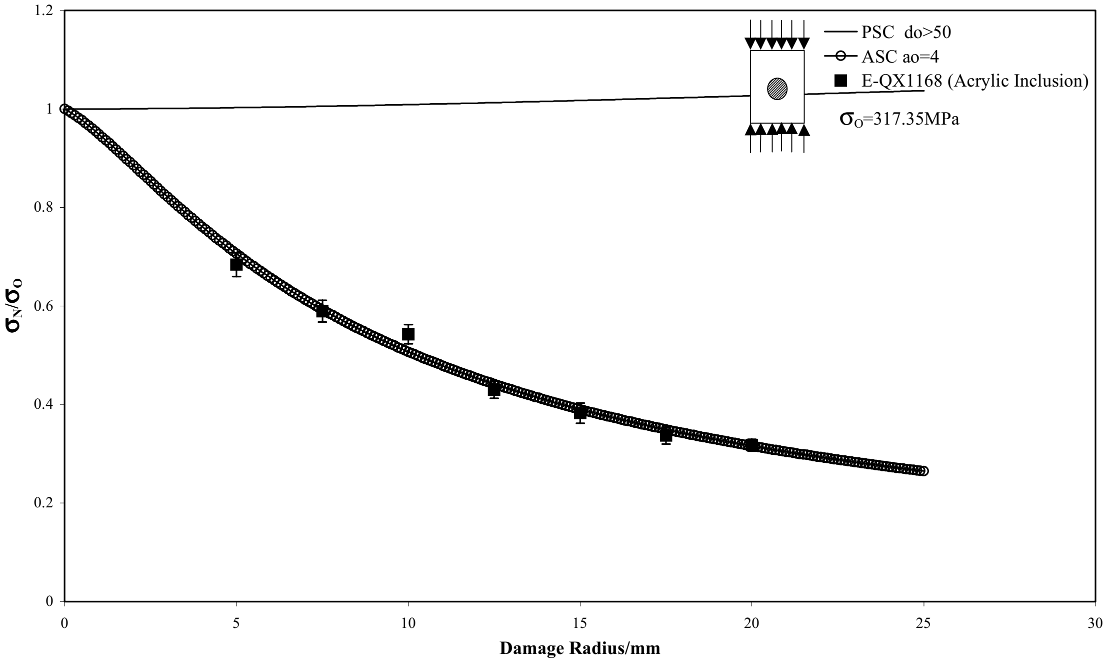

Fig 8: Comparison between experimental and predicted failure stresses for specimens containing an Acrylic Inclusion loaded in uniaxial compression

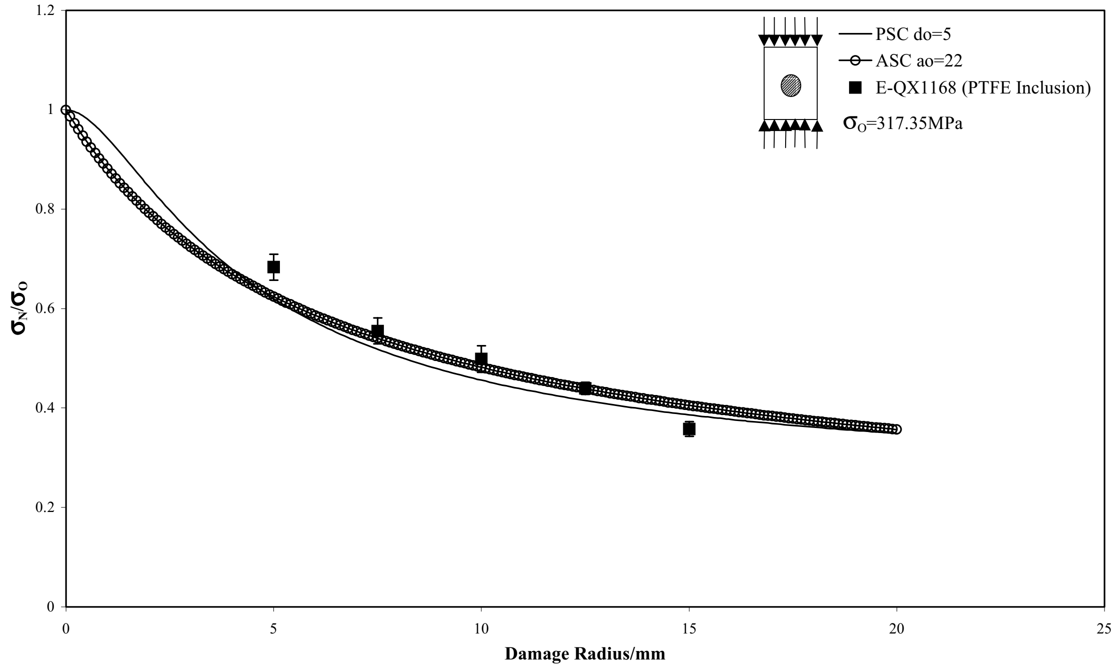

Fig 9.: Comparison between experimental and predicted failure stresses for specimens containing a PTFE inclusion loaded in uniaxial compression

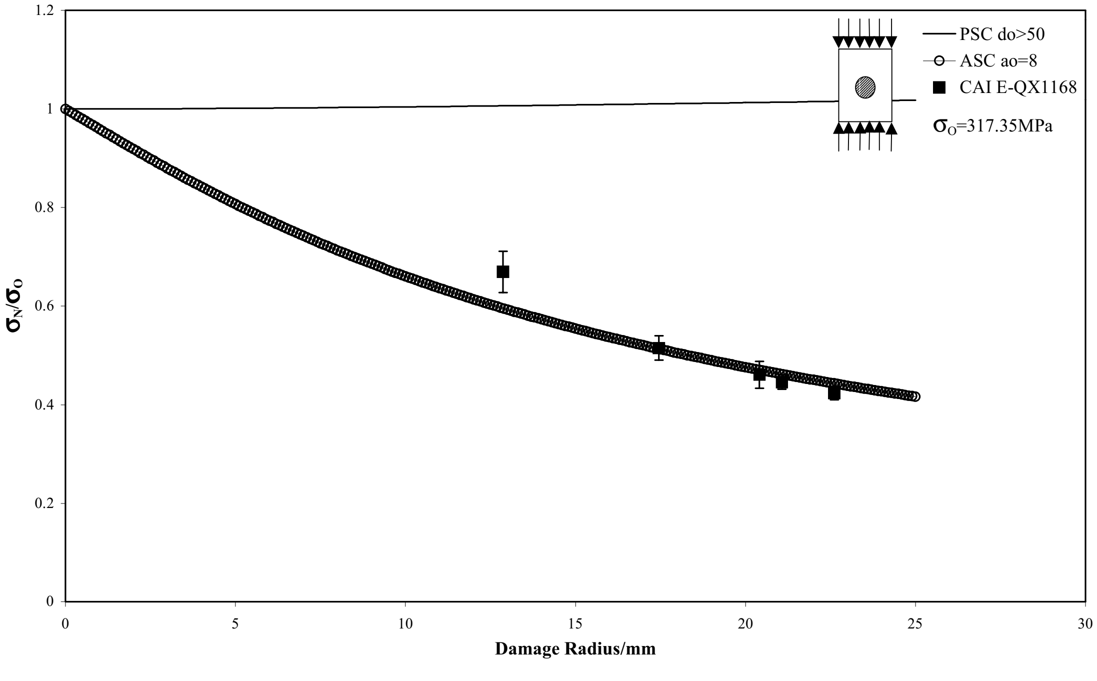

Fig 10.: Comparison between experimental and predicted failure stresses for specimens containing impact damage loaded in uniaxial compression

As can be seen from figs 7 to 10, the ASC gives better predictions than the PSC, (in some cases the PSC is not applicable). The characteristic length, a_o, although originally intended to reflect the materials sensitivity to damage, hence the reference to existence of flaws of a critical size, to some extent reflects the effect of changing damage stiffness with retained strength. The increase in retained strength and insert stiffness is mirrored by an increase in characteristic length. However, this trend is not maintained by the results from the specimens containing the PTFE inserts. This discrepancy is thought to be caused by a mathematical anomaly within the ASC equation.

DISCUSSION

This investigation into the effects of damage stiffness upon compression behaviour and compressive strength revealed the expected decrease in compressive strength with decreasing insert stiffness. Although insert failure modes differed between the three insert types, the failure of the composite was the same for each. This was mainly due to the incomplete load transfer between the insert and the composite. However, all specimens exhibited a pseudo-CAI type failure with initial buckling of the damage zone with delamination spreading from the sides of the insert boundaries.

The predictive method developed for impact damaged materials provided good agreement (for the ASC only) with experimental data and reflected the observed trend of increasing damage tolerance with increasing impact damage stiffness. The use of an *average* impact damage modulus for the predictive method takes into account the assumed change in damage stiffness with impact size. It is assumed that impact damage stiffness is a function of the number of cracks and delaminations, which is related to the size of the impact damage.

CONCLUSION

This paper provides an insight into the effects of impact damage stiffness upon retained strength of a Non-Crimp-Fabric material subjected to compressive loading. Behaviour of this material when containing an insert is akin to that containing impact damage. The expected decrease in strength with decreasing insert stiffness was observed. The predictive method provides an opportunity to assess the damage tolerance of a material quantitatively, via the use of the characteristic length as a type of damage severity indicator, which takes into account the *average* damage stiffness. However, further work is necessary to make this method viable for other in-plane loading conditions.

ACKNOWLEDGEMENTS

The authors would like to thank BG technology for studentship that they provided Dr S.E. Aramah and general assistance with programme.

REFERENCES

1. Cantwell W.J. and Morton J., “The Significance of Damage and Defects and their Detection in Composite Materials: A Review”, *J of Strain Anal., 1992, Vol. 27(1), pp29-42*

2. Hogg P.J., Prichard J.C. and Stone D.L., “A Miniaturised Impact Compression Test” *ECCM, Composites Testing and Standardisation (CTS), September 1992, Netherlands, (EACM, Bordeaux, 1992), pp 357-370*

3. ASTM D3410-87, “Standard Test Method for: Compressive Properties of Unidirectional or Cross-ply Fibre-Resin Composites”, *Annual Book of ASTM Standards, 1994, Vol. 15.03, pp 132-141*

4. Whitney J.M., and Nuismer R.J., “Stress Fracture Criteria for Laminated Composites Containing Stress Concentrations”, *Journal of Composite Materials, July 1974, Vol. 8, pp. 253-265*

13TH INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS

Beijing China, June 25 – 29, 2001

AGREEMENT FOR THE TRANSFER OF COPYRIGHT

Copyright of the text and illustrations of the paper entitled :_ COMPRESSION TESTING OF GLASS EPOXY NON-CRIMP FABRICS CONTAINING ELASTIC INSERTS authored by: Dr. S.E. Aramah and Proff P.J. Hogg

____

to be published in the Proceedings of the Thirteenth International Conference on Composite Materials is hereby transferred to the publishers : The Chinese Society for Composite Materials and China Universties Alumni Association, Beijing, China.

The publishers agree that the authors retain the right to use the substance of the paper in future works, including lectures, press releases and reviews, provided that the usual acknowledgements are made regarding copyright, the original reference and the publishers. Should the paper not be published for any reason, then the copyright reverts to the authors.

In making this transfer, the authors confirm in respect of the above-mentioned paper that :

(a) they currently own the copyright to it ;
(b) it has not been previously published in the English Language ;
(c) it is not under consideration by any other publisher ;
(d) it contains no libelous or unlawful statements and does not infringe on the rights of others ;
(e) all necessary permissions have been obtained for the reproduction of text or illustrations ;
(f) any claims for exemptions or any special conditions are stated below ;
(g) the undersigned is empowered by any co-authors to make this agreement.

Exemption / Special Conditions : ______________________________

______________________________-

Authorized Signature : Simon Aramah______________________ Date : 15th May 2001
Full name of Authorised Person : Dr. Simon Ejechi
Aramah______________________________

Chinese Society for Composite Materials

China Universities Alumni Association
Beijing China Tel. : (010) 82317092 FAX : (010) 82317099
Iccm13@buaa.edu.cn http://www.iccm13.org

.

13TH INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS
Beijing China, June 25 – 29, 2001

DETAILS OF PAPER PRESENTER FOR USE BY

1.0 SESSION CHAIRMAN

Please use this form to provide clear, legible information for the Session Chairman.

01	Paper ID	1608
02	Paper Title	COMPRESSION TESTING OF GLASS EPOXY NON-CRIMP FABRICS CONTAINING ELASTIC INSERTS
03	Paper Author(s)	Dr. S.E. Aramah and Proff. P.J. Hogg
04	Title and Name of Paper Presenter	Proff. P.J. Hogg
05	e-mail of Paper Presenter	p.j.hogg@qmw.ac.uk
06	Post address of Paper presenter	*Department of Materials, Queen Mary, University of London, MileEnd Roda, E1 4NS, London, UK*
07	FAX of Paper Presenter	0044-0208-981-9804
08	Position and Affiliation of Paper Presenter	Fellow of Institute of Materials
09	Qualifications and Experience	PhD, 20 years of Composite Experience
10	Professional	

	Interests	
11	Authorized Signature	P.J.Hogg
12	Date	15-05-01