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Ultrasonic Evaluation of Defects in High Strength Steel Pressure Vessels using AMS Notches

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Abstract **-High strength steel viz. Maraging steel is used as the raw material for deriving pressure vessels like large size solid rocket motor casings. Such vessels are designed with very low factor of safety in order to keep a minimum dead weight. Generally a fracture based design is carried out to arrive at the thickness of the casing. The important considerations for such design include the initial size of the flaw, critical flaw size and sub-critical flaw growth characteristics. Ultrasonic Testing plays a significant role in detecting and evaluating all critical flaws. In case of sub-critical flaws, it is required not only to characterize the flaw but also size it for taking right decisions. Currently such defects/flaws are sized using standard AMS reference notches viz. E- Notch, F- Notch and G- Notch. Many times the design estimates for area of a critical flaw is in the order of several mm^2. Whereas the said AMS Notches are of very meagre area An attempt is made to correlate AMS Notches with tight cracks. A tight crack equivalence correlation has been developed w.r.t tight cracks and AMS notches. A Typical case study involving various Fracture based design conditions and application of proper evaluation criteria is discussed.**

Keywords — ***Ultrasonic Evaluation, Tight Crack Equivalence, Acceptance Criteria***

I. INTRODUCTION

The structural integrity of materials, components and structures has to be assessed for quality control, safety regulations and product specifications. Numerous testing techniques have been developed for maintenance and condition monitoring. These techniques can be categorized into two main classes: destructive testing based on fracture mechanics, and non-destructive testing which leaves the inspected component undamaged. Non-destructive testing (NDT) is particularly relevant to the inspection of large and expensive components. The aerospace, nuclear and offshore industries are only a few examples of industries which employ a wide range of NDT techniques. Aerospace Products call in for Stringent Quality screening both in raw material and finished product stage. During raw material production, especially in Rolling, Forging and Extrusion processes, there is a high probability of occurrence of discontinuities like laminations [1]. During manufacturing/production of aerospace structures, there may be occurrences of multiple defects. To establish and quantify the presence of defects NDT is required. The primary propulsive system of any launch vehicle/missile is the rocket motor which comprises of metallic casing made of high strength steels like maraging steel which are fracture prone. Such structures are derived using welding process. The probability of tight crack occurrence in weldments is common. Ultrasonic testing is the only suitable NDT method sensitive for detection of planar defects like cracks. The acceptance criteria w.r.t Ultrasonic Testing is derived from various standards [2]. Such an acceptance criteria has to be validated against the critical flaw size to cause failure which is an output of fracture based design. Many times it is seen that the linear dimensions of critical defects arrived from fracture mechanics approach exceed the specification of the standards (AMS E,F & G Notches). In the current study EDM notches of various standard configurations are examined using angle beam ultrasonic testing and compared with maraging steel specimens fabricated with known planar defects. Thereby tight crack equivalences for the AMS Notches is estimated. The critical defect sizing pertaining to a typical configuration of pressure vessels is discussed.

II. FRACTURE CONTROL

Pressure vessels often contain small flaws or defects that are inherent in the materials or introduced during the fabrication process. These defects can, in many cases, causes severe reduction in the load-carrying capability and the operational life of pressure vessels. If the flaws are large in comparison to those causing failure at the proof-pressure stress levels, failure of the vessels will occur during initial pressurization. If the initial flaws are small, vessels may withstand the operational pressure but that also before the flaw may grow into a size that will lead into failure. The very purpose of this paper is to formulate an acceptance criteria based on fracture principles and that has to be used for Ultrasonic Non-Destructive Testing. To prevent failures, the actual initial flaw sizes shall be less than the critical flaw sizes. The flaw size required to cause fracture at a given applied stress level is called the critical size (In case of aerospace pressure vessels like rocket motor casings, the same is called as the Mean Effective Operating pressure - MEOP). In an elastic stress field , the critical flaw sizes depend on applied stress levels(σ), the material fracture toughness (KIc), pressure vessel wall thickness and flaw size (a), flaw geometry and orientation. The critical flaw sizes for surface discontinuties in an uniformly stressed pressure vessel is expressed as :

$$\left(\frac{a}{Q}\right)_{cr} = \frac{1}{1.21\pi}\left(\frac{K_{IC}}{\sigma}\right)^2 \tag{1}$$

To predict critical flaw sizes of thin-walled pressure vessels, it is necessary to know the stress intensity for flaws that become very deep with respect to the wall thickness. The stress-intensity solution shown in equation 1 for the semi-elliptical surface flaw was derived by Irwin [3] and is found reasonably accurate for elliptical defects and upto 50% of the material thickness. At greater depths, the applied stress intensity is magnified by the effect of the free surface near the flaw tip. This means that in thin-walled vessels, the flaw-tip stress intensity can attain critical value at a flaw size significantly smaller than that which would be predicted using equation.

Figure 1 shows the relationship between the flaw-shape parameter Q and the flaw depth-to-length ratio.

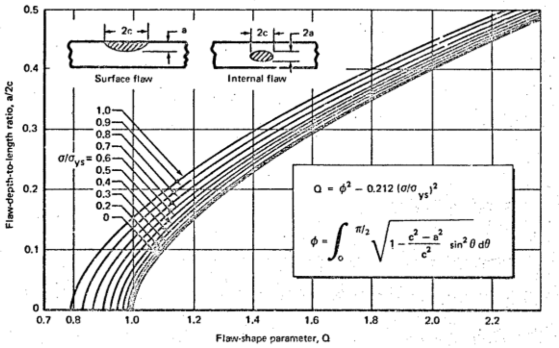

Fig 1. Flaw Shape Parameter Curves

III. ULTRASONIC NDE

Ultrasonic Testing (UT) uses high frequency sound waves (typically in the range between 0.5 and 10 MHz) to conduct examinations and make measurements. It has wide use in engineering applications such as flaw detection/evaluation, dimensional measurements and material characterization. In general, ultrasonic testing is based on the capture and quantification of either the reflected waves (pulse-echo) or the transmitted waves (through-transmission).

A pulse-echo angle-beam UT inspection technique is employed to evaluate steel pressure vessels. Driven by a pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. Knowing the velocity of the waves, travel time can be directly related to the distance that the signal traveled. From the signal, information about the reflector location, size, orientation and other features can be gained. A typical angle beam inspection scheme is represented in Figure 2.

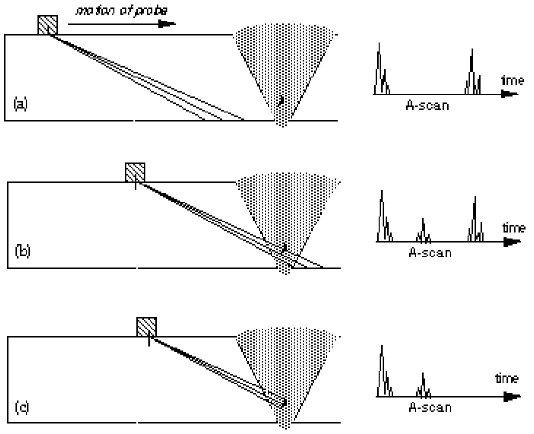

Fig 2. Angle-beam pulse echo examination

a. Only the surface and back-wall echoes are present in A-Scan
b. The defect signal also becomes apparent, registering between the two component echoes
c. The defect signal becoming predominant thereby creating a complete back-wall echo loss.

A. AMS Acceptance Standards:

For weldment inspections using angle-beam technique AMS 2632 is predominantly used. The Acceptance level is selected from E,F,G and H notches. The Notch acceptance criterion is chosen to correspond to critical crack size arrived by fracture design.Selected notch is prepared on a welded coupon plate of the thickness equivalent to that of the pressure vessel to be inspected. Notches are created in both longitudinal and transverse direction . Scanning of this reference notch is carried out with the angle probes to establish the Distance Amplitude Curve (DAC) for various angles ($45^{0,}$ 60^0 and 70^0).

Table 1. dimensions of different AMS notches.

AMS Notch	Length in mm	Depth in mm	Width in mm	Area in mm^2
E	1.02	0.51	0.25 max	0.52
F	1.27	0.76	0.25 max	0.97
G	2.54	1.27	0.25 max	3.23
H	4.06	2.03	0.25 max	8.24

For the purpose of Ultrasonic Inspection, Notches shall be made on parent metal and welded plates in the manner shown in Fig. 3. Notches are made in both Weld region and Heat Affected Zone (HAZ) region and in transverse and longitudinal direction as shown.

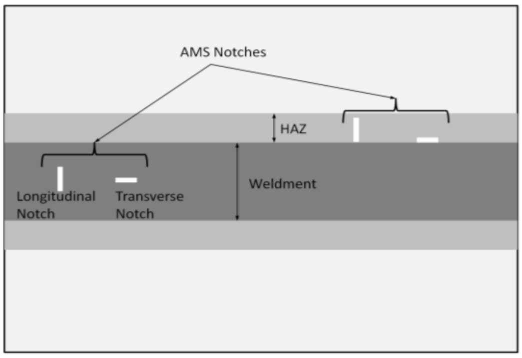

Fig.3 Typical Ultrasonic Welded Reference Plate

B. Generation of DAC Curve :

Acoustic signals from the same reflecting surface will have different amplitudes at different distances from the transducer. Distance amplitude correction (DAC) provides a means of establishing a graphic ‘reference level sensitivity’ as a function of sweep distance on the A-scan display. The use of DAC allows signals reflected from similar discontinuities to be evaluated where signal attenuation as a function of depth has been correlated [4]. A distance amplitude correction curve is constructed from the peak amplitude responses from reflectors of equal area at different distances in the same material. A-scan echoes are displayed at their compensated height and the peak amplitude of each signal is marked on the flaw detector screen or, preferably, on a transparent plastic sheet attached to the screen.

A defect in the weldment may occur at any depth across the thickness i.e. from the surface to interior. Anyhow surface defects are eliminated by visual and Dye penetrant inspections. But to gage the depth of the defect that is occuring and to properly size it DAC with different probe stand-off distance is to be generated. The Distance-Amplitude Curve (DAC) shall be plotted in ½, 1, 1½ and 2 skip distances (stand of distances shown in Fig. 4). The gain shall be fixed in such a way that the amplitude of highest echo (½ skip echo) shall touch 80% of the FSH. The DAC shall be drawn between 20% to 80% of the FSH. Individual DAC curves are drawn for Transverse and Longitudinal Notches and in weld and HAZ region (totalling 4 DACs)

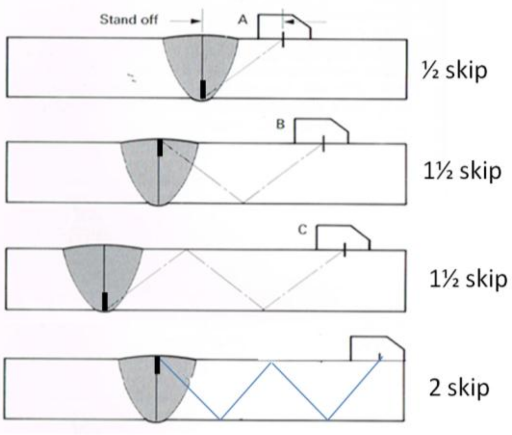

Fig. 4. Probe Stand-off distance

Typical DAC for the same type of notch drawn with various angle probes is shown in figure 5.

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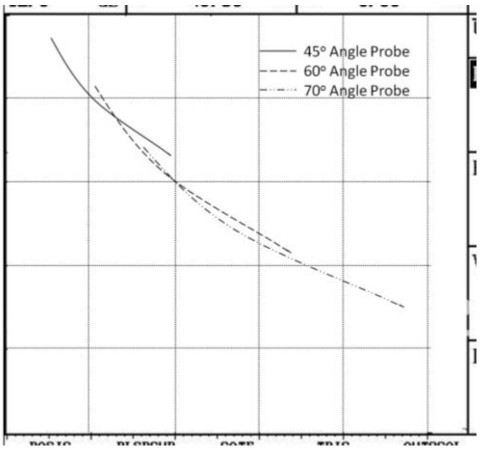
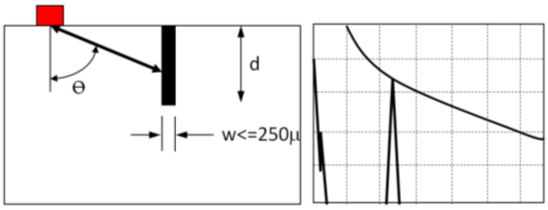


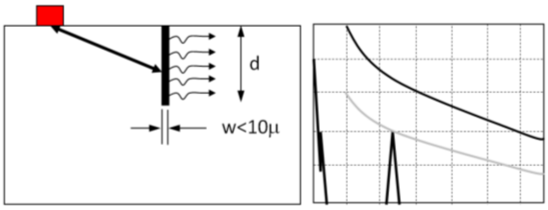
Fig 5. Typical DAC Curve for various probe angles

C. Tight Crack Equivalance:

The cited AMS notches have a definitive width of atleast 0.25mm (250 micros). Whereas Tight cracks of width more than 1 micron can also be detected by ultrasonic test. However tight cracks can cause partial transmission of energy. Hence in the A scan, the relative echo height of the tight crack of same depth of that of a notch is lesser.(Figure 6). To compensate the loss of echo, the gain of the instrument has to be increased. This increment in gain gives us a rough estimate of the magnification/equivalence factor of the particular notch.



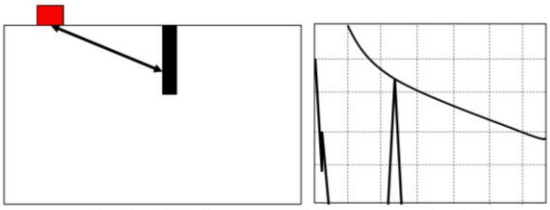
Reference Notch Ultrasonic reflection Pattern



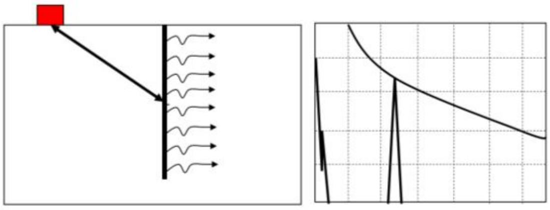
Reflection Pattern in tight crack condition

Fig.6 Reflection Pattern in tight crack condition

In a DAC, same Amplitude conditions may correspond to higher crack depth in tight crack condition (See Fig.7). Hence the area of the elliptical tight crack will be higher than that of the the AMS Notch. Therefore, there is a technical requirement to fix a scale factor for tight cracks w.r.t. standard AMS notches so as to match with the Fracture based design requirements.



Amplitude with Reference Notch (0.25mm Notch width)



Amplitude with Equivalent Tight Crack (width < 10µ)

Fig.7. Typical AMS Notch Tight crack condition

IV. EXPERIMENTAL EVALUATION

An experimental work is attempted to ascertain the said scale factor between the AMS notches and tight cracks. For this purpose, standard AMS notch specimens and tests specimens with simulated planar defects are used. Ultrasonic testing of the AMS Notches and the corresponding amplitude gain on the defective specimen is correlated. The specimen with defect is subjected to tensile loading and the failure load is estimated. Based on the failure load, an approximate defect size is arrived at by using fracture mechanics approach.

by conducting tensile tests on notched tensile specimens and ultrasonic testing of welded samples with simulated defects is attempted to establish the said correlation between AMS Notches and tight cracks.

A. Ultrasonic Examination

Maraging steel welded Test plate 300 x 300 x 3.6mm with the above said notches is prepared. Based on series of trials, the probe & parameters are optimized. 70° ,4 MHz & 80°, 4 MHz probes are used to draw DAC (Fig. 9) with reference to standard reference to F Notch.

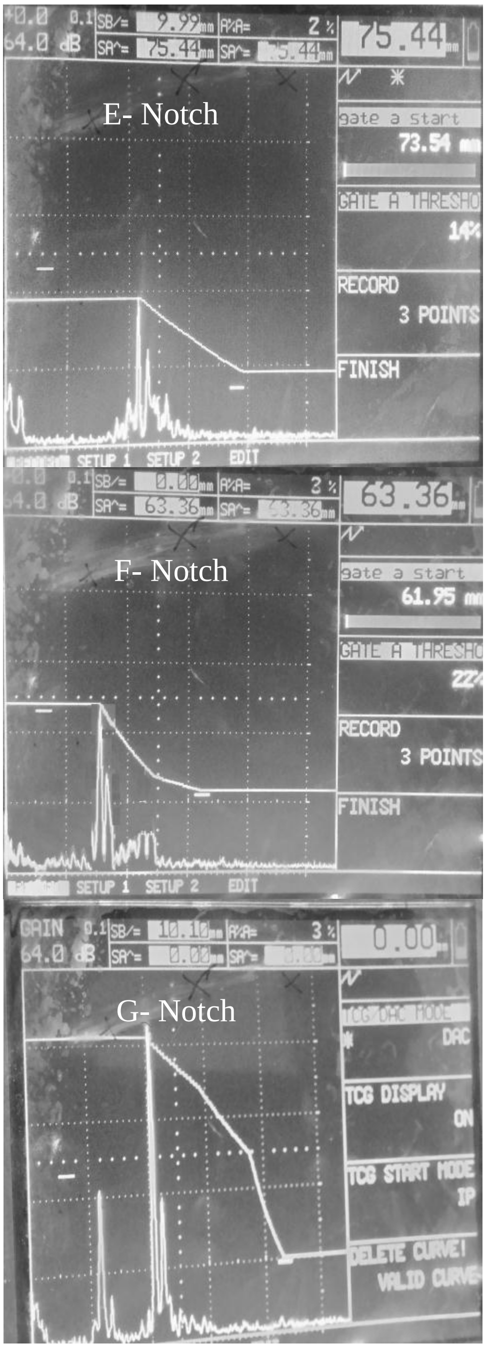


Fig. 8: DAC curve for E, F, G notches on maraging steel plate for reference 64 dB

Distance Amplitude Correction Curve is drawn at 64 dB of Amplitude. Ultrasonic A-Scan was performed on the sample plate with E, F & G notches with the same gain. The G Notch has almost raised upto 100% of the screen at the 1st skip. On the other hand, at the same gain, F notch raised to 45% and E-Notch to 25%. This is illustrated in Fig.6. This portrays an approximate relation between G,F and E notches i.e G= 2.5 x F, F=2 x E [5]. These correlations enable us to easily select between various notches for ease of reference. The adjustment gain to match between various notches is given in table 2 below.

Table 2: Inter Notches Adjustment Gains

	E-Notch (Ref. 75dB)	F-Notch (Ref. 64dB)	G-Notch (Ref. 49dB)
E-Notch	--	58.3dB	63.9 dB
F-Notch	68.6dB	--	58.5 dB
G-Notch	60.3dB	73.2dB	--

In general the gain is represented by the following expression :

$$dB = 20.0 \ \log \left(\frac{A_2}{A_1} \right) \qquad (2)$$

where A1 and A2 are two different amplitudes and dB is the gain in going from amplitude A1 to A2.

It can be seen from the above table that dB difference between G-Notch to E-Notch is approximately 14.8 dB. This approximately corresponds to 5.5 times. Similarly the difference between F-Notch to E-Notch is 5.8dB and this is approximately 1.9 times. Hence it can be deduced that G=5.5 E and F=1.9E.

B. Testing of specimens with defects :

Ultrasonic inspection and tensile tests have been carried out on the specimens with defects. The tensile test setup and specimens used are shown in Fig.7 (a) & (b). The equivalent tight crack that is required to cause failure is calculated using LEFM approach and tabulated in Table 3 [6]. The actual failure loads and the relative ultrasonic gain w.r.t to refernce F-Notch is also shown.

(a) (b)

Fig.9: (a) 300KN Universal Testing Machine
(b) Tensile Specimens with

Table 3: Experimental data showing calculated tight crack area and relative gains.

Specimen Specification	Failure Load (in KN)	Equivalent Crack area (in mm^2)	Amplitude Gain (Ref.: F Notch at 64 dB)	Sizing w.r.t F Notch
Specimen 1	80.1	3.2	70.3 dB	2.05 less
Specimen 2	70.2	6.1	64.9 dB	1.1 less
Specimen 3	67.9	19.5	54.1 dB	3.1 more

It can be seen that a Specimen1 which failed at 80.1 KN is calculated to have a defect of approximately 3.2mm^2 area. In comparison to F Notch, it took and adjustment of 6.3 dB to equate the amplitude. This implies that specimen1 had a defect that was 2.05 times lesser that that of an AMS 'F' Notch. Similarly Specimen 3 had a defect that was 3.1 times that of F Notch and specimen2 has a defect quite equivalent to F Notch. Based on the above correlation tight crack equivalences of AMS Notches may be tabulated as follows (Table 4).

Table 4: AMS Notch and Tight Crack Equivalences

AMS Notch	Length x Depth (width = 0.25mm)	Tight Crack Equivalance (infinitesimal width)	AMS Notch Area in mm^2	Tight Crack Equivalance Area in mm^2
E	1.02 x 0.51	2.35 x 1.17	0.52	2.75
F	1.27 x 0.76	3.12 x 1.82	0.97	5.68
G	2.54 x 1.27	5.84 x 2.92	3.23	17.05

On the other hand, the acoustic equivalence portrayed by ultrasonic inspection also clearly indicates that F-Notch effect is approximately half that of G-Notch and E-Notch is half of F-Notch. The same has also been confirmed by area estimation also.

IV. CASE STUDY

A Typical Aerospace pressure vessel of diameter 1000mm and thickness 3..0mm required to operate at an MEOP of 70ksc (6.86 MPa) and made up of high strength steel (Maraging steel) is taken as a case. The typical mechanical properties of the material is provided in Table 5.

Table 5: Mechanical Properties of Maraging Steel

Tensile Strength σ_{UTS}	1780 MPa
Yield Strength σ_Y	1520 MPa
Plane Stress Fracture Toughness K_C	120 MPa $(m)^{1/2}$
Plane Strain Fracture Toughness for parent material K_{ICP}	90 MPa $(m)^{1/2}$
Plane Strain Fracture Toughness for weld material K_{ICW}	75 MPa $(m)^{1/2}$

The acceptance of such pressure vessels are by subjecting it to pressure 1.1 times proof pressure. In the longitudinal welds, a maximum weld mismatch (e) of 5% is allowable. These are also taken into consideration for calculation of stress. The maximum stress condition is observed during Proof pressure test.
The maximum operating stress (Hoop) is taken as

$$\sigma = \frac{PD}{2t}(1+3e) \qquad (3)$$

$$\sigma = \frac{7.55*1000}{2*3.0}(1+3*0.05) = 1447 MPa$$

Fracture Based Acceptance Criteria:

For a thickness of t=3.0mm of Maraging steel, fracture is likely happen before leak. Hence the rocket motor casing under the case study is prone to fracture failure.

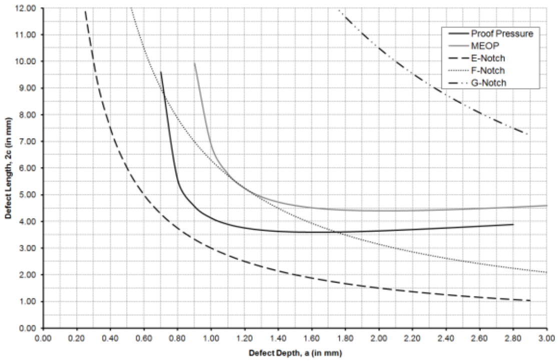


Fig 10. Crack depth Vs Crack Aspect Ratio

The critical flaw size for the surface flaws is computed and plotted in the above figure. Since the motor casing design is fracture critical, the flaw shall be controlled well outside the surface defects failure boundary for Proof pressure shown in the Figure 8. It can be seen from figure that a crack of size approximately 3mm x 1mm as acceptance criteria is safe at Proof Pressure. The equivalent AMS Notch condition for a tight crack area of 3 mm^2 is E-Notch. As per the standard procedure of Ultrasonic testing of welds (AMS 2632) the E-notch is the most stringent acceptance criteria which can be detected. It can also be observed that a defect of size 1.5 x 4.5mm (6.5mm^2 area)is marginally safe at MEOP condition. This is equivalent to an AMS F-Notch. Anyhow, considering sub-critical defects shall only be allowed and the pressure vessel has to be tested at 1.1 times MEOP (Proof pressure) as acceptance test, the size is downgraded to E-Notch which is much safer at MEOP.

V. CONCLUSION

In the current work, a typical relation between various AMS Notches has been derived i.e G=3F and F=2E (approximate expressions). The tight crack equivalence of AMS Notches are also established using experimental studies. It has been found that an AMS 'F' notch is having an equivalent tight crack area of 5.68mm^2 and corresponds to a defect of approximately 3.12mm x 1.82 mm (or 4mm x 1.4mm). Such a correlation is helpful in selecting proper acceptance criteria to satisfy the fracture based design requirements.

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