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DEVELOPMENT OF CALIBRATION EQUATION FOR ULTRASONIC RESPONSE OF SMALL 3-D CRACKS IN STEEL STRUCTURES

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ABSTRACT
Reliable nondestructive evaluation of cracks is of utmost importance for assessing the structural integrity as well as predicting the serviceability of the parts based on fracture mechanics. However, in order to apply fracture mechanics, sensitive evaluation of the crack is a pre-requisite. Recently, the ultrasonic small-incidence method of testing has been developed for the sensitive evaluation of smaller tight cracks in structural components. The present paper describes the development of very accurate empirical calibration equations for predicting the ultrasonic small-incidence responses of smaller cracks in the depth range of 0.5~7.0mm. The calibration equation has been derived as a function of probe position, crack size and wall thickness, which can be applied for both the cases of 2-D and 3-D cracks. The reliability as well as accuracy of the calibration equations has been verified through the comparison of the calculated responses with those measured for the cracks having different crack depth, length and specimen thickness.

Keywords: Calibration equation, Ultrasonic small-incidence method, 2-D crack, 3-D semi-elliptical crack, Stainless steel.

1. INTRODUCTION
A crack is the most dangerous defect in structural components. After a crack has been detected on the surface of a structural component, evaluation of its depth is an important practical issue for fracture analysis and repair considerations.

Metal fatigue or failure usually begins at the surfaces of structural components. The surface cracks are usually of two types – one is the straight 2-D cracks and the other the 3-D semi-elliptical cracks. In actual structures, the three-dimensional semi-elliptical cracks are more commonly encountered than the two-dimensional ones. Figure 1 illustrates the geometry of the specimens containing a straight 2-D and a 3-D semi-elliptical crack at the back-wall of stainless steel plates. The crack depth and length are represented by the symbols, *a* and *b*, respectively.

There are many conventional non-destructive testing for cracks as dye penetrate, magnetic particle, radiographic and eddy current testing. But most of these methods are found to be inadequate for detecting the smaller closed fatigue cracks. When small cracks are treated, most of the time they are left undetected due to their small size as well as high closing stresses. It is essential to detect the cracks with high sensitivity and to evaluate them quantitatively. The potential of using ultrasonic techniques in this regard has been recognized and also verified by fundamental experiments. [1-12].

Quantitative evaluation of tight cracks, especially the small ones, has thus become a key subject in the field of NDE of cracks. For sizing closed cracks, an evaluation method was reported using ultrasonic shear wave [13], based on the principle of change in ultrasonic wave

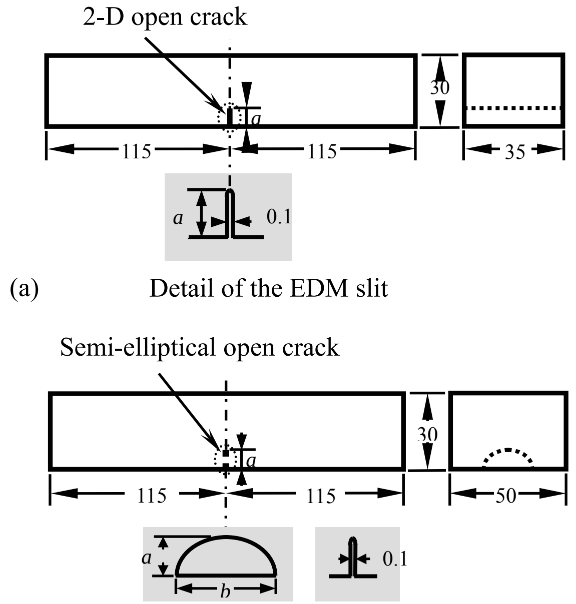

Fig 1. Geometry of specimen containing (a) a straight 2-D crack (b) a 3-D semi-elliptical crack

velocity as a result of plastic deformation occurring around the crack. Again a procedure for treating a vertically oriented closed crack using the normally incident longitudinal wave was proposed [14] in which the reflection and transmission of the wave at the closed crack surface has been analyzed theoretically based on dynamic elasticity. Later, introducing an automatic scanning scheme, a simplified nondestructive evaluation method [15] has been reported for the closed cracks using the same approach in which an empirical calibration equation derived for the open cracks has been considered as the basis for sizing the cracks.

For evaluating a crack quantitatively, sensitive detection of the crack is a perquisite. In an attempt to enhance the sensitivity of the ultrasonic evaluation technique, recently a novel angle beam evaluation approach, namely, the ultrasonic small-incidence method of testing has been developed [16-17]. This method has the ability to deal with smaller tight cracks with sensitivity. By analyzing the measured response of an unknown crack, the method can determine the associated crack depth as well as the extent of crack closure by solving an inverse problem. In order to solve the inverse problem, the solution of the forward problem is prerequisite. The solution of the forward problem is basically the derivation of a calibration equation by which the response of a crack can be calculated as a function of crack size and the associated wall thickness.

In this paper, based on the experimental observation, a very accurate calibration equation has been developed for predicting the ultrasonic small-incidence response of small 3-D cracks in steel structural components. The calibration equation can predict the response curve of a given crack as a function of the probe position, provided the crack depth and the associated wall-thickness are known. The accuracy as well as reliability of the calibration equation has been verified by comparing the calculated results with those obtained by direct measurement. It has been verified that the same calibration equation can readily be applied for the cases of 2-D cracks as well.

2. EXPERIMENTAL DETAILS

In this paper, we confined ourselves to the determination of depths of smaller surface cracks from the inaccessible side of the wall. Open cracks having different crack depths, lengths and closures are considered for the present study. Again, in each category, the straight two dimensional and semi-elliptical surface cracks are investigated. All of the test specimens were prepared as plates and were extracted from the original sample of stainless steel AISI304. The open cracks were modeled by narrow slits (width=0.1 mm) which were machined on the specimens by electric discharge machining and were situated in the L-S orientation of the plate (ASTM code for the crack plane orientation). Five specimens containing the slits with known depths of 0.5, 1, 3, 5 and 7 mm were prepared as plates having the dimension of $35 \times 230 \times 30$ mm.

The experimental setup is shown schematically in Fig 2. In this experiment, the ultrasonic wave is being incident on the specimen surface by the single flat pulse-echo transducer having a center frequency of

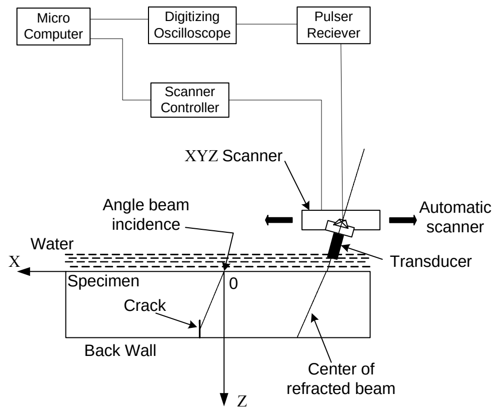

Fig 2. Schematic diagram of the ultrasonic testing configuration.

5MHz and radius of a_t =3.2mm. If any discontinuity is founded the beam reflects and returns back. All the received signals were post amplified and then sent to the digitizing oscilloscope from which the digitized data were downloaded directly to a computer.

3. NORMALIZATION OF THE MEASURED ECHO AMPLITUDE

The amplitude of the first back wall echo of the associated longitudinal wave $\left|\overline{\sigma}_0\right|^{ex}$ was discretely measured for the specimens against positions of the transducer under the influence of beam incidences and the corresponding difference in amplitude with that of a crack free condition is expressed in a normalized form by the quantity $\Delta\sigma^{ex}$ as follows:

$$\Delta\sigma^{ex} = \frac{\left|\overline{\sigma}\right|^{ex} - \left|\overline{\sigma}_0\right|^{ex}}{\left|\overline{\sigma}_0\right|_n^{ex}} \tag{1}$$

Where,

$\left|\overline{\sigma}\right|^{ex}$ = Amplitude of back-wall echo measured at any position across the crack.

$\left|\overline{\sigma}_0\right|^{ex}$ = The amplitude of the reference back wall echo obtained for a position where no crack is present.

$\left|\overline{\sigma}_0\right|_n^{ex}$ = The corresponding reference value obtained under the normal incident beam.

4. EFFECT OF CRACK DEPTH AND CRACK LENGTH ON THE MEASURED RESPONSE

In an attempt to examine the influence of crack depth and length on the ultrasonic angle beam response, experiments are performed with known open two dimensional as well as semi-elliptical cracks. It is noteworthy that for the depth testing of a crack having unknown crack enclosure, a consistent dependency of the response on crack depth is of prime importance for the entire range of depth of crack. In the case of 2D crack, the calibration equation has been proposed as a function of transducer position (x/a_t) and crack depth (a/a_t). Fig. 3 illustrates the influence of crack depth on the optimum incident response against the two dimensional open cracks in the size range of 0.5 ~ 7.0 mm. In the case of 3D crack it is a function of transducer position (x/a_t), crack depth (a/a_t) and specimen thickness (t).

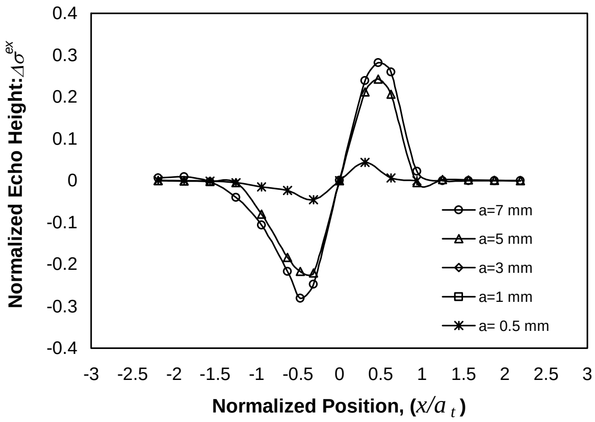

Fig 3. Effect of crack depth on small incidence response against the 2D cracks.

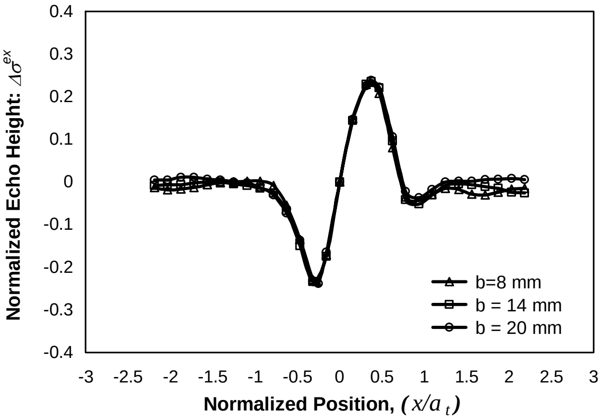

Fig 4. Small-incidence responses against the open semi-elliptical cracks having different lengths(a=3 mm).

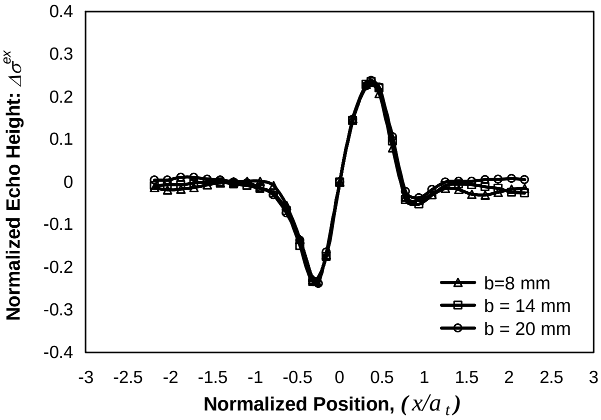

Fig 5. Small-incidence responses against the semi-elliptical and 2D cracks of identical depth (a = 3 mm).

Furthermore, analyzing the experimental results of a number of open semi-elliptical cracks of different lengths along with two dimensional cracks, it is identified that crack length has no significant influence on the optimum incident responses against the semi-elliptical cracks (a = 3 mm) having lengths in the range of 8 ~ 20 mm are presented in Fig. 4 This crack length, independent characteristic of the optimum incidence, is further confirmed when the result of small semi-elliptical crack is compared with that of a straight 2D crack of identical depth (Fig. 5). On the other hand, from the experimental data it is found that normalized echo height, $\Delta\sigma^{ex}$ is proportional to crack depth (a/a_t) and inversely proportional to specimen thickness (t).

5. CALIBRATION EQUATION FOR TWO DIMENSIONAL CRACKS

In this section, the measured ultrasonic responses obtained for the open cracks under the influence of optimum incidence are analyzed in the perspective of crack depth in order to establish empirical calibration equations for them.

Analyzing the result of a number of two dimensional open cracks having different depths, a general form of the equation is supposed to qualitatively imitate the measured response $\Delta\sigma^{ex} \sim x/a_t$, incorporating a number of unknown functions of crack depth in it. On the basis of the observed nature of variations of the functions with respect to crack depth, the functions are determined explicitly by a computer algorithm where the calculated functions are compared with the experimental ones and the corresponding differences are minimized. The empirical calibration equation established for the small incidence response of open cracks as a function of crack depth and transducer position is as follows:

$$\Delta\sigma_s = e^{\left[h_1\left(\frac{x}{a_t}\right) - h_2\left(\frac{x}{a_t}\right)^2 + h_3\left(\frac{x}{a_t}\right)^3 - h_4\right]} \cos\left[\left(\frac{x}{a_t}\right)^3 + 1.569 - h_5\left(\frac{x}{a_t}\right)\right] \times \left[\sin\left(h_6\left(\frac{x}{a_t}\right)\right) + 1\right] \quad (2)$$

where,

$$h_1 = 1.967 e^{\left[-0.1078\left(\frac{a}{a_t}\right)\right]} - 20.4\, e^{\left[-13.13\left(\frac{a}{a_t}\right)\right]}$$

$$h_2 = -0.06894\, e^{\left[1.33\left(\frac{a}{a_t}\right)\right]} + 6.345\, e^{\left[-2.289\left(\frac{a}{a_t}\right)\right]}$$

$$h_3 = 261.9\, e^{\left[-0.8007\left(\frac{a}{a_t}\right)\right]} - 265.0\, e^{\left[-0.8187\left(\frac{a}{a_t}\right)\right]}$$

$$h_4 = 2.604\, e^{\left[-2.22\left(\frac{a}{a_t}\right)\right]} + 0.4719\, e^{\left[0.4409\left(\frac{a}{a_t}\right)\right]}$$

$$h_5 = -0.3543\left(\frac{a}{a_t}\right)^3 + 2.282\left(\frac{a}{a_t}\right)^2 - 3.27\left(\frac{a}{a_t}\right) + 3.323$$

$$h_6 = -1.893\, e^{\left[-0.08061\left(\frac{a}{a_t}\right)\right]} + 19.5\, e^{\left[-12.93\left(\frac{a}{a_t}\right)\right]}$$

and

$$0.15 \le \frac{a}{a_t} \le 2.20$$

$\Delta\sigma_s$ = Calculated normalized echo height
a = Crack depth
a_t = Normalizing constant = 3.2

In order to examine the accuracy as well as reliability of the calibration equation, experimental results are compared with that predicted by equation (2). Figs. 6-8 show the comparison of $\Delta\sigma^{ex} \sim x/a_t$ and $\Delta\sigma_s \sim x/a_t$ relations obtained for some of the cracks with different crack depth and lengths. Calculated relations are found to vary in similar fashion to that of experimental ones taking into account the crack depth appropriately. Good agreement between the experiment and prediction thus establishes the validity of using the calibration equation in the theoretical analysis of closed cracks.

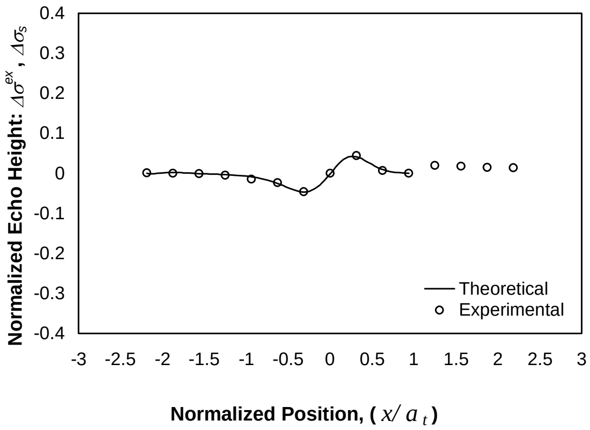

Fig 6. Comparison of experimental and calculated responses for 2D crack (a=0.5 and t=30.0 mm)

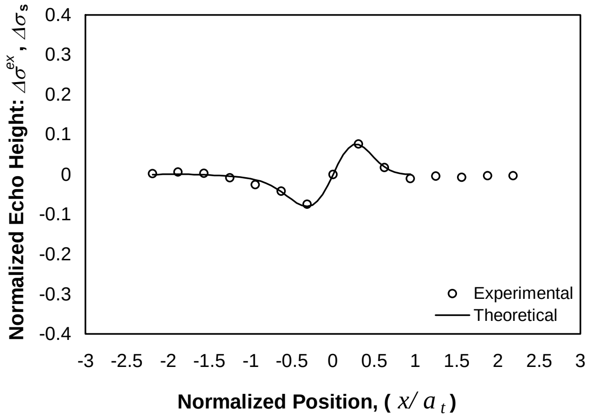

Fig 7. Comparison of experimental and calculated responses for 2D crack (a=1.0 and t=30.0 mm)

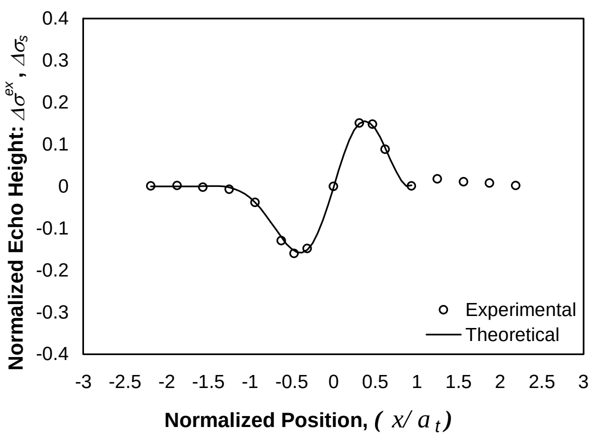

Fig 8. Comparison of experimental and calculated responses for 2D crack (a=3.0 and t=30.0 mm)

6. CALIBRATION EQUATION FOR THREE-DIMENSIONAL CRACKS

In this section, the measured ultrasonic responses obtained for the cracks are analyzed in the perspective of crack depth as well as plate thickness, in order to derive empirical calibration equation for them.

In an attempt to generalize the evaluation algorithm, a suitable form of the calibration has been proposed as a function of transducer position and crack depth in the above section. In this section, the calibration equation is simply extended for the case of varying wall thickness, keeping the range of crack size the same, i.e., 0.5 ~ 7.0 mm. In extending the equation, first, a general form of the equation is supposed to imitate experimental relation, $\Delta\sigma^{ex} \sim x/a_t$, incorporating eight new unknown functions of plate thickness. The values of these unknown functions are found to be varied nearly parabolically or exponentially or in straight line when analyzed in respective of specimen thickness. On the basis of the observed nature, the functions are determined explicitly by a computer algorithm in which the predicted functions are compared with the experimental ones and the corresponding differences are minimized. The empirical calibration equation thus established is as follows:

$$\Delta\sigma_s = e^{\left[h_1 g_1\left(\frac{x}{a_t}\right) - h_2 g_2\left(\frac{x}{a_t}\right)^2 + h_3 g_3\left(\frac{x}{a_t}\right)^3 - h_4 + g_4\right]} \times \cos\left[\left(\frac{x}{a_t}\right)^3 + 1.569 - h_5 g_5\left(\frac{x}{a_t}\right) + g_7\right] \times \left[\sin\left(h_6 g_6\left(\frac{x}{a_t}\right)\right) + 1 + g_8\right] \quad (3)$$

where,

h_1 to h_6 are the same as stated for Eq. (2)

$$g_1 = -0.04051\left(\frac{t}{a_t}\right)^2 + 0.5697\left(\frac{t}{a_t}\right) - 0.7802$$

$$g_2 = -1.911\left(\frac{t}{a_t}\right) + 11.75 \qquad [\text{ if } 7 \le t < 15]$$

$$g_2 = 19.73\, e^{\left[-0.4888\left(\frac{t}{a_t}\right)\right]} + 0.7981 \qquad [\text{ if } 15 \le t \le 30]$$

$$g_3 = -0.8337\left(\frac{t}{a_t}\right) + 8.816 \qquad [\text{ if } 15 \le t \le 30]$$

$$g_4 = -0.07859\left(\frac{t}{a_t}\right)^2 + 0.8598\left(\frac{t}{a_t}\right) - 1.154$$

$$g_5 = -0.002232\left(\frac{t}{a_t}\right)^2 + 0.1347\left(\frac{t}{a_t}\right) - 0.06707$$

$$g_6 = -1.621\left(\frac{t}{a_t}\right) + 8.637 \qquad [\text{ if } 7 \le t < 15]$$

$$g_6 = -0.008107\left(\frac{t}{a_t}\right) + 1.076 \qquad [\text{ if } 15 \le t \le 30]$$

$$g_7 = -0.0006282\left(\frac{t}{a_t}\right)^2 + 0.007264\left(\frac{t}{a_t}\right) - 0.01288$$

$$g_8 = 0.2388\left(\frac{t}{a_t}\right)^2 - 3.355\left(\frac{t}{a_t}\right) + 10.46 \qquad [\text{ if } 7 \le t < 15]$$

$$g_8 = 0.004284\left(\frac{t}{a_t}\right) - 0.04016 \qquad [\text{ if } 15 \le t \le 30]$$

and

$$2.2 \le \frac{t}{a_t} \le 9.4$$

$\Delta\sigma_s$ = Calculated normalized echo height
a = Crack depth
a_t = Normalizing constant = 3.2
t = Specimen thickness

In order to examine the accuracy as well as reliability of the calibration equation, experimental results are compared with that predicted by equation (3). Figs. 9, 10, 11 and 12 show the comparison of $\Delta\sigma^{ex} \sim x/a_t$ and $\Delta\sigma_s \sim x/a_t$ relations obtained for some of the cracks with different crack depth and lengths. Calculated relations are found to vary in similar fashion to that of experimental ones taking into account both the crack depth and specimen thickness appropriately. Good agreement between the experiment and prediction thus establishes the validity of using the calibration equation in the theoretical analysis of closed cracks.

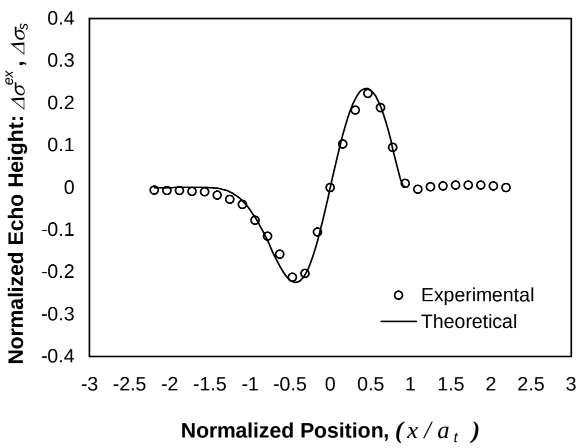

Fig 9. Comparison of experimental and calculated responses for 3D crack (a=4.7, t=30.0 and b=15.0 mm)

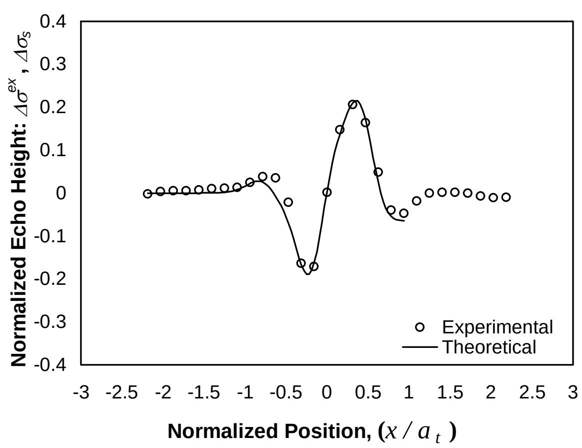

Fig 10. Comparison of experimental and calculated responses for 3D crack (a=3.0, t=7.0 and b=14.0 mm)

The important characteristic of this equation is that it can be used for both 2D and 3D cracks with constant or variable plate thickness. While extending the equation of 2D crack for the 3D crack , the new coefficients which are the function of plate thickness , have been fitted in such a way that the equation of 3D crack should also applicable in the case of 2D crack with variable or constant plate thickness (Figs. 13 & 14).

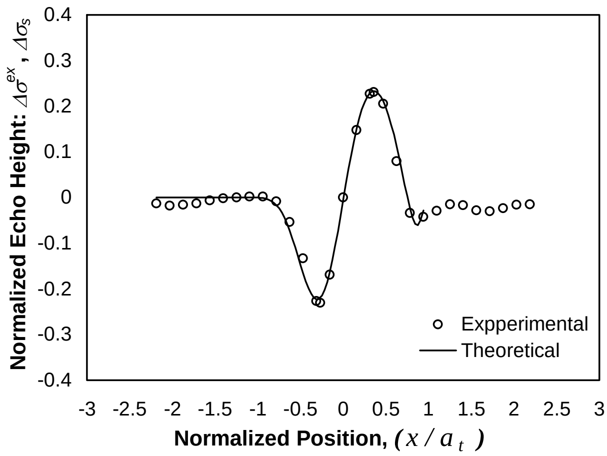

Fig 11. Comparison of experimental and calculated responses for 3D crack (a=3.0, t=15.0 and b=8.0 mm)

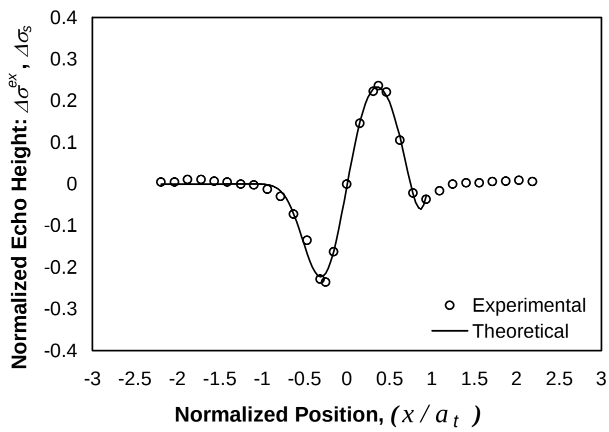

Fig 12. Comparison of experimental and calculated responses for 3D crack (a=3.0, t=15.0 and b=20.0 mm)

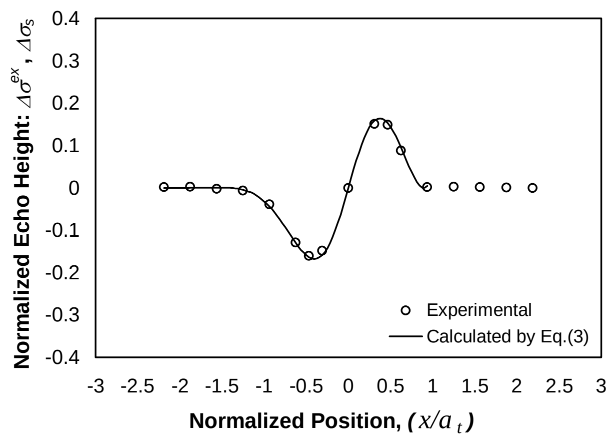

Fig 13. Comparison of experimental and calculated (by using 3D crack equation) response for 2D crack (a=3.0 and t=30.0 mm)

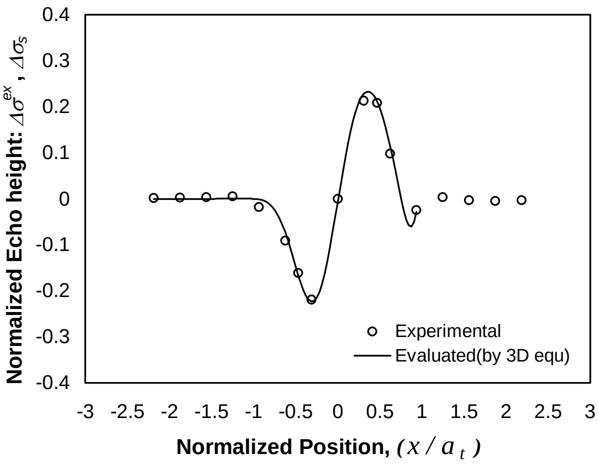

Fig 14. Comparison of experimental and calculated (by using 3D crack equation) response for 2D crack (a =3.0 and t=15.0 mm)

7. CONCLUSIONS

In this paper, a very accurate calibration equation has been developed for predicting the ultrasonic small-incidence response of small 3-D cracks in steel structural components. This equation is developed as a function of crack depth and specimen thickness. The same calibration equation can readily be applied for the cases of 2-D cracks as well. Moreover, this calibration equation can be used to solve the inverse problem to determine the crack depth together with the extent of crack enclosure from the measured response of an unknown crack.

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