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STRUCTURAL INTEGRITY ASSESSMENT PROCEDURES FOR EUROPEAN INDUSTRY

SINTAP

COMPARISON : VARIOUS LEVELS OF THE SINTAP PROCEDURE FOR HOMOGENEOUS STRUCTURES

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1. INTRODUCTION

In the last London meeting at HSE on June 15 & 16, 1998, the SINTAP procedure has been finalised. In the proposed SINTAP procedure, various levels are set out to cope with quality of input information, for instance, of material's tensile data.

This report provides validations of the proposed procedure, through worked examples. Firstly, detailed assessment equations are summarised in Section 2. The resulting assessment curves of various levels are compared and discussed in Section 3 for continuous hardening materials. Section 4 compares the resulting assessment curves of various levels for materials with Lüders plateau. It is shown that the assessment curves for materials with Lüders plateau in general are quite conservative. In this context, a possible (preliminary) modification is given to reduce such excessive conservatism, which is subject to further experimental and numerical verifications.

NB :

This report is a collation of three faxes (which have been sent to BS, NEL and UC) plus their comments, see references:

2. SUMMARY OF THE PROPOSED ASSESSMENT CURVES

In the following, the assessment curves for homogeneous structures are summarised according to the decision made in the London meeting on June 15-16th, 1998.

2.1 Level 1 (Only Yield Stress Data Available)

2.1.1 Lüders strain expected

$$f(L_r) = \left(1 + \frac{1}{2} L_r^2\right)^{-1/2} \qquad \text{for} \qquad L_r \le L_r^{max} = 1 \qquad \textbf{(2.1)}$$

2.1.2 Lüders strain not expected

$$f(L_r) = \left(1 + \frac{1}{2} L_r^2\right)^{-1/2} \cdot \left[0.3 + 0.7 \exp\left(-0.6 \cdot L_r^6\right)\right]$$

$$\text{for} \qquad L_r \le L_r^{max} = 1 + \left(\frac{150}{YS}\right)^{2.5} \qquad \textbf{(2.2)}$$

2.2 Level 2 (Yield and Ultimate Stress Available)

2.2.1 Lüders strain expected

$$f(L_r) = \left(1 + \frac{1}{2} L_r^2\right)^{-1/2} \qquad \text{for} \qquad L_r < 1$$

$$f(1) = \left(\lambda + \frac{1}{2\lambda}\right)^{-1/2} \qquad \text{for} \qquad L_r = 1$$

$$\lambda = 1 + \frac{0.0375 \cdot E}{\sigma_Y}\left(1 - \frac{\sigma_Y}{1000}\right) \qquad \textbf{(2.3)}$$

$$f(L_r) = f(1) \cdot \left(L_r\right)^{(N-1)/2N} \qquad \text{for} \qquad 1 < L_r \le L_r^{max} = \frac{1}{2}\left(\frac{\sigma_Y + \sigma_U}{\sigma_Y}\right)$$

$$N = 0.3\left(1 - \frac{\sigma_Y}{\sigma_U}\right)$$

2.2.2 Lüders strain **not** expected

Level 2-1

$$f(L_r) = \left(1 + \frac{1}{2} L_r^2\right)^{-1/2} \cdot \left[0.3 + 0.7 \exp\left(-0.6 \cdot L_r^6\right)\right] \tag{2.4}$$

$$\text{for} \quad L_r \le L_r^{max} = \frac{1}{2}\left(\frac{\sigma_Y + \sigma_U}{\sigma_Y}\right)$$

Level 2-2

$$f(L_r) = \left(1 + \frac{1}{2} L_r^2\right)^{-1/2} \cdot \left[0.3 + 0.7 \exp\left(-\mu \cdot L_r^6\right)\right] \text{for} \quad L_r \le 1$$

$$\mu = 0.001 \cdot \frac{E}{\sigma_Y} \tag{2.5}$$

$$f(L_r) = f(1) \cdot (L_r)^{(N-1)/2N} \qquad \text{for} \quad 1 < L_r \le L_r^{max} = \frac{1}{2}\left(\frac{\sigma_Y + \sigma_U}{\sigma_Y}\right)$$

$$N = 0.3\left(1 - \frac{\sigma_Y}{\sigma_U}\right)$$

2.3 Level 3 (Full Stress-Strain Data Available)

$$f(L_r) = \left(\frac{E\varepsilon}{\sigma} + \frac{0.5 L_r^2}{(E\varepsilon/\sigma)}\right)^{-1/2} \qquad \text{for} \quad 1 < L_r \le L_r^{max} = \frac{1}{2}\left(\frac{\sigma_Y + \sigma_U}{\sigma_Y}\right) \tag{2.6}$$

2.4 Level 4 (J available)

$$f(L_r) = \left(\frac{J}{J_e}\right)^{-1/2} \qquad \text{for} \quad 1 < L_r \le L_r^{max} = \frac{1}{2}\left(\frac{\sigma_Y + \sigma_U}{\sigma_Y}\right) \tag{2.7}$$

3. COMPARISON OF VARIOUS LEVELS FOR CONTINUOUS HARDENING MATERIALS

In this section, the various levels of assessment curves for continuos hardening materials, given in the previous section, are compared. Total six materials with continuous hardening behaviours are considered, covering a wide range of hardening capacity. Table 1 lists brief descriptions of materials considered, and Fig. 1a shows stress strain curves.

Table 1: Materials considered in this note

Material	E (GPa)	σ_Y (MPa)	σ_U (MPa)	μ**	Y/T	N***
mas	210	840	900	0.25	0.93	0.02
wss	180	450	680	0.4	0.662	0.102
316L	195	294	611	0.6	0.481	0.156
ass	180	320	710	0.6	0.451	0.165
X6CrNi1811	195	227	617	0.6	0.368	0.190
Al2024-FC	72	82.4	224	0.6	0.368	0.190

* mas = micro-alloyed steel ; wss = stainless welding steel ;
ass = aged stainless steel

** calculated according to $\mu=0.001(E/\sigma_Y)$

*** calculated according to $N=0.3(1-\sigma_Y/\sigma_U)$

The level 4 curve requires the J integral from the elastic-plastic FE analyses. In this report, four different geometries are considered, covering various constraint conditions:

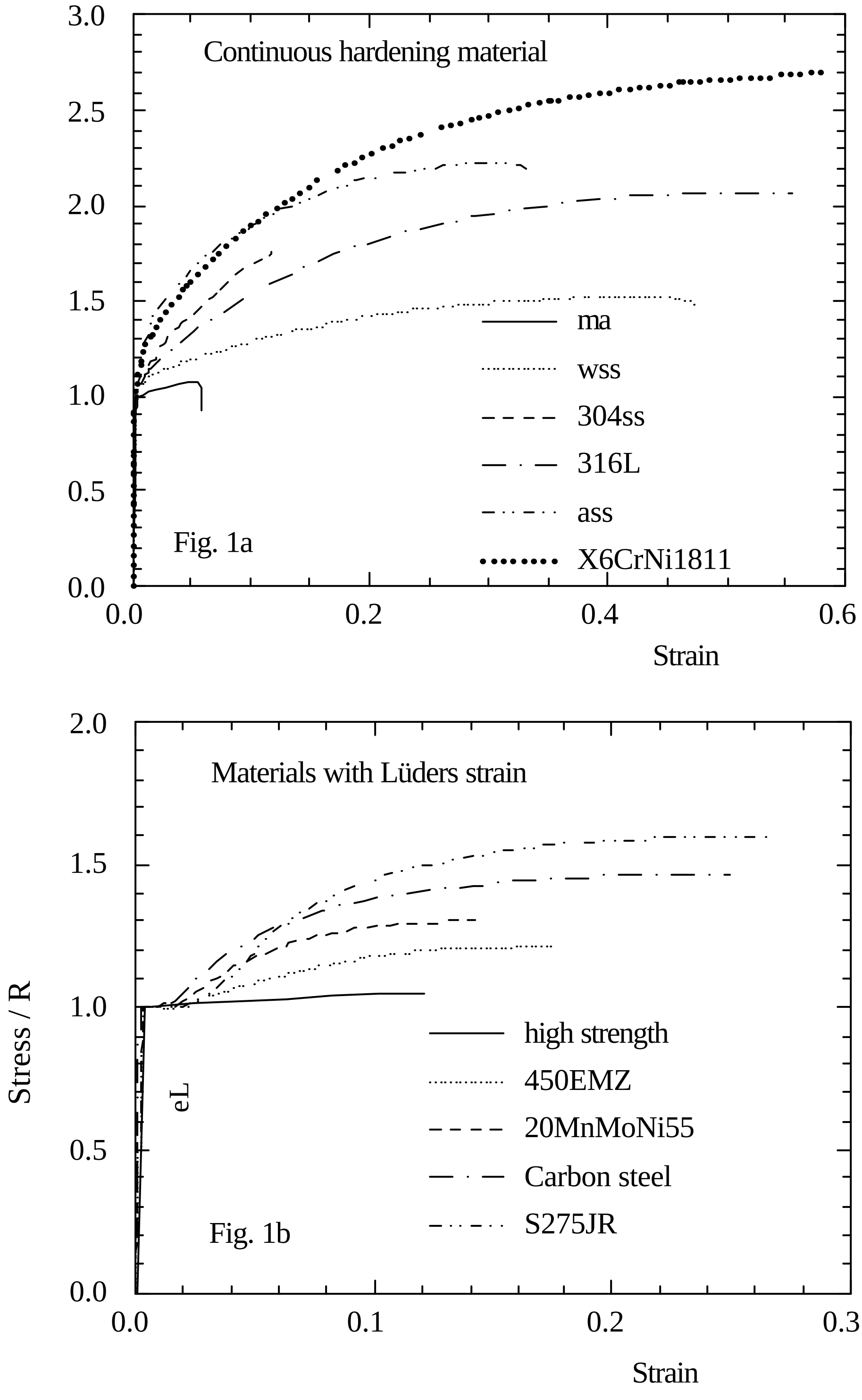
- centre cracked tensile plate with a/W=0.5 (plane stress) ; CCT0.5PS
- centre cracked tensile plate with a/W=0.5 (plane strain) ; CCT0.5PE
- single edge cracked bend specimen with a/W=0.2 (plane strain) ; SECB0.2PE
- single edge cracked bend specimen with a/W=0.5 (plane strain) ; SECB0.5PE

The resulting curves of various levels 2, 3 and 4 are compared in Fig. 2a-2f. The results show that generally the curves are in the correct order; the higher level leads to the less conservative results.

It should be noted that for some cases the level 2 curves can be slightly less conservative than the level 3 curve (see Fig. 2b. stainless welding steel; Fig. 2c. 316L). Such less conservatism of level 2 curves, compared to the level 3 curve, results from hardening behaviours. There are two classes of hardening behaviours :

- One is high hardening rate from the beginning (for instance, aged stainless steel and Al2024-FC, see Fig. 3a). In this case, our equation, N=0.3(1-Y/T), gives quite conservative estimate of N
- The other is initially low hardening rate but increasing hardening rate with plastic deformation (for instance, welding stainless steel, 316L etc., see Fig. 3b). In this case, N=0.3(1-Y/T) could provide a slightly higher value of N. Note that this has been also observed from the UC work showing that some data points of N vs. Y/T are even below the N=0.3(1-Y/T) line, depending on how they are measured.

Consequently when we compare two materials with similar Y/T ratios, they can show completely different hardening behaviours. See Fig. 4 for comparison. Although 316L and aged stainless steel have similar Y/T ratio, initial hardening rates are very different. Note that for assessment the initial hardening rate is a major concern (below cut-off). For X6CrNi1811 and Al2024-FC, the similar argument applies. However, as Bob Ainsworth (NE) pointed out, there will always be the possibility of an unusual shape to the stress strain curve that means a power law fit may not be adequate. Thus it is preferable to generate a lower level curve which is reasonably accurate rather than be overconservative in an attempt to ensure it will always be inside the higher level curves. In this sense we should tolerate such slightly less conservatism in certain cases.



3.0
2.5
2.0
1.5
1.0
0.5
0.0
Continuous hardening material
ma
wss
304ss
316L
ass
X6CrNi1811
Fig. 1a
0.0
0.2
0.4
0.6
Strain
2.0
1.5
1.0
0.5
0.0
Stress / R
Materials with Lüders strain
eL
high strength
450EMZ
20MnMoNi55
Carbon steel
S275JR
Fig. 1b
0.0
0.1
0.2
0.3
Strain

Fig. 1

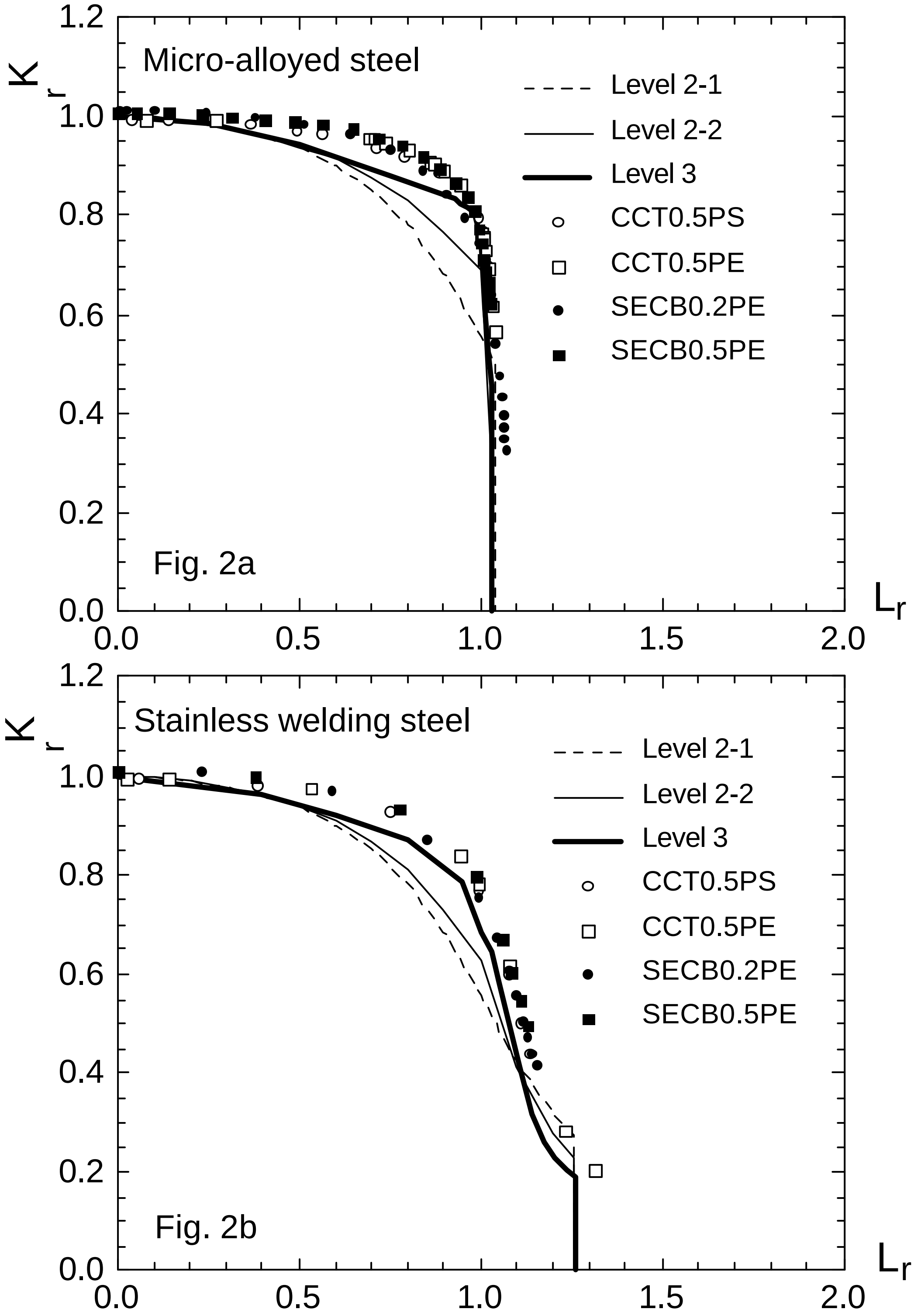
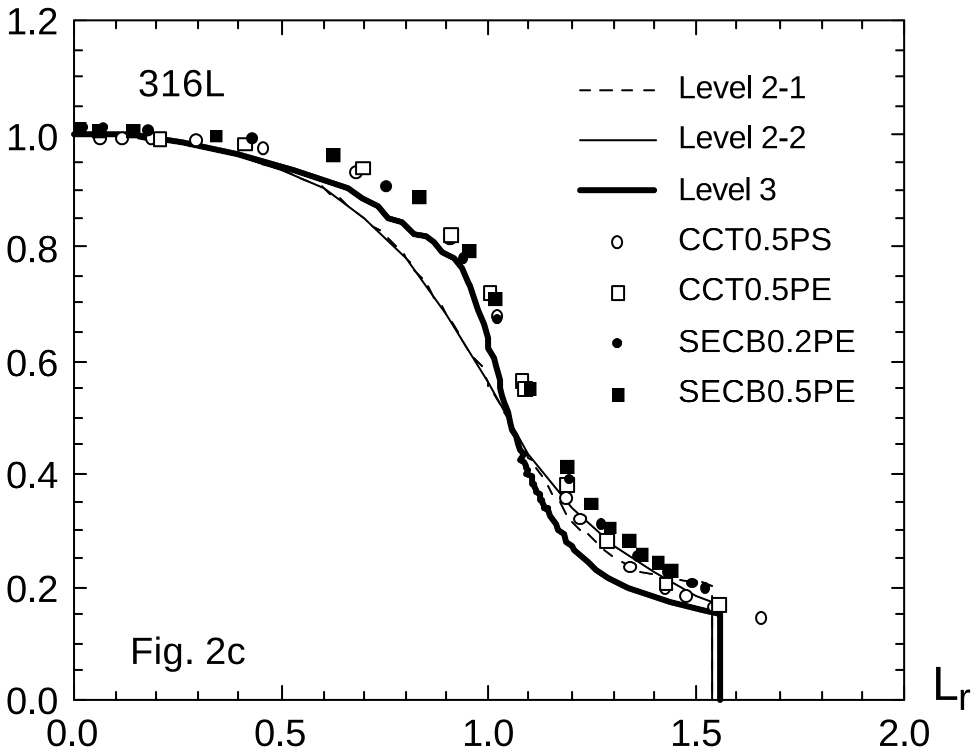

Micro-alloyed steel
Level 2-1
Level 2-2
Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
Fig. 2a
Stainless welding steel
Level 2-1
Level 2-2
Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
Fig. 2b
K_r
L_r
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.5
1.5
2.0

Fig. 2


1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
316L
Level 2-1
Level 2-2
Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
Fig. 2c
Lr

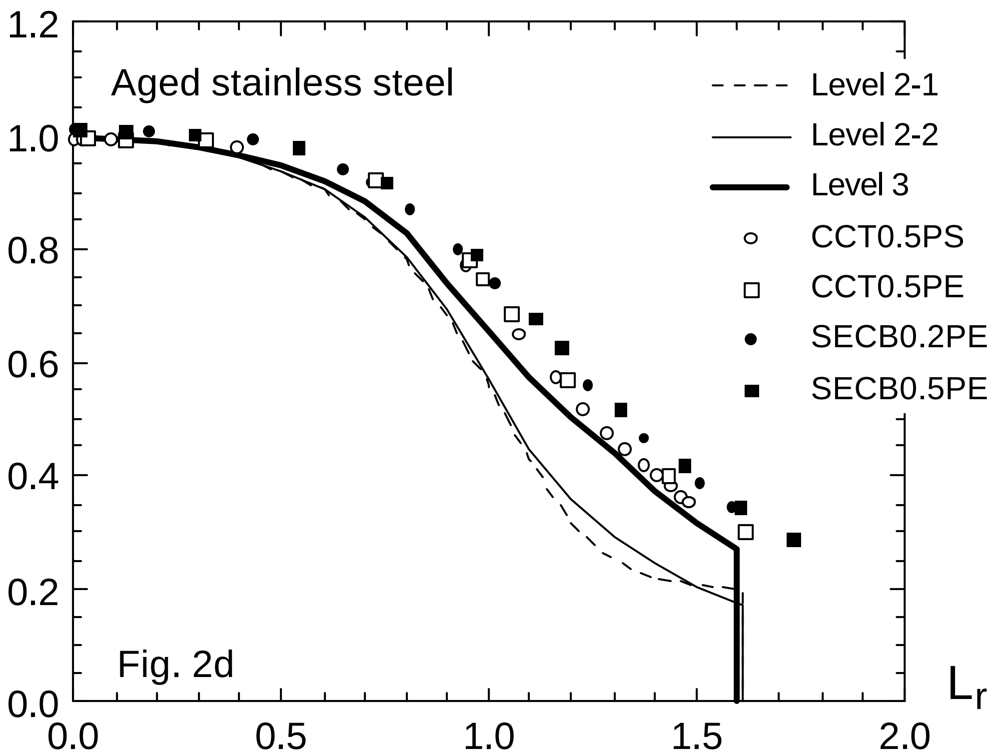
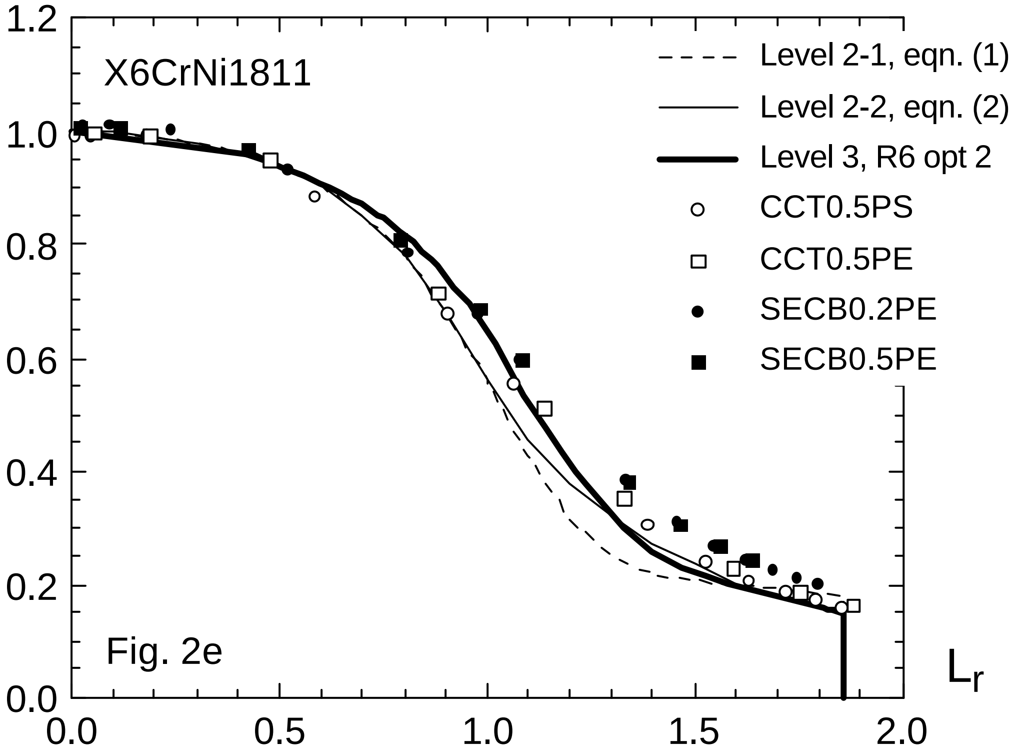

1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
Aged stainless steel
Level 2-1
Level 2-2
Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
Fig. 2d
Lr

Fig. 2 (Cont'd)


X6CrNi1811
Level 2-1, eqn. (1)
Level 2-2, eqn. (2)
Level 3, R6 opt 2
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
Fig. 2e
L_r
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.5
1.5
2.0

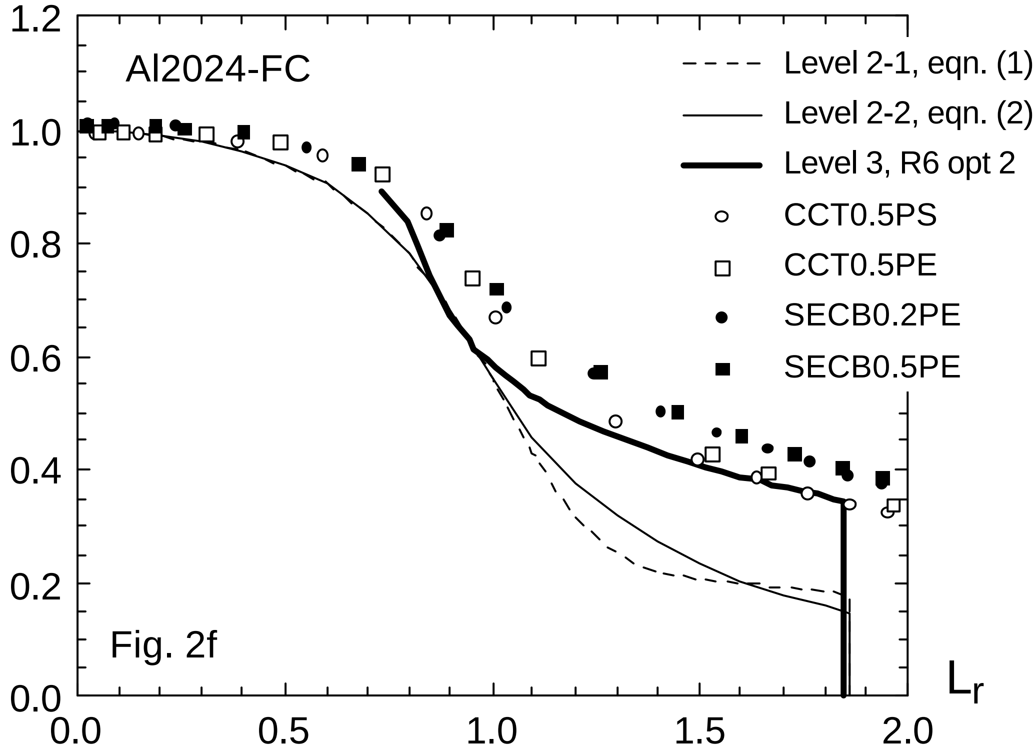
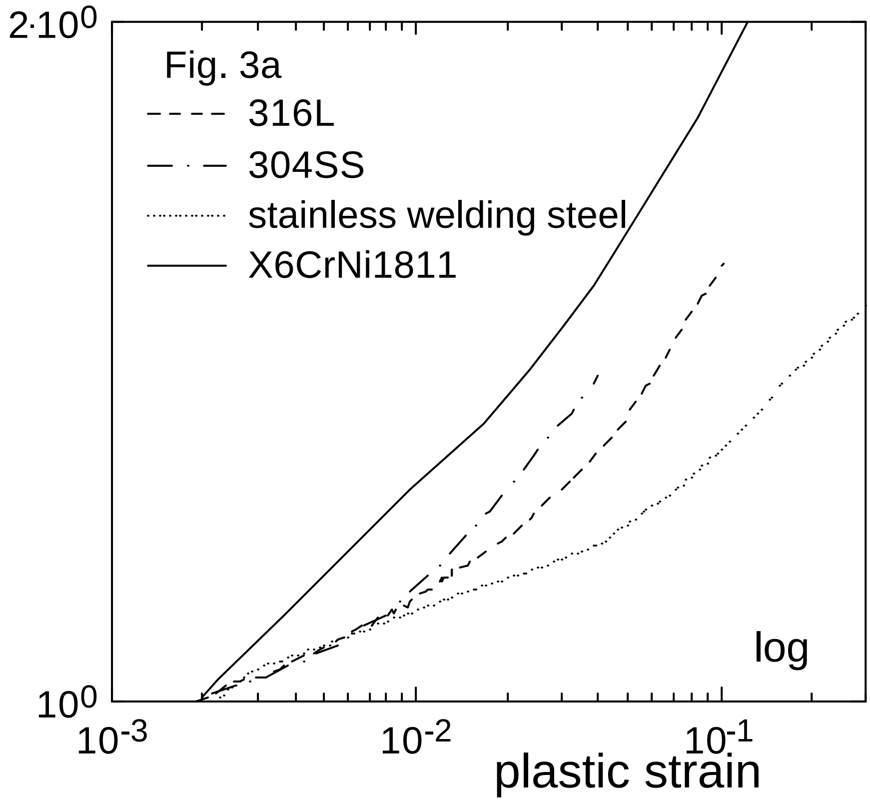
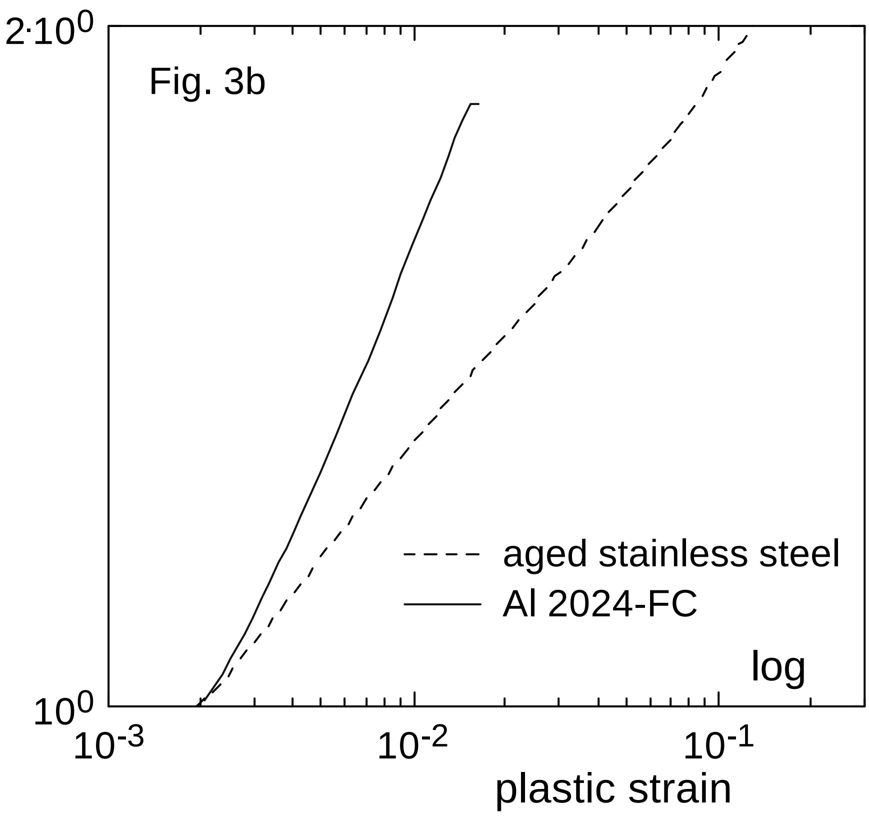

Al2024-FC
Level 2-1, eqn. (1)
Level 2-2, eqn. (2)
Level 3, R6 opt 2
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
Fig. 2f
L_r
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.5
1.5
2.0

Fig. 2 (Cont'd)

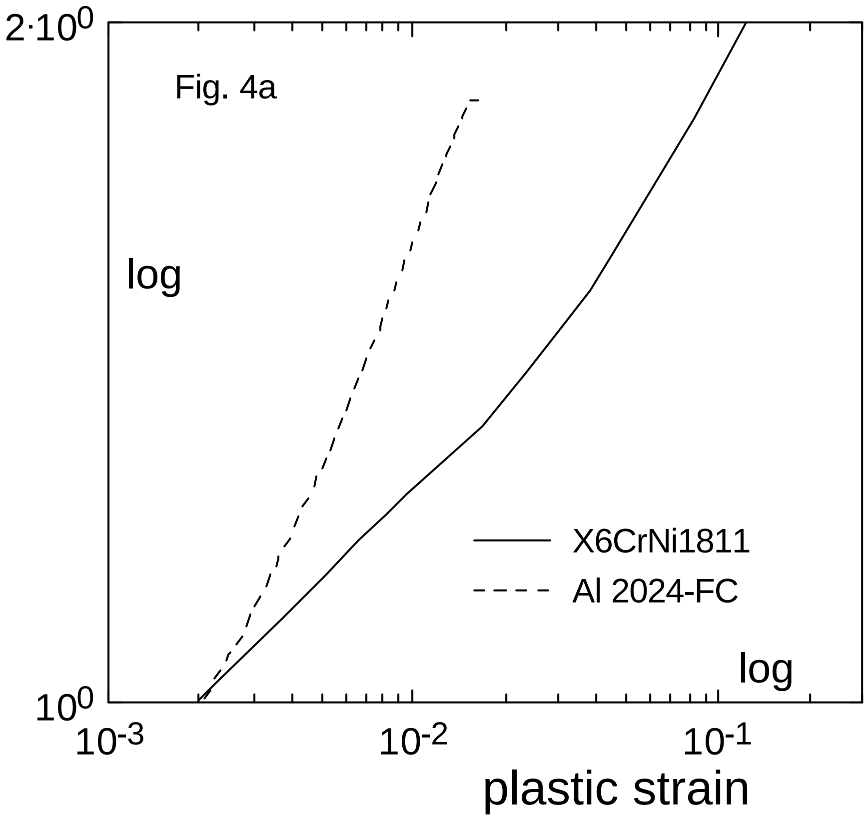


2·10^0
10^0
10^-3
10^-2
10^-1
Fig. 3a
316L
304SS
stainless welding steel
X6CrNi1811
log
plastic strain



2·10^0
10^0
10^-3
10^-2
10^-1
Fig. 3b
aged stainless steel
Al 2024-FC
log
plastic strain

Fig. 3


2·10^0
Fig. 4a
log
X6CrNi1811
Al 2024-FC
log
10^0
10^-3
10^-2
10^-1
plastic strain

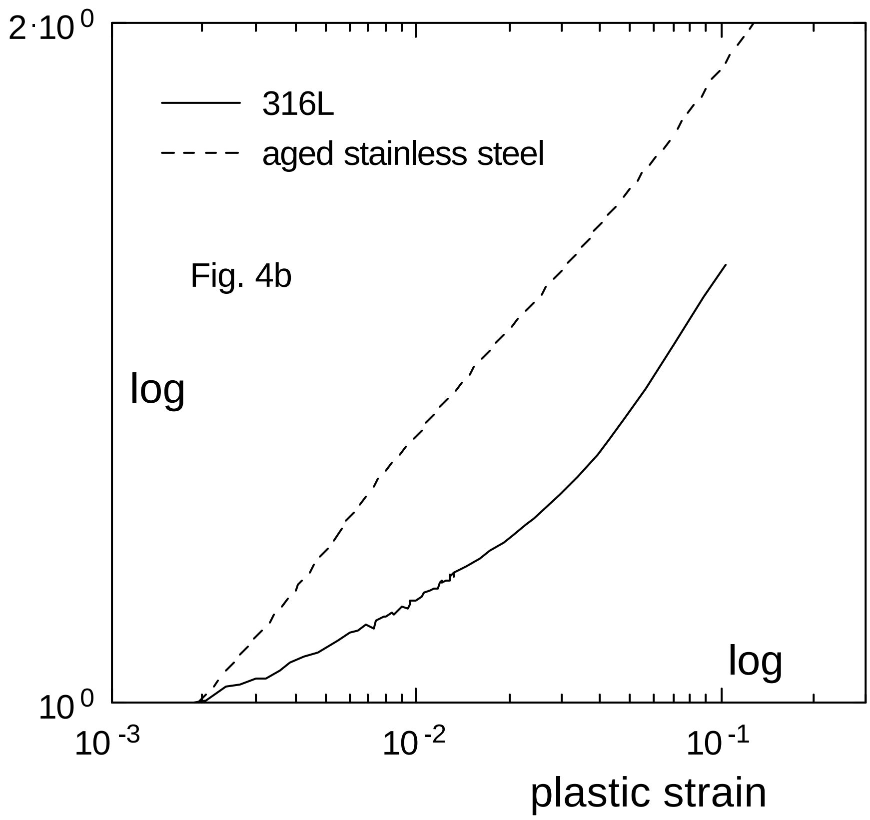

2·10 0
316L
aged stainless steel
Fig. 4b
log
log
10 0
10 -3
10 -2
10 -1
plastic strain

Fig. 4

4. COMPARISON OF VARIOUS LEVELS FOR MATERIALS WITH LÜDERS PLATEAU

In this section, the various levels of assessment curves for materials with Lüders plateau, given in the previous section, are compared. Total six materials with continuous hardening behaviours are considered, covering a wide range of hardening capacity. Table 2 lists brief descriptions of materials considered, and Fig. 1b shows stress strain curves.

Table 2: Materials considered in this note

Material	σ_Y (MPa)	σ_U (MPa)	ε_L **	N***	N****
high strength	800	840	0.0075		0.0143
StE 690*	740	841	0.0098	0.04	0.036
450EMZ*	540	656	0.017	0.09	0.053
20MnMoNi55	543	707	0.017	0.13	0.07
355EMZ*	400	543	**0.023**	0.12	0.08
Carbon steel	285	410	0.027	0.13	0.09
S355J2*	415	626	0.022	0.18	0.10
S275JR*	361	577	0.024	0.2	0.11

* Data from British Steel in Sub-Task 2.3

** calculated according to ε_L=0.035(1-σ_Y/1000)

*** estimated from stress strain data

**** calculated according to N=0.3(1- σ_Y/σ_U)

The level 4 curves are obtained for four different geometries:

- centre cracked tensile plate with a/W=0.5 (plane stress) ; CCT0.5PS
- centre cracked tensile plate with a/W=0.5 (plane strain) ; CCT0.5PE
- single edge cracked bend specimen with a/W=0.2 (plane strain) ; SECB0.2PE
- single edge cracked bend specimen with a/W=0.5 (plane strain) ; SECB0.5PE

The resulting curves of various levels 2, 3 and 4 are compared in Fig. 5a-5f. The results again show that generally the curves are in the correct order; the higher level leads to the less conservative results. The following comments are worth noting:

- First of all, the level 2 curve is quite conservative, compared to the level 3 curve. One of the sources of such excessive conservatism is $N=0.3(1-\sigma_Y/\sigma_U)$. The N values deduced from stress strain data are compared with those from $N=0.3(1-\sigma_Y/\sigma_U)$ in Table 2. On the other hand, the equation $\varepsilon_L=0.035(1-\sigma_Y/1000)$ seems to be satisfactory.
- Secondly, it can be seen that, for materials with Lüders strain, even the level 3 curve is quite conservative, compared to the level 4 (FE results) curves. It seems that the entire length of ε_L is not relevant for cracked specimens. In this context, a pragmatic way has been proposed to remove such high conservatism by reducing ε_L by a factor of 2, which will be described below. **It should be noted however that the current approach should be retained as it is and that such proposal can be reconsidered in the future when sufficient experimental and numerical results are available to resolve this issue.**

<u>Proposal for Modifying Level 3 Curves for Materials with Lüders Plateau</u>

For materials with Lüders strain, the SINTAP level 3 (R6 option 2) curve is generally conservative for Lr>1. Although such conservatism can be tolerated in structural assessment, the less conservative assessment curve would be desired. The key observation is that the entire length of ε_L measured from tensile specimens may not be relevant for cracked specimens.

The procedure can be set out as follows:

- Determine full stress strain data for materials with Lüders strain, for instance, see Fig. 6a.
- Determine the lower yield stress R_{eL} and the extent of Lüders strain, ε_L, according to BSxxx or ASTM E8, Fig. 6b.
- Discard all data below $\varepsilon=\varepsilon_L$, see Fig. 6b.
- Subtract $\varepsilon_L/2$ (fixed number) from the strain:

$\varepsilon_{new}=\varepsilon-\varepsilon_L/2$, Fig. 6c.

(This formula is based on observation from FE results that in cracked specimens, the entire ε_L is not relevant, but approximately half of ε_L would be relevant.)

- Apply the following equation:

$$f(L_r)=\left(1+\frac{1}{2}L_r^2\right)^{-1/2} \qquad \text{for} \qquad 0 \le L_r < 1$$

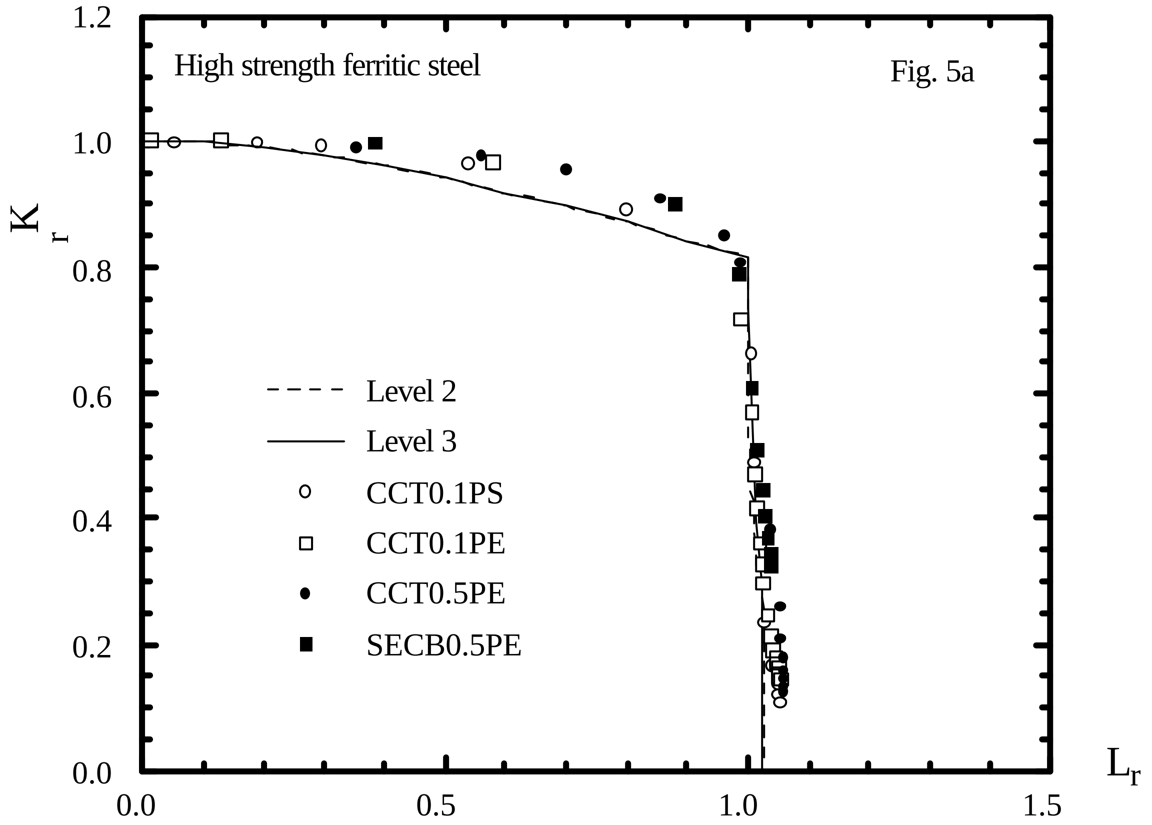
$$f(1)=\left(\lambda+\frac{1}{2\lambda}\right)^{-1/2} \qquad \text{for} \qquad L_r = 1$$

$$\lambda = 1+\frac{E}{\sigma_y}\cdot\left(\frac{\varepsilon_L}{2}\right) \qquad ;\ \varepsilon_L \text{ measured from stress strain data}$$

$$f(L_r)=\left[\frac{E\,\varepsilon_{ref}}{\sigma_{ref}}+\frac{L_r^2\sigma_{ref}}{2E\,\varepsilon_{ref}}\right] \qquad \text{for} \qquad 1 < L_r \le L_r^{max} = \frac{\sigma_y+\sigma_u}{2\sigma_y}$$

Figure 7 shows comparison of the proposed curve with the original SINTAP level 3 curve (R6 option 2), together with selective FE results. For information on material data, see Table 2.

Finally it should be again noted that the current SINTAP approach should be retained as it is. The proposal given in this section is simply an option which can be reconsidered in the future when sufficient experimental and numerical results are available to resolve this issue.


High strength ferritic steel
Fig. 5a
Level 2
Level 3
CCT0.1PS
CCT0.1PE
CCT0.5PE
SECB0.5PE
K
r
L
r
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5

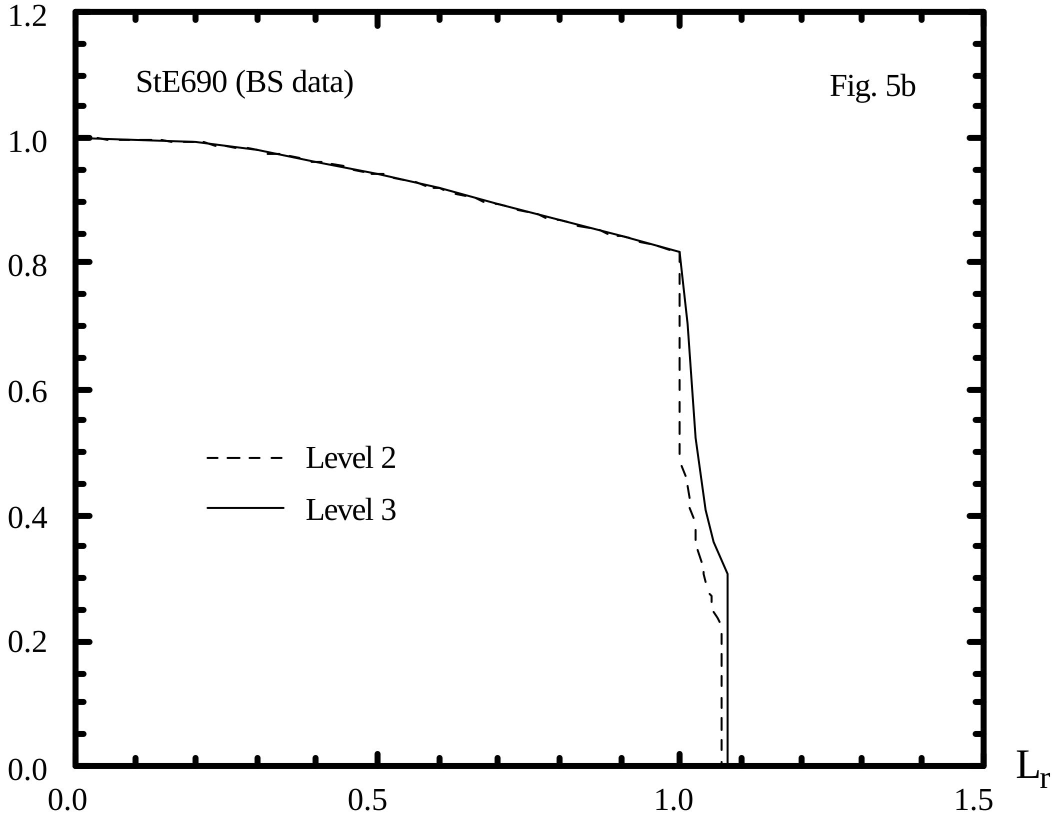
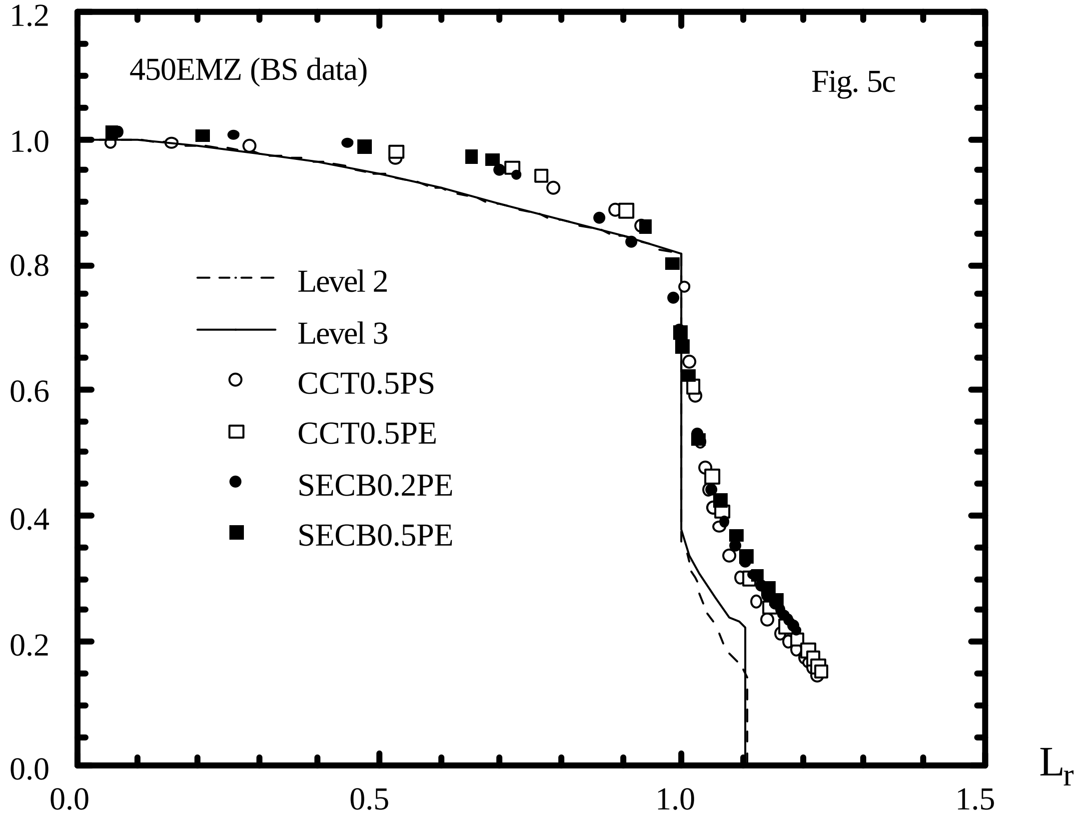

StE690 (BS data)
Fig. 5b
Level 2
Level 3
L
r
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5

Fig. 5


450EMZ (BS data)
Fig. 5c
Level 2
Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
L_r

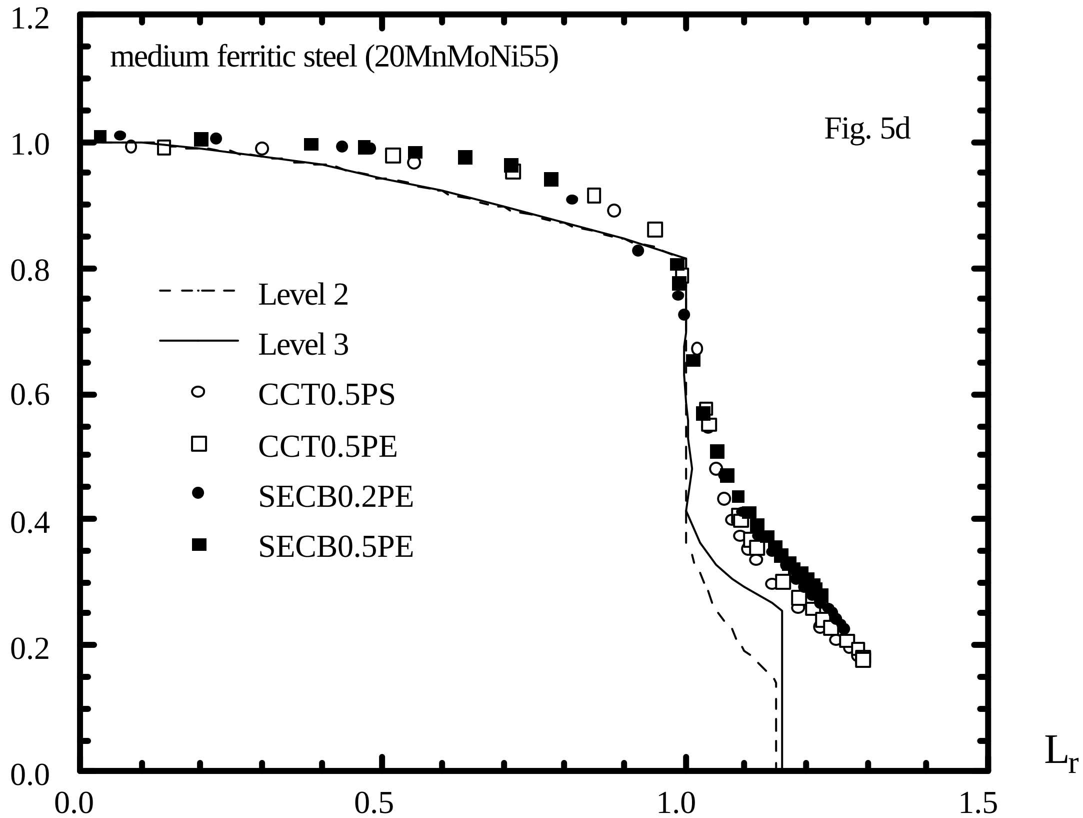
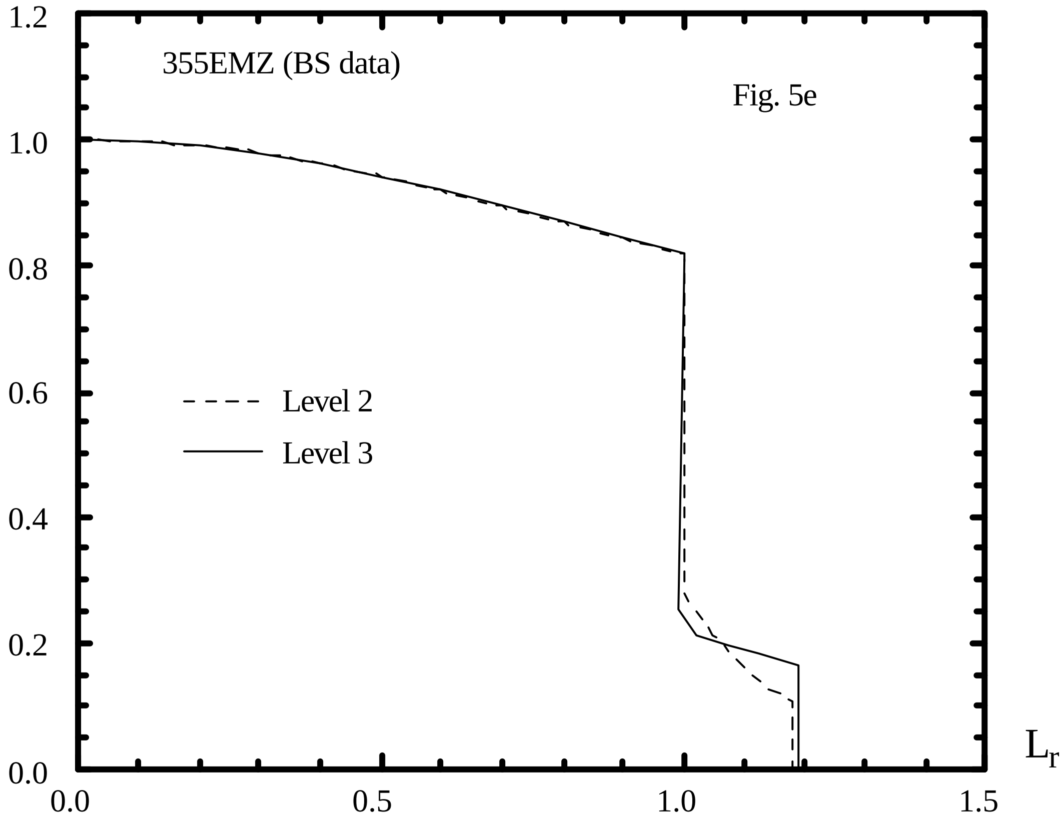
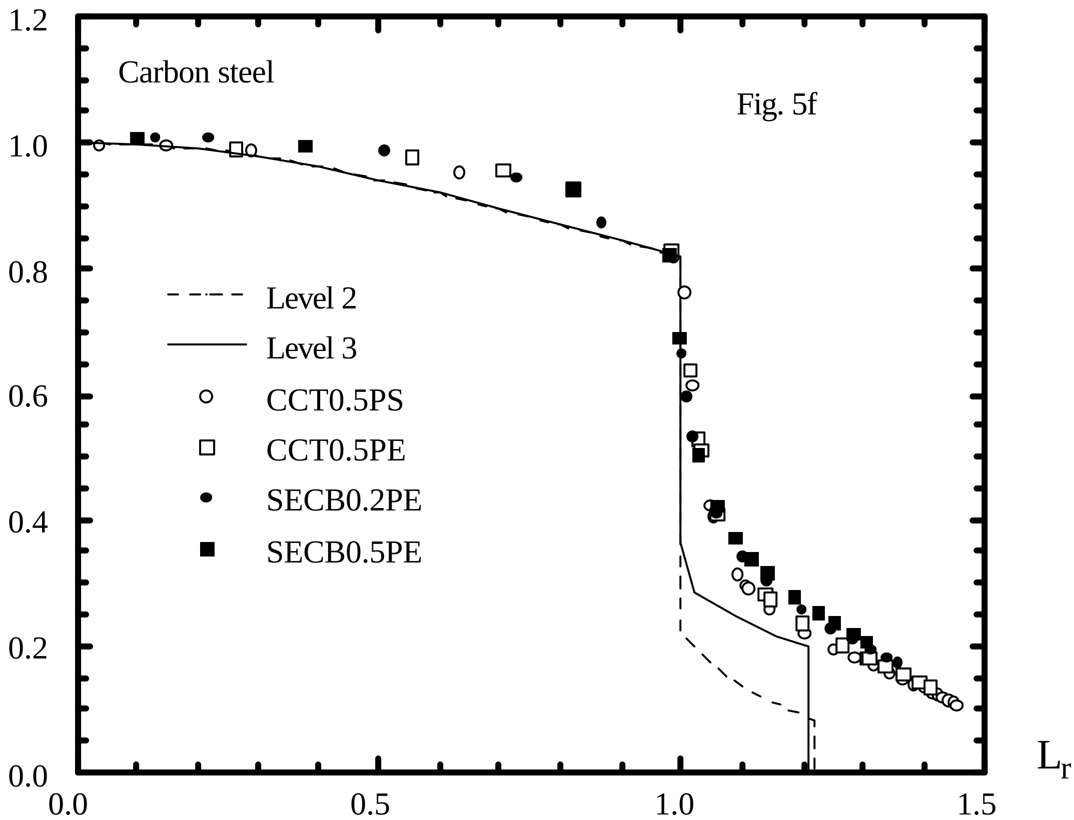

medium ferritic steel (20MnMoNi55)
Fig. 5d
Level 2
Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
L_r

Fig. 5 (Cont'd)

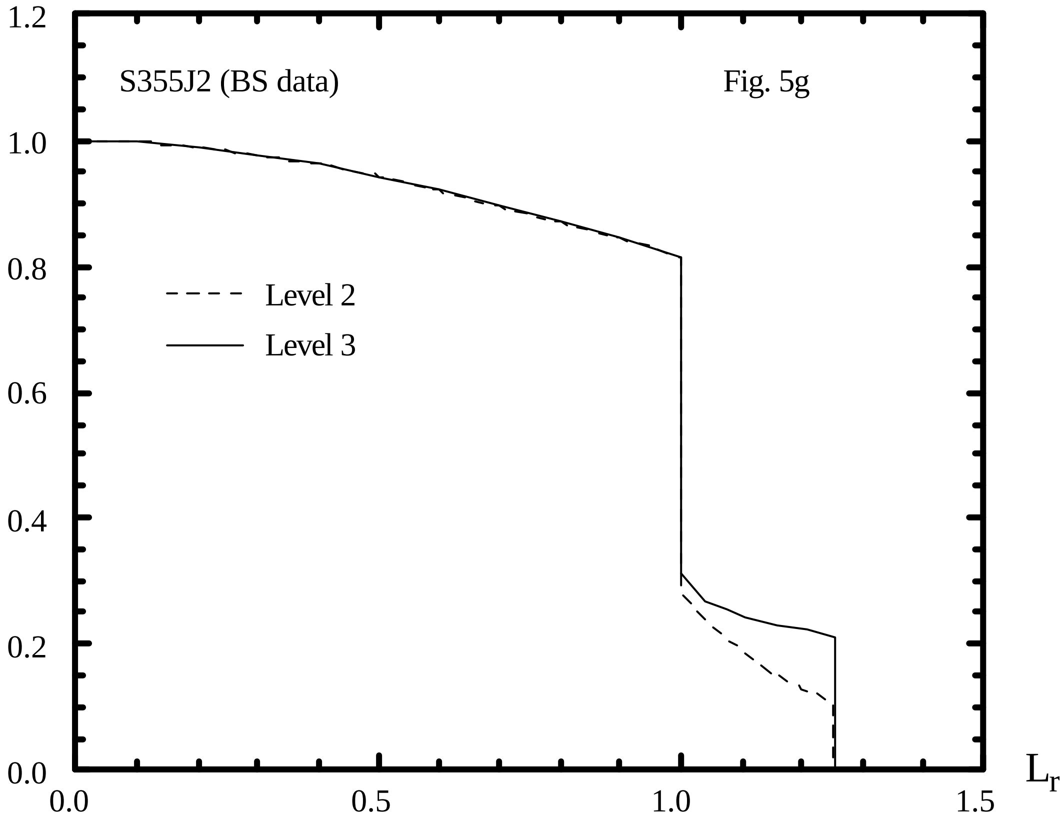


1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
355EMZ (BS data)
Fig. 5e
Level 2
Level 3
L_r



1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
Carbon steel
Fig. 5f
Level 2
Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
L_r

Fig. 5 (Cont'd)


S355J2 (BS data)
Fig. 5g
Level 2
Level 3
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
L_r

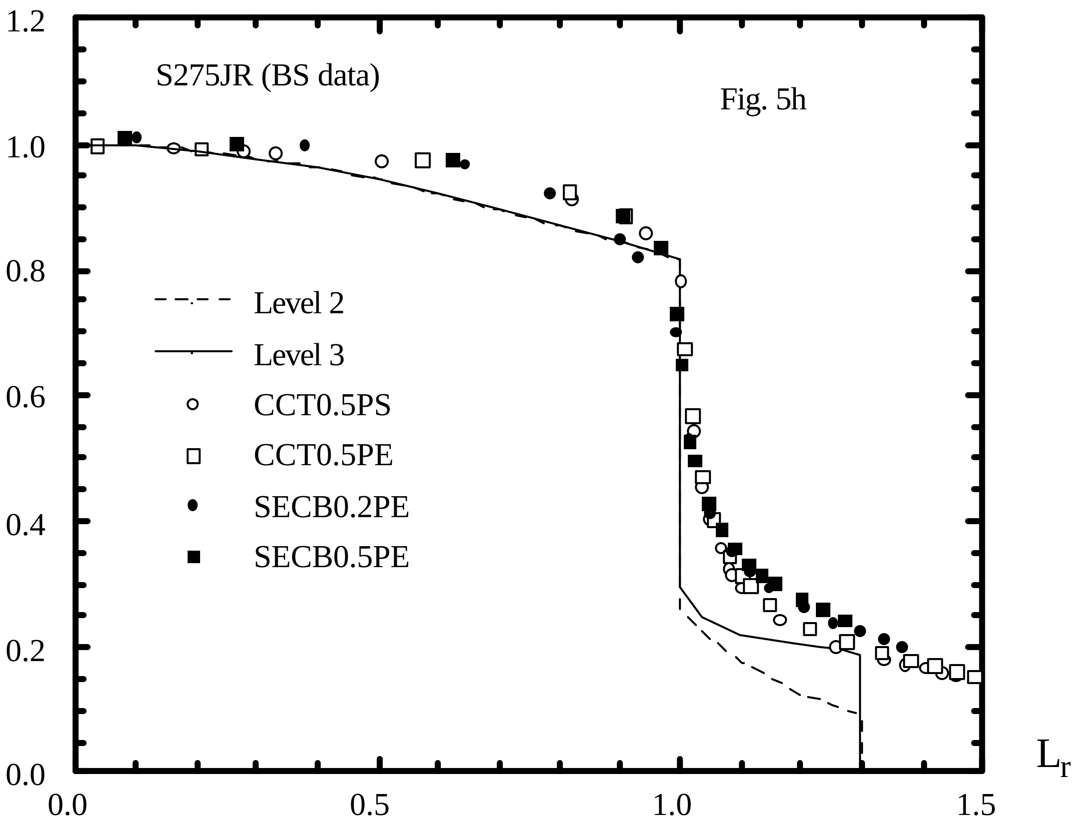

S275JR (BS data)
Fig. 5h
Level 2
Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
L_r

Fig. 5 (Cont'd)

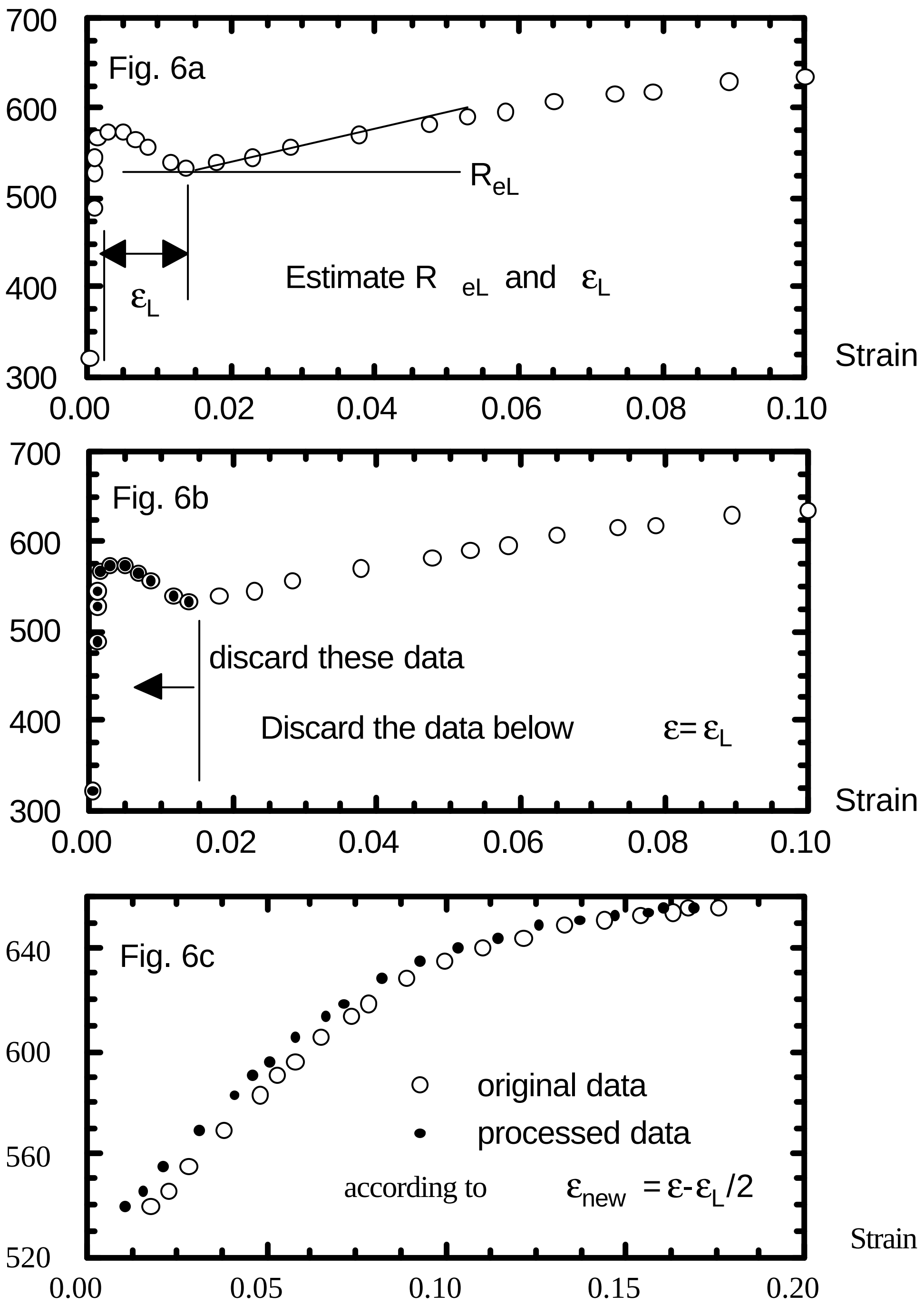
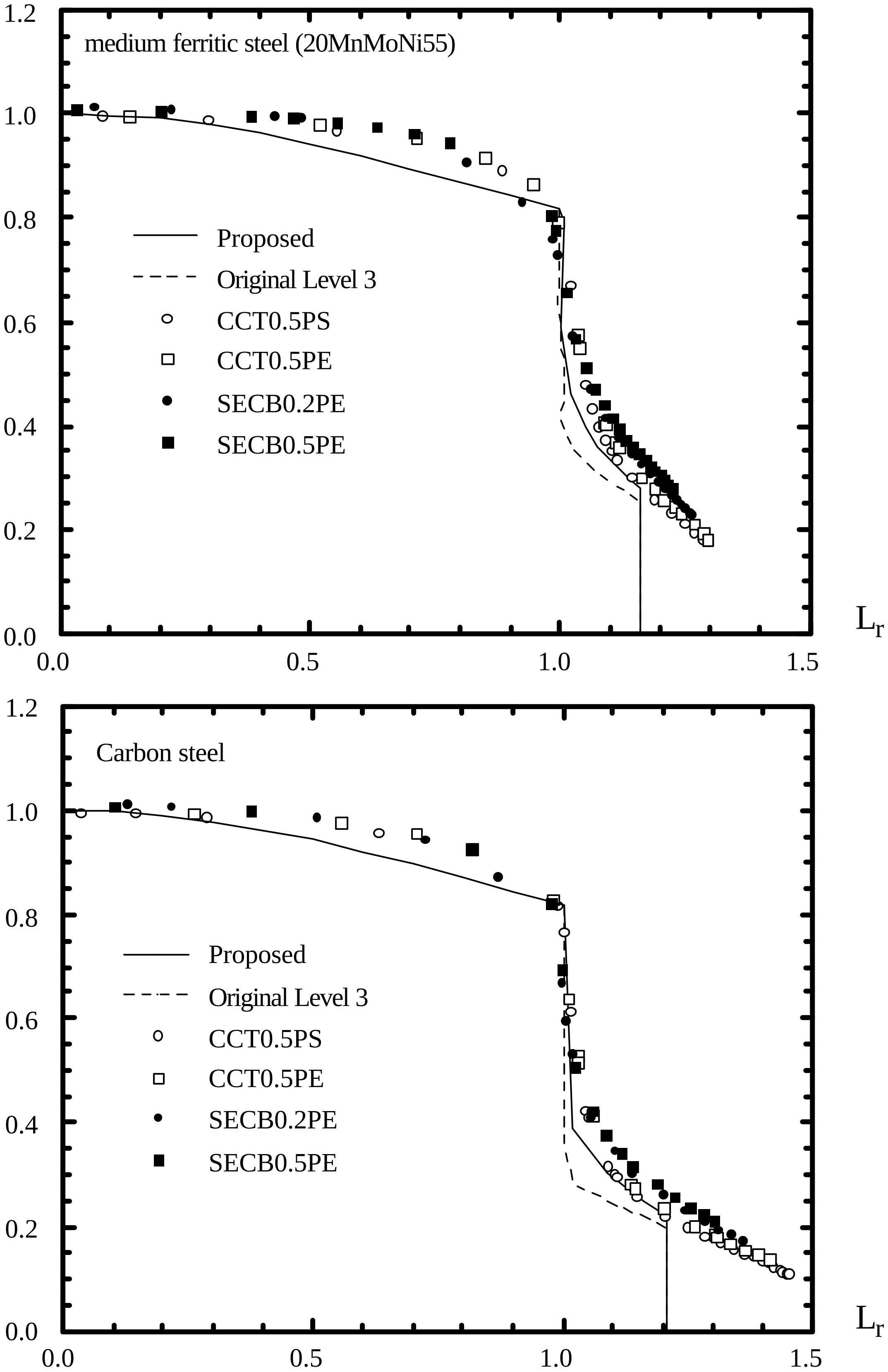

700
600
500
400
300
0.00
0.02
0.04
0.06
0.08
0.10
Fig. 6a
R_eL
Estimate R eL and ε_L
ε_L
Strain
700
600
500
400
300
Fig. 6b
discard these data
Discard the data below ε= ε_L
Strain
640
600
560
520
0.00
0.05
0.10
0.15
0.20
Fig. 6c
original data
processed data
according to ε_new = ε-ε_L/2
Strain

Fig. 6



medium ferritic steel (20MnMoNi55)
Proposed
Original Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
0.5
1.0
1.5
Lr
Carbon steel
Proposed
Original Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
0.5
1.0
1.5
Lr

Fig. 7

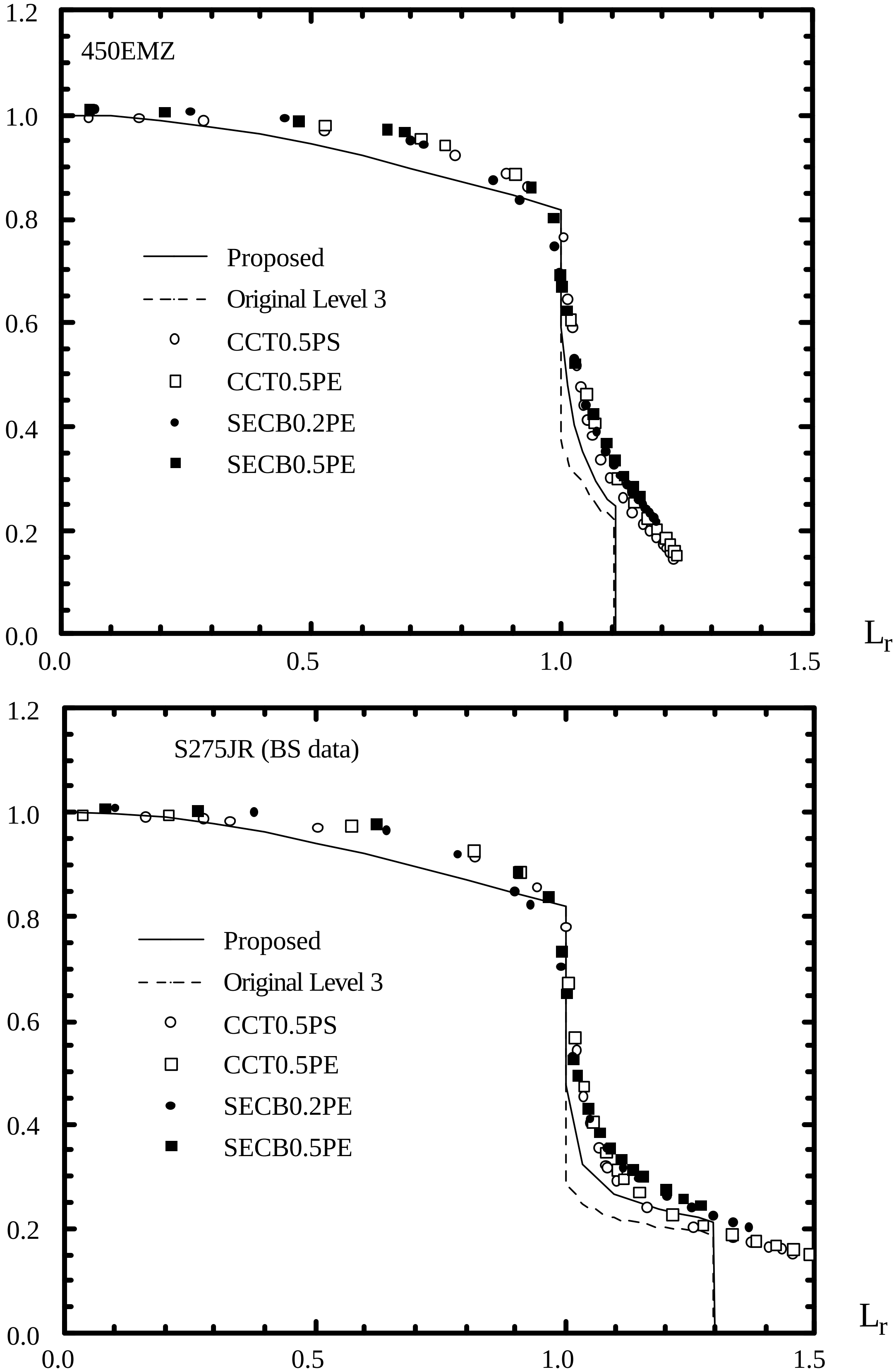

450EMZ
Proposed
Original Level 3
CCT0.5PS
CCT0.5PE
SECB0.2PE
SECB0.5PE
S275JR (BS data)
L_r
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.5
1.5

Fig. 7 (Cont'd)

References

- Comparison of Level 2 and 3 curves for continuous hardening materials, based on recommendations from the London meeting, fax from GKSS to NEL, BS and UC on July 2, 1998.

- Comparison of Level 2,3 and 4 curves for materials with Lüders strain, based on recommendations from the London meeting, fax from GKSS to NEL, BS and UC on July 6, 1998.

- Proposal for modification of the level 3 (R6 Option 2 curve) for materials with Lüders strain, fax from GKSS to NEL and BS on July 6, 1998.

- Comments by Bob Ainsworth (NEL) on above three faxes

- Memorandum, minutes of SINTAP Task 5 meeting on 15-16th June 1998 at HSE London, British Steel, 22 June 1998.