# DYNAMIC ELASTIC-PLASTIC CHARACTERIZATION OF NUCLEAR PRESSURE VESSEL MATERIAL

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## ABSTRACT

In this work a new type of test is described, which strongly implements standard tests techniques, like pre-cracked instrumented Charpy, widely used to characterize pressure vessel steels.

## KEYWORDS

VLB test; $J_d$-R curve; dynamic load-displacement; dynamic toughness; crack-arrest.

## INTRODUCTION

Due to the small size, the Charpy specimen is still nowadays of utmost interest, mainly in the field of nuclear vessel surveillance. The Charpy test has been continuously refined during these last years through the use of more and more complex instrumentations and test techniques.

A new type of test (VLB test) and instrumentation, which both extend the Charpy specimen performances, are here introduced. Material parameters like:

i) dynamic value of J-integral at crack initiation ($J_{Id}$),

ii) $J_d$-R curve,

iii) toughness and velocity of a running crack ($K_D$, v),

iv) toughness of a crack at arrest ($K_A$),

will shown to be obtained from VLB test.

## INSTRUMENTATION

To the Charpy tester, besides conventional instrumentation, an especially developed CISE transducer was added (Fig. 1) which gives the time evolution of the load point displacement during the test. All the following parameters (conventional and unconventional) are measured during an impact test:

i) Force vs. time : $F = f(t)$,

ii) Energy vs. time : $E = f(t)$,

iii) Hammer velocity at impact : $V_o$,

but, more important :

iv) Displacement vs. time : $\delta = f(t)$ and

v) Force Vs. displacement : F = f ( δ).
A general view of the instrumented Charpy tester is given in Fig. 2.

Fig. 1. Displacement transducer.

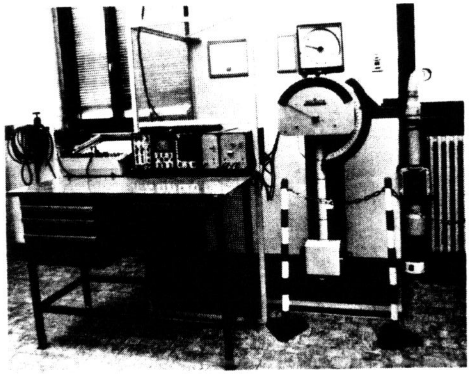

Fig. 2. General view of the equipment.

VLB TEST TECHNIQUE

The peculiarity of the VLB (Very Low Blow) test technique lies on the selection of very small blow angles liable to keep the pendulum energy insufficient to completely sever the specimen ligament: in this way just a small and controlled crack propagation is produced in the specimen. The hammer velocity decreases down to zero during the test, after that the elastic energy stored in the machine-specimen system is released back and the pendulum direction inverted, as shown in Fig. 3.

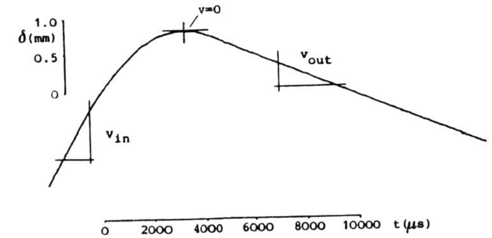


Fig. 3. Typical δ-t record from a VLB test.

Due to this velocity variation, both the conventional instrumentation and test methods are outruled; when load is however plotted vs. displacement signal, meaningful and easy to handle plots, as shown in Fig. 4, are obtained.



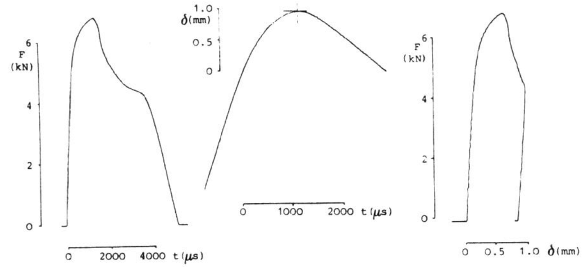


Fig. 4. Typical F-t, δ-t and F-δ records from a VLB test.

EXPERIMENTS

Tests were made on an A533B-Cl 1 steel plate fully characterized in TL orientation by instrumented precracked Charpy ($PCC_V$) tests, according to EPRI procedures, as developed by Server and co-workers (1977); the results are given in Fig. 5.
VLB tests were then performed on TL oriented $PCC_V$ specimens (a/W = 0.5) from the same plate, at three temperatures of interest:
100 °C (upper shelf)
-25 °C (mid transition)
-40 °C (lower shelf)
Tests at upper shelf - Five specimens were tested; the load-displacement traces at different striker velocities are given in Fig. 6. Heat tint was used to mark crack extensions (Δa); specimens were then open-broken in liquid nitrogen and Δa measured using a nine point integrated average technique. J values were determined through the widely known Rice expression for deeply notched bars in bending. J and Δa va-

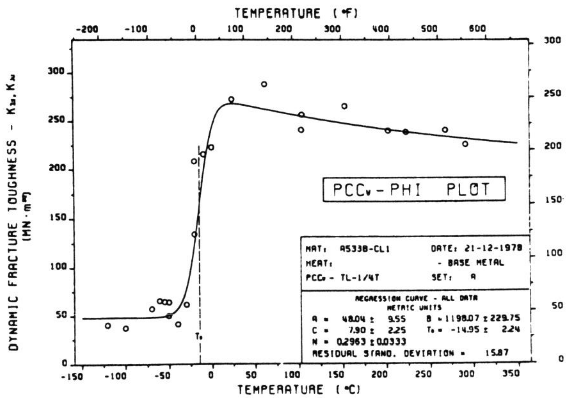


Fig. 5. A533B-Cl 1 results from $PCC_V$ according to EPRI procedures.

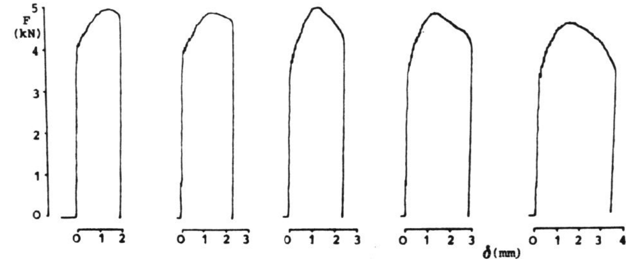


Fig. 6. F-δ records from VLB tests at 100 °C.

lues were then used to develop the J-R curve shown in Fig. 7; in the same figure are also plotted, for comparison, static values obtained on the same material via $PCC_v$ specimens tested in slow bend. $J_{Id}$ at crack initiation was then determined at the intersection between $J_d$-R curve and blunt line.
Evidence is made on equivalent mean[1] K rates which were found to be around $0.5 \cdot 10^5$ MPa $\sqrt{m}$/s, as required by a fully dynamic test, in spite of the low velocity of the pendulum (0.8 ÷ 1 m/s).
Tests at transition - In the velocity range between 0.7 ÷ 0.9 m/s a $J_d$-R curve was again developed, thus allowing the determination of $J_{Id}$ at true crack initiation. The results are given in Fig. 8 together with the static J-R curve; load vs. displacement records are given in Fig. 9.
Surprisingly, while trying an input velocity higher than 0.9 m/s to add another point at the right side along the $J_d$-R curve, unstable crack propagation and crack-arrest were produced in the specimen, as shown in Fig. 10.
Fractographic examination showed a well defined cleavage fracture (Fig. 11), while other stable specimens revealed a ductile tearing mechanism typically active at upper shelf temperatures (Fig. 12).

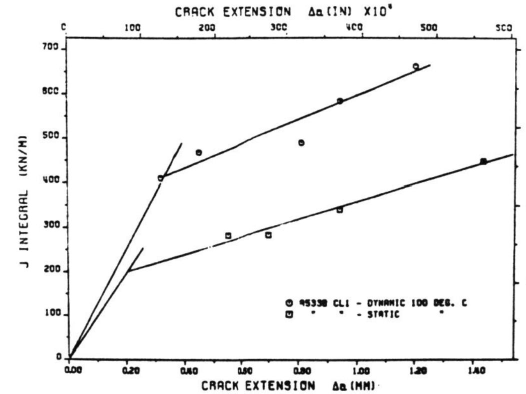


Fig. 7. Static and dynamic J-R curves at 100 °C.

[1]Mean value between beginning of the loading and hammer stop; mean value between beginning of the loading and maximum load was $1.3 \cdot 10^5$ MPa $\sqrt{m}$/s .



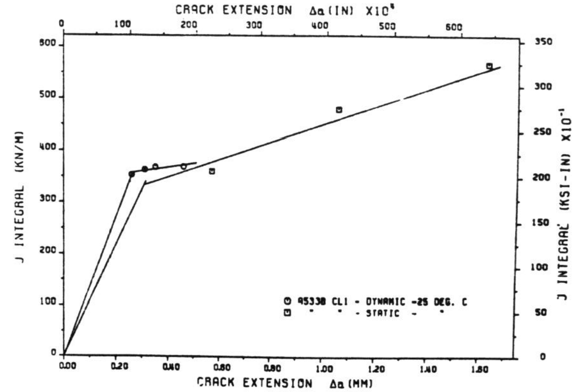


Fig. 8. Static and dynamic J-R curves at -25 °C.

Tests at lower shelf - At -40 °C unstable behaviour was always experienced. A limit velocity ($V_{min}$), at which no fracture occured, was found, for $V > V_{min}$ all the specimens fractured completely without crack-arrest. Typical load-displacement records are given in Fig. 13.

## DISCUSSION OF RESULTS

All $K_{jd}$ and $K_A$ results obtained from VLB tests are plotted in Fig. 14 around the transition curve previously given in Fig. 5.
Upper shelf - The $K_{jd}$ value obtained from VLB test at crack initiation well agrees with the value determined according to EPRI procedures: this agreement suggests that on this material no stable crack growth takes place before maximum load.
Transition temperature - Two different behaviours were here observed: stable and unstable.

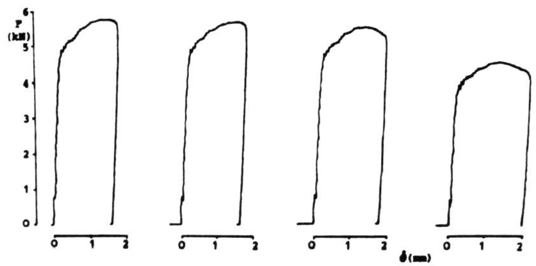


Fig. 9. F-δ records from VLB tests at -25 °C.

- Stable behaviour - $K_{jd}$ at crack initiation was found to be $K_{jd} \sim 290$ MPa $\sqrt{m}$: both this value, and the observed fracture mechanism are typical of the upper shelf behaviour (see Fig. 14). On the other hand the $J_d$-R curve is quite flat (Fig. 8) which suggests that the material is approaching instability (dJ/da = 0). This behaviour could probably be better analyzed through an extension into the dynamic regime of the "Tearing instability" concept by Paris (1977); a work on this line is now in progress.

- Unstable behaviour -Three different F.M. parameters were determined from the specimen (Fig. 10) which showed unstable behaviour:

i) $K_{jd}$ at maximum load - $K_{jd}$ (125 MPa $\sqrt{m}$) was found to be the same as obtained from EPRI procedures.

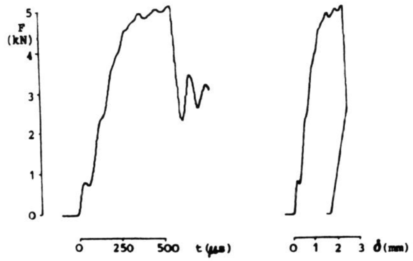


Fig. 10. Unstable crack growth at -25 °C: F-t and F-δ records.


Fig. 11. Unstable clivage at -25 °C(v=0.86 m/s).


Fig. 12. Stable tearing at -25 °C(v=0.83 m/s).



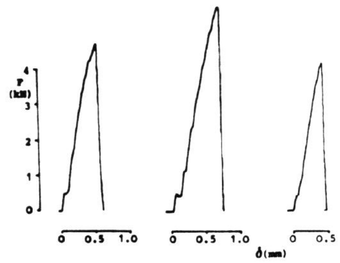


Fig. 13. F-δ records from VLB tests at -40 °C.

ii) $K_D$ during fast crack propagation - $K_D$, determined according to Angelino(1977), was found to be $K_D$ = 78 MPa $\sqrt{m}$ at a crack velocity v = 50 m/s. This value is compared in Fig. 15 with Hahn and co-workers (1976) results on A533B-Cl 1 steel; the agreement is really quite good.

iii) Stress intensity factor at arrest $K_A$; it represents the lowest toughness value at test temperature and fits well at the left of the transition curve of Fig. 14.

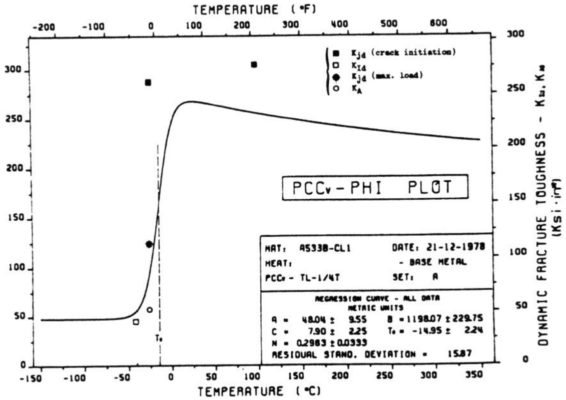


Fig. 14. Comparison between $K_d$ obtained on A533B-Cl 1 from VLB tests and standard EPRI procedures.

Lower shelf - At this temperature, the VLB test technique seems to offer no particular advantage with respect to EPRI procedures; $K_{ID}$ values here determined are however in good agreement with the reference curve of Fig. 14.

## CONCLUSIONS

The determination of $J_{Id}$ at crack initiation is of great practical relevance and VLB test can be used to qualify, on a specific material, the confident adoption of EPRI procedures at upper shelf, which were found to be slightly conservative on this material. Several FM parameters ($K_{jd}$, $K_D$, v, $K_A$) were shown to be deducible from a single VLB test at transition temperatures; the most relevant finding consists how-

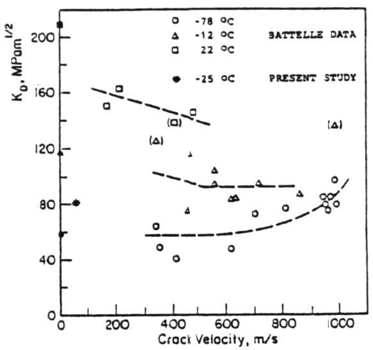


Fig. 15. A533B-Cl 1 $K_D$ data at different velocities and temperatures.

ever in the double face behaviour of the material in this region, where brittle or ductile fracture mechanism is selected by the material as a consequence of small changes in loading characteristics, which are typical of VLB test only.

## ACKNOWLEDGEMENTS

The authors express their gratitude to ENEL-DSR (Ente Nazionale per l'Energia Elettrica - Direzione Studi e Ricerche) which supported this work under the contract ISMAT 900. Thanks are also due to Mr. B. Riva for transducer construction and application and to Mr. S. Mammana for the development of electronic hardware. Special acknowledgements are finally due to Mr. A. Aguzzi for the patient and skilful performance of all the tests.

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