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COMPARISON OF TEST CONFIGURATIONS FOR THE DETERMINATION OF G_{IIC} : RESULTS FROM AN INTERNATIONAL ROUND ROBIN

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Abstract:

This paper presents a summary of the tests performed within a VAMAS (Versailles Project on Advanced Materials and Standards) round robin to examine the measurement of mode II interlaminar fracture toughness using four different test methods based on: End Notched Flexure (ENF), Stabilised End Notched Flexure (SENF), End Loaded Split (ELS), and four point End Notched Flexure (4ENF) carbon fibre reinforced epoxy specimens. Tests were performed by members of ESIS (European Structural Integrity Society), JIS (Japan Industrial Standards group) and ASTM (American Society for Testing and Materials).

Keywords: Delamination ; Fracture tests ; Mode II ; Interlaminar shear ; Fracture toughness

1. Introduction

Interlaminar crack propagation is one of the most common failure modes in fibre reinforced composites and considerable efforts have been made in recent years to produce standard test methods to measure delamination resistance [1]. There is now general agreement on a mode I test procedure, and a test based on the DCB (double cantilever beam) specimen is being balloted by ISO (International Standards Organization). The determination of the resistance of composites to crack initiation and propagation under mode II (in-plane shear) loading is now also being addressed. Several mode II tests have been proposed [2] but these have provoked considerable controversy in recent years (e.g. [3,4]). Nevertheless reliable values of G_{IIC} are necessary to complete the mixed mode failure envelope. The mode II round robin described here was proposed at the 1996 ISO meeting with the aim of comparing the different test methods available, in order to be able to select one for proposal as a new ISO test method. Three principal test configurations were considered initially (ENF, ELS and SENF), and these were examined by members of each of the three standards groups. A fourth test method based on the four point ENF (4ENF) specimen was added later. This was initially tested in only one laboratory, but a second series of tests was then organised in six laboratories and is currently underway.

This round robin exercise had several objectives :

- the main aim was to determine the influence of test configuration on G_{IIc} values.

Other aims were

- to examine the influence of crack starter type (insert, tension precrack or shear precrack) on these values,
- to assess the difficulties associated with each test method, and
- to evaluate different data reduction methods.

2. Materials tested

The materials consisted of unidirectional Besfight HTA-12000 carbon fibres in Toho 113 epoxy resin (nominal 59% fibre volume fraction), produced from Toho Q-1113-1450 prepreg and cured at 130°C. The starter film was 13 microns thick PTFE. Materials supply and specimen cutting was organised by the JIS group. Properties of the material were given as: E_{Lf} (flexural modulus) = 122 GPa, G_{LT} (in-plane shear modulus) = 3.9 GPa. Specimen thickness varied in the range from 2.9 to 3.15 mm between all specimens. Mode I precracking showed small jumps at initiation in some specimens but most initiated in a stable manner. Tests at IFREMER indicated an average G_{Ic} value for this material at initiation of 130 J/m².

3. Test methods

The four test configurations studied will now be briefly presented. For the first series of tests three test procedures were supplied by ASTM (ENF), ESIS (ELS) and JIS (SENF) and distributed to all participants [5]. A 4ENF procedure was drafted by MERL for the second set of tests, which are still underway at the time of writing. The critical points on the load-displacement plots used to define G_{IIc} were non-linearity (NL), and the first of 5% slope change or maximum load, whichever occurs first. A visual definition of initiation was not included, (although it may yield conservative values in some cases), because it is operator dependent and hard to verify after the test.

(a) End Notched Flexure (ENF)

Figure 1

The development of the ENF specimen, shown above, for composite testing was based on work on the fracture of wood [2,6,7]. It is the most widely used mode II configuration and JIS [8] and AECMA [9] ENF standard test methods exist already. The following analyses were applied here :

Compliance method: $C = C_o + ma^3$, $G_{IIc} = \dfrac{3P^2 ma^2}{2B}$ (1)

Simple beam theory: $G_{IIc} = \dfrac{9P^2 a^2}{16B^2 E_1 h^3}$ (2)

Corrected beam theory: $G_{IIc} = \dfrac{F}{N}\dfrac{9P^2 a^2}{16B^2 E_1 h^3}\left(1 + 0.2\dfrac{E_1}{G_{13}}\left(\dfrac{h}{a}\right)^2\right)$ (3)

A spreadsheet including these calculations, developed by J. Winter at the University of Hertfordshire in collaboration with MERL, was used to standardise ENF data presentation.

(b) Stabilised End Notched Flexure (SENF)

Figure 2

Work in Japan led to a number of procedures for stabilising the test on ENF specimens (SENF) by feedback control of the test machine [8,10]. Two methods were applied in the VAMAS round robin. The first is referred to as CSD (Crack Shear Displacement) control [10], in which crack shear displacement is measured as shown in Figure 2. This is then used as the input parameter fed negatively into a feedback loop and the CSD rate is kept constant. An alternative is to use the CCC (Co-ordinate Conversion Control) method [11,12]. In this case the load P and crosshead displacement δ are input to a circuit which gives an output $C = \delta - \alpha P$. When C is controlled so as to increase monotonically, the crack propagation is stabilised. Data can be analysed using the methods presented above for the ENF specimen, but the compliance method proposed by the JIS group involves a different calibration:

$$a/2h = \beta_1 (B\lambda)^{1/2} + \beta_o \qquad (4)$$

where β_1 and β_o are the slope and intercept of a plot of crack length/specimen thickness versus the square root of the product of width (B) and measured compliance (λ).

(c) End Loaded Split (ELS)

Figure 3

This specimen was developed at Texas A&M University [13] and has been used extensively by the ESIS group. The specimen is held in a clamp which is free to slide horizontally. The analyses applied were:

Simple beam theory, $G_{IIc} = \dfrac{9P^2a^2}{4B^2E_1h^3}$, (5)

Experimental compliance calibration, $G_{IIc} = \dfrac{3P^2ma^2}{2B}$ (6)

where m is the slope of a plot of compliance versus the cube of crack length.

Corrected beam theory $G_{IIc} = G_{IIBT}\left(1-\theta_1\left(\dfrac{\delta}{L}\right)^2-\theta_2\left(\dfrac{\delta\, l_1}{L^2}\right)\right)$ (7)

with θ_1 and θ_2 large displacement and loading block corrections [14].

(d) Four point End Notched Flexure (4ENF)

Figure 4

This modified version of the ENF configuration was proposed by Martin and Davidson [15]. The analysis is by experimental compliance calibration only, the slope m is determined from a plot of compliance versus crack length, then:

$$G_{IIc} = \frac{P^2m}{2B} \qquad (8)$$

4. Test performed

Table 1 presents a simplified overview of the tests performed. This shows that all the specimen-defect combinations have been covered, although relatively few shear precracked specimens were tested.

Test	Insert	Mode I precrack	Mode II precrack	Total number
ENF	IC (5) IFR (5) NASA (5) Bell (5) KU (3)	IFR (4) KU (4)	NASA (5) Bell (5)	41
SENF	IC (8) Bell (10) KU (5) TPU (5) UT (4)	TPU (5) KU (6) UT (6)	UT (5)	54
ELS	IC (5) IFR (5) Bell (5) TPU (5)	IFR (9) Bell (5) TPU (5)	IC (5)	44
4ENF	MERL (12)	MERL (5)	MERL (7)	24
Total number	87	49	27	163

Bell tests subcontratcted to Cincinnati Testing Laboratory.
Table 1. Tests performed (specimen numbers in brackets).

The large number of tests performed and the number of parameters involved (defect types, different test conditions, analyses) make interpretation complex. The following aspects will be discussed briefly:

- Repeatability and reproducibility
- Influence of specimen configuration
- Stability of propagation and R-curves
- Influence of initial defect type
- Data analysis (beam theory versus experimental compliance)

a) Repeatability and Reproducibility

In order to assess the significance of differences between different specimen configurations it is useful to have an idea of the variations which arise when the same tests are performed in different laboratories. This is not easy when small numbers of specimens are involved, but for the three series of tests from inserts over 20 specimens were tested in at least 4 different laboratories for each specimen type. This is also a case for which crack length measurements are straightforward, thus removing one variable in the comparison. Corrected beam theory results are shown in Table 2, for non-linearity and for 5% or maximum load points. These results give a first idea of what scatter may be expected.

Laboratory	ENF	SENF	ELS
1	16, 16	19, 14	24, 11
2	23, 22		3 , 17
3	8 , 8		
4	7 , 8	18, 14	10, 6
5		6 , 4	
6		21, 11	*73*, 19
7		8 , 5	
All specimens	14 , 14	23 , 14	*51* , 17

Table 2. Coefficients of variation (%) for different sets of results, (NL, Max.).

Most of the coefficients of variation are reasonably low, there is one anomalous set of values for the ELS specimen which is caused by very low and variable values for non-linear load points. Apart from this one set there do not appear at first sight to be large differences in variability between the different test methods.

b) Influence of test configuration

The main aim of this round robin exercise was to assess how different test configurations evaluate the delamination resistance of the same material. One important factor is stability, and this will be discussed below, but it is important to establish whether the different tests give comparable values. Figure 5 shows values of G_{IIC} for the four specimen types, measured from the insert (5a), from mode I precracks (5b) and mode II precracks (5c), analysed using corrected beam theory at non-linearity and maximum load (except the 4ENF, for which experimental compliance analysis is used).

Figure 5

These figures are obtained by grouping all results in each case. It appears from these mean results that:

- ENF gives higher NL values from inserts and shear precracks.
- Maximum load values are similar for all three specimens from inserts
- NL values from mode I precracks are similar for all three specimens
- Maximum load values from mode I precracks are highest for ELS and lowest for SENF.
- Limited 4ENF data suggests high NL values from inserts and mode I precracks.

c) Stability

The stability of the four test configurations employed is summarised in Table 3 below:

Specimen	**Expected stability**	**Stable**	**Unstable**
ENF	Unstable a/L<0.7	None	All
ELS	Stable a/L>0.55	IC IFR 1 mm/min.	Bell (a/L=0.5) IFR 5mm/min
SENF	Stable	UT, KU, TPU Bell with wire	IC 4/8 Inserts Some inserts KU, TPU Bell no wire
4ENF	Stable	All mode I precracks	Some inserts

Table 3. Stability of tests.

The use of a wire insert appeared to stabilize SENF crack growth, but this effect was only noted in one laboratory and needs further study.

Promoting stable crack propagation has two benefits: first, the R-curve of the material can be determined, as for mode I, and this may be of interest for damage tolerance improvement. Second, and probably more important for the standardization procedure, a stable R-curve allows the validity of the initiation values to be established as in the mode I procedure.

With respect to the propagation values of G_{IIc}, a comparison of R-curves from the three stable specimen types shows no significant differences. Figure 6 below shows an example.

Figure 6

The ranges of crack lengths covered are not identical, the SENF specimen results are based on shorter cracks than the 4ENF and ELS specimens. Initiation from inserts is often unstable and during propagation there is then a tendency for crack resistance to increase slightly with crack advance.

d) Influence of initial defect type

Several authors have presented results comparing initiation from inserts with precracked specimens. It has frequently been found that precracking gives lower G_{IIc} values than inserts, although there are often doubts over the validity of the insert films used. The G_{IIc} values plotted in Figure 5 are shown presented as fractions of insert values in Table 4 below. This shows that values from precracks are lower than values from inserts in all but one case (and that case should be treated with caution as very low values were involved). There is little difference between mode I and mode II precracks here.

Precrack type	ENF	ELS	SENF	4ENF
Mode I	0.59 0.82	1.07 0.98	0.82 0.71	0.88 -
Mode II	0.83 0.88	0.91 0.71	0.72 0.65	0.74 0.88

Table 4. Mean values of G_{IIc} from precracks, as a fraction of mean insert values

(CBT, NL (upper) and 5%/Max. (lower)).

These results, for a material which does not show a strong R-curve, suggest that values from precracks should be included in a standard test method. Scatter for each type of defect is shown in Table 5, and appears to be lowest for shear precracked specimens. This is surprising, as shear precrack lengths are not easy to determine and in the past this has been used as an argument in favour of mode I precracks. It should be stressed that the test procedure being developed is intended to provide quantitative data for input into calculations. It should therefore be designed to simulate the damage mechanism seen in service. This will influence the type of starter defect to be adopted, as it has been argued that a mode I precrack is not likely to be present when shear loads dominate.

Precrack type	ENF	ELS	SENF	4ENF
Insert	14	(51)	23	11
	14	17	14	10
Mode I	22	40	21	10
	14	11	10	4
Mode II	5	15	4	9
	5	7	4	14

Table 5. Coefficients of variation, all values

e) Data Analysis

There has been much discussion over the analysis of mode II tests. The relatively small changes in compliance with crack length have made the validation of analytical analyses difficult, and in general in the past finite element analyses have been used to check the analytical expressions. Nevertheless, by sliding the specimen in the fixture before the test it is possible to obtain compliance versus crack length cubed plots, and this was done in most ENF and SENF tests here. For the ELS and 4ENF specimens a compliance calibration is possible using propagation values. It is of interest to compare the corrected beam theory and experimental compliance analyses, and Figure 7 shows the ratio of G_{IIc} values from corrected beam theory and experimental compliance for ENF tests in 5 laboratories.

Figure 7.

The absolute value of this ratio is of course very sensitive to the value of modulus used in the beam theory expression, but there is clearly also considerable scatter between laboratories. For the ENF the coefficient of variation for experimental compliance values of G_{IIc} is 21%, rather than 14% for the CBT analysis. Experimental compliance calibrations require measurements of both crack length and load point displacement in addition to the load. There is thus far more scope for variations than when the only measurement needed is the load. For ELS and SENF specimens the correlation between experimental and beam theory expressions was generally better than for the ENF tests.

5. Concluding comments

The aim of this paper is primarily to present the results from the round robin. Nevertheless, some comments may be made :

- Scatter in results is low for all specimen types in nearly all cases, generally coefficients of variation are less than 20%, and often less than 10%.

- No test configuration gives consistently higher or lower G_{IIc} values than the others, though under some conditions (e.g. from inserts) ENF values are higher.

- Stable mode II crack propagation can be obtained with ELS, SENF and 4ENF specimens. For this carbon/epoxy the R-curves obtained are flat, and are similar for the three configurations.

- For this material precracking gives consistently lower values than inserts.

There are many factors to be considered in the selection of a mode II test method for a new ISO Work Item. These include:

- consistency of results
- simplicity of fixtures
- time needed to run tests
- stability of propagation
- checks on validity

By way of conclusion, Table 6 summarises the advantages and disadvantages of each configuration

Specimen	Advantages	Disadvantages
ENF	Widely used Simple procedure	Unstable
SENF	Stable	Complicated control
ELS	Stable Long crack propagation	Clamping variability
4ENF	Stable. Simple test set-up	Little current experience

Table 6. Advantages and disadvantages of the four specimen configurations.

The ENF test is the most widely used mode II test, but its inherent instability is a serious drawback.

The ELS test was developed in the USA and has worked very well in ESIS round robins, although in the current round robin problems were encountered outside Europe (one set of very low initiation values, and unstable propagation in another case due to short starter cracks).

The SENF test was developed in Japan and satisfactory results were obtained there, but when employed elsewhere some unstable propagations were noted.

The 4ENF configuration may offer a compromise alternative to the ELS and SENF as it appears to be simple and stable. At present only the laboratory proposing the test has supplied results, but additional tests on 4ENF specimens are currently underway.

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Figures

Figure 1. End Notched Flexure (ENF) specimen

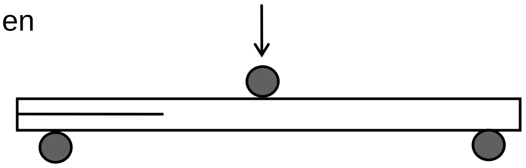

Figure 2. Stabilised End Notched Flexure (SENF) specimen

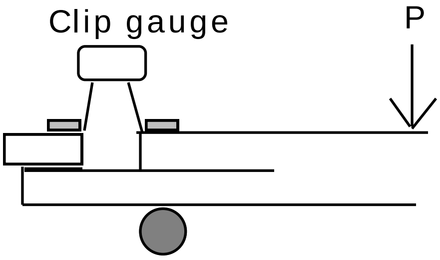

Figure 3. End Loaded Split (ELS) specimen

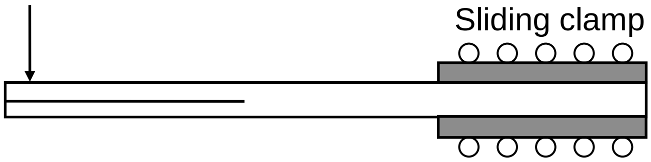

Figure 4. Four point End Notched Flexure (4ENF) specimen

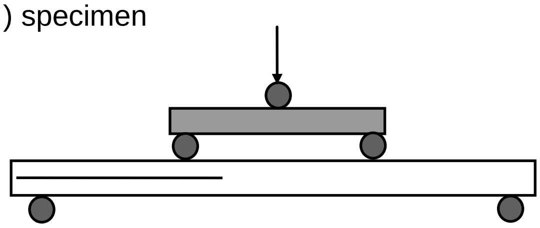

Figure 5. Influence of specimen configuration on measured values.

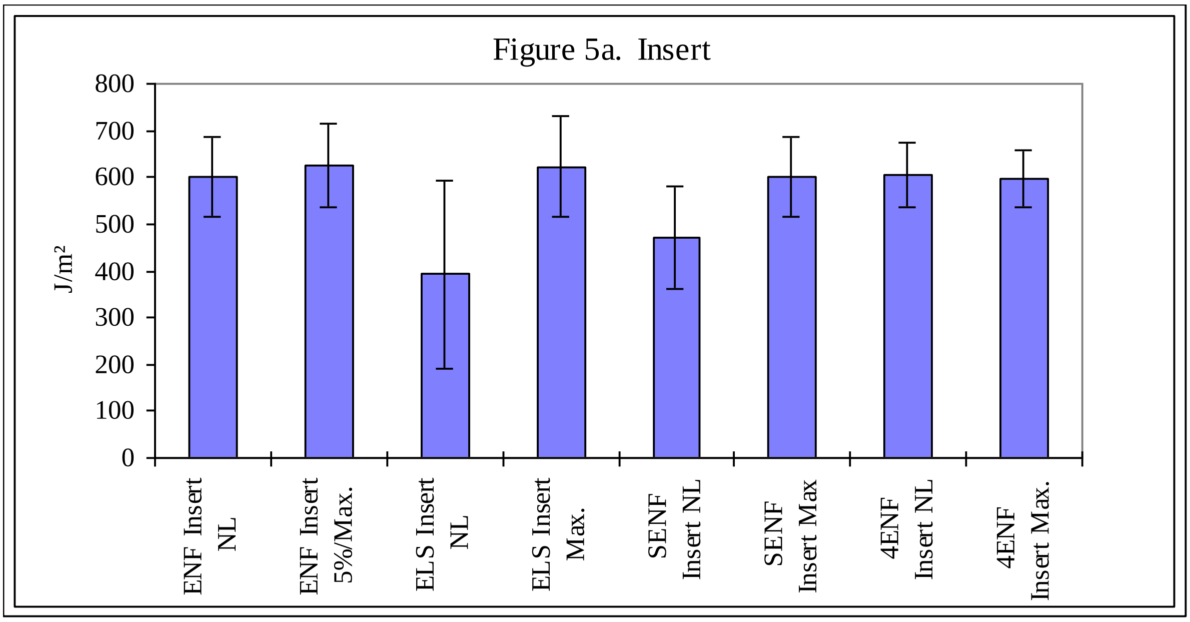
Figure 5a. Insert

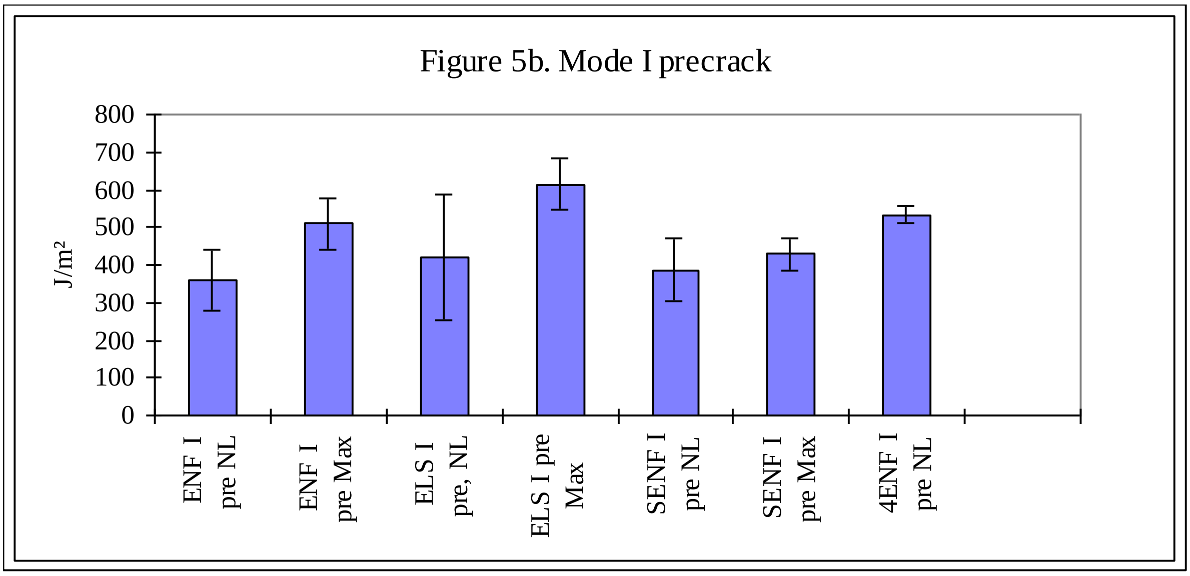
Figure 5b. Mode I precrack

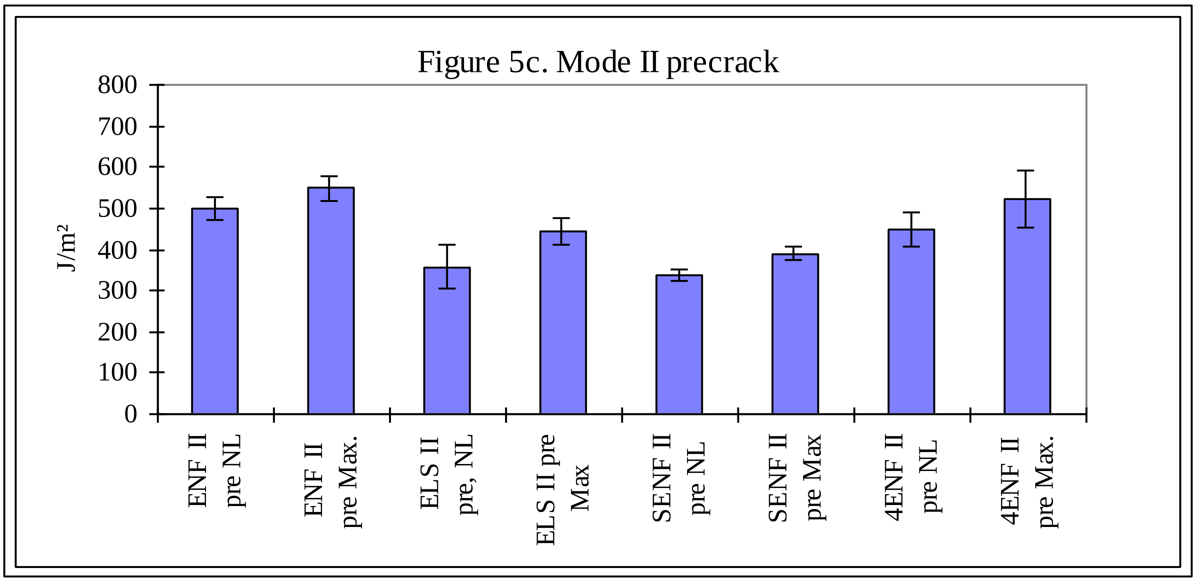
Figure 5c. Mode II precrack

Figure 6. Examples of mode II R-curves

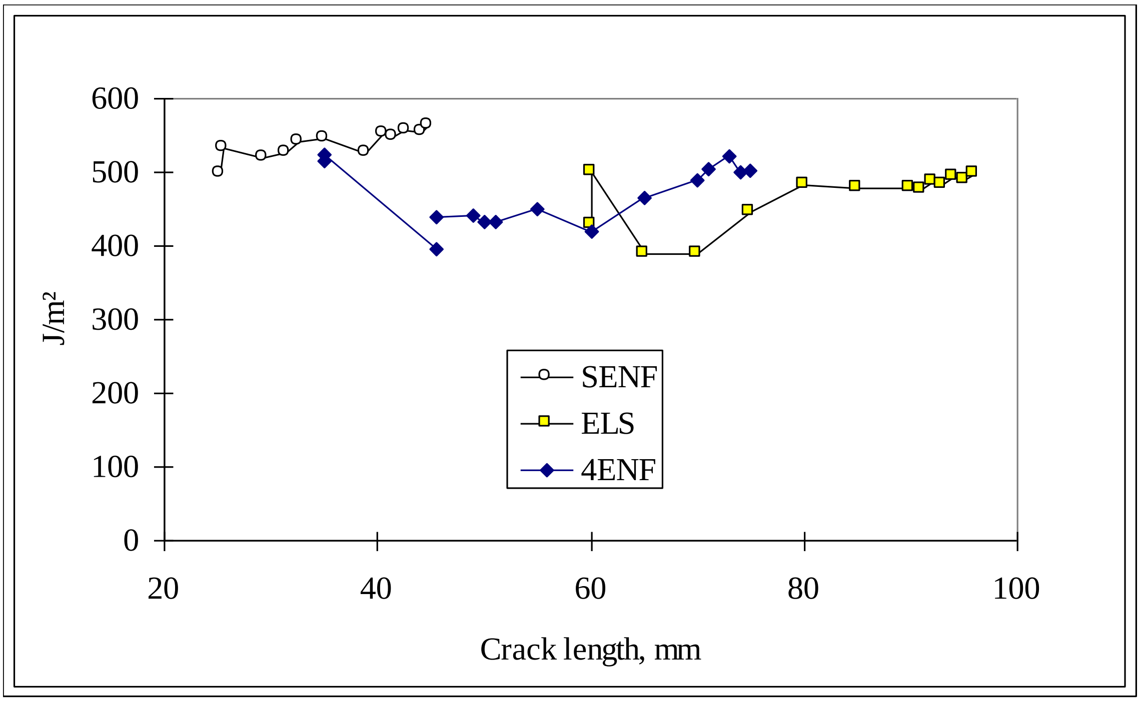

Figure 7. Ratio of G_{IIc} values determined using experimental compliance and corrected beam theory, ENF NL from insert