

DEFINING EXPERIMENTALLY THE PROBABILITY OF DETECTION OF HIDDEN SECOND-LAYER CRACKS

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ABSTRACT

Aircraft structures designed and certified to the damage-tolerance requirements must be inspected periodically for cracks. These inspections usually result in significant aircraft downtime and may be expensive to implement. In order to reduce the cost of inspections, without compromising aircraft safety, the use of low-frequency eddy-current (LFEC) non-destructive inspection (NDI) techniques is being investigated. The use of this technique has the potential of significantly increasing inspection intervals for some structural details. Unfortunately there is a lack of a sufficient statistical database of crack detection capability for the LFEC NDI. That database is needed in order to implement, with a reasonable reliability, this NDI method for damage tolerance certification. Based on experimental data, this study estimates the LFEC NDI statistical parameters of crack detection probabilities.

INTRODUCTION

Often, in a highly loaded joint, the hidden second layer must be inspected for cracks. One possibility is to use an X-Ray NDI method, which is imprecise and expensive. Another possibility is to detect the crack only after it emerges from beneath the hidden layer. In both cases, safety considerations will dictate very short inspection intervals. A third possibility is to use the low-frequency eddy-current (LFEC) non-destructive inspection (NDI) technique. This inspection method has the capability to detect cracks in the hidden second layer of joint. As a result, it allows us to track the crack while it is still hidden, as opposed to detecting a crack only when it becomes visible. The use of this technique has the potential of significantly increasing inspection intervals. Unfortunately there is a lack of sufficient statistical data, in the open literature, to determine parameters for the detection capability of LFEC method. The decisions for setting the crack inspection periodic intervals resulting from damage tolerance analysis, relates strongly on the crack detection inspection method and its statistical probability of detection. Crack detection by means of eddy-current non-destructive inspections for an uncovered layer (first layer) is widely used, thoroughly investigated and well established in the aircraft industry. This method uses a technique of high-frequency eddy-current (HFEC). That technique has an extensive statistical database, and a reasonably accurate, well-correlated statistical model of crack detection probability. On the basis of that model, and the results of tests conducted in the framework of this study, we are able to set statistical parameters, in order to establish probabilities of detection correlations for the LFEC NDI. This will allow us to implement the LFEC NDI benefits to the damage-tolerance considerations for inspection intervals.

EDDY CURRENT N.D.I. METHOD

The eddy-current inspection method uses a 200 Hz to 6 MHz signal, applied to a coil, which induces an eddy-current in the part. Measurement of the induced current indicates defects or discontinuities [1].

High-frequency eddy-current (HFEC) NDI, which uses 50 KHz to 6 MHz signal, is a crack detection method practiced for an uncovered layer (first layer). HFEC NDI is widely used, thoroughly investigated and well established in the aircraft industry. That technique has an extensive statistical database, and a reasonably accurate, well-correlated, statistical model of crack detection probability.

On the other hand the low-frequency eddy-current (LFEC) NDI, which uses 200 Hz to 50 KHz signal, is a crack detection method capable of detecting cracks at a hidden second layer. This ability can, for some structural details, significantly contribute to enlarge the interval period between in-service inspections. The use of this method tends to decrease the inspection cost and increase operational availability of the aircraft.

Figure 1 presents a typical structural example that shows the need to detect cracks in a second hidden layer. The benefit of using the LFEC NDI method is expressed as a reasonable and standard inspection interval determination of 5,000 flights. This can be compared to other inspection methods, such as, X-Ray, which is imprecise and expensive, or to detect the crack only after it emerges from beneath the hidden layer. In both cases the inspection intervals would have been significantly shorter.

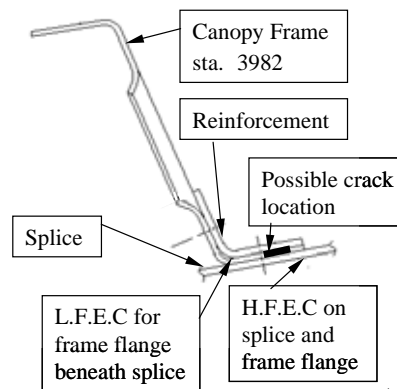


Figure 1: Typical structural detail requiring cracks detection in a hidden layer

LFEC NDI technique does not have an extensive statistical database to determine valid parameters for the detection capability. In this study we are examining the LFEC NDI method, gathering crack detection results as a function of cover plate thickness and crack length parameters. On the basis of the HFEC NDI statistical model for crack detection probability, we are establishing the parameters for a reasonably correlated statistical model that will predict the LFEC NDI crack detection capability.

THE TEST PROGRAM

A test program was conducted in order to examine the LFEC capability for detection of different cracks sizes at a base-plate (second layer) installed beneath different thickness of cover plates. The base plate has 100 holes, which 30 of them have a crack that emerges out of the hole. The 30 cracked holes are randomly arranged. The cracks appear at five different lengths, which are of typical crack lengths for in-service inspections (0.10, 0.15, 0.20, 0.25, 0.50 inch) and at different orientations. The cracks were manufactured by the electrical discharge machining (EDM) process, to very precise dimensions, with a constant crack width of 0.0085 inch (manufactured by NDT Engineering Corporation). Six different cover plates, with different thicknesses (0.25, 0.20, 0.16, 0.12, 0.08, 0.04 inch), containing 50% plain holes and 50% countersunk holes, are used. The two thinnest cover plates (0.08 & 0.04 inch) do not contain countersunk holes (in order to avoid “knife edge” contact). See Figures 2 and 3 for the base and cover plate details. The material used for all plates is AL7075-T6, which is a very common material used in aircraft structures.

The inspected base and cover plates are fastened tightly together by means of HI-LOK fasteners that are installed at all holes. The inspections are performed around the holes from the cover plate side, without removing the HI-LOK fasteners. These features are of typical structural aircraft details and of typical in-service inspections. Inspectors perform the LFEC inspections, using their own instruments and methods (probes, oscilloscopes, calibration etc.). For each inspection test, a different cover plate is being installed upon the base plate and all the holes are inspected. In order to maintain an objective test, the holes are numbered and each cover plate is being rotated differently relatively to the base-plate, at the pre-installation stage, so that the inspector will not be aware of the specific crack locations.

The inspection results are reported for each hole whether a crack had been detected or not, and in a case of crack detection, the magnitude of the signal appearing on the oscilloscope is reported. Each inspection test includes data concerning the equipment and method used: type of test probe, test frequency used, test phase, horizontal and vertical test sensitivity and the cover plate thickness. The tests were conducted at Israel Aircraft Industries (IAI) by an NDT specialist, and at Israel Air Force (IAF) by an NDT specialist and by depot inspectors.

Five different probes were used during the tests:

1. Ring s/n G01640 (IAI)
2. Pencil LP-40/5k (IAI)
3. Ring SPO-2030 (IAI)
4. Sliding SPO-1893 (IAI)
5. Ring SPO-996 (IAF)

Table 1, shows the extent of the test performed, and exhibits which probe had been used for which cover plate and the number of tests performed (performing one test means inspecting all 100 holes by a specific probe, from the cover plate side, for a specific cover and the base plates that are fasten together).

		Cover plate thickness [inch]						Total
		0.25	0.20	0.16	0.12	0.08	0.04	
Test probe	Ring SPO 2030	3	2	1	1	3	-	10
	Ring s /n G 01640	-	-	-	-	-	1	1
	Pencil LP	No response	No response	No response	No response	No response	1	1
	Sliding SPO 1893	1	1	1	1	-	-	4
	Ring SPO 996	-	-	-	34	-	-	34
								50

Note : Sliding probe is used on c'sink holes only

Table 1: The number of tests performed for the various probes and cover plates

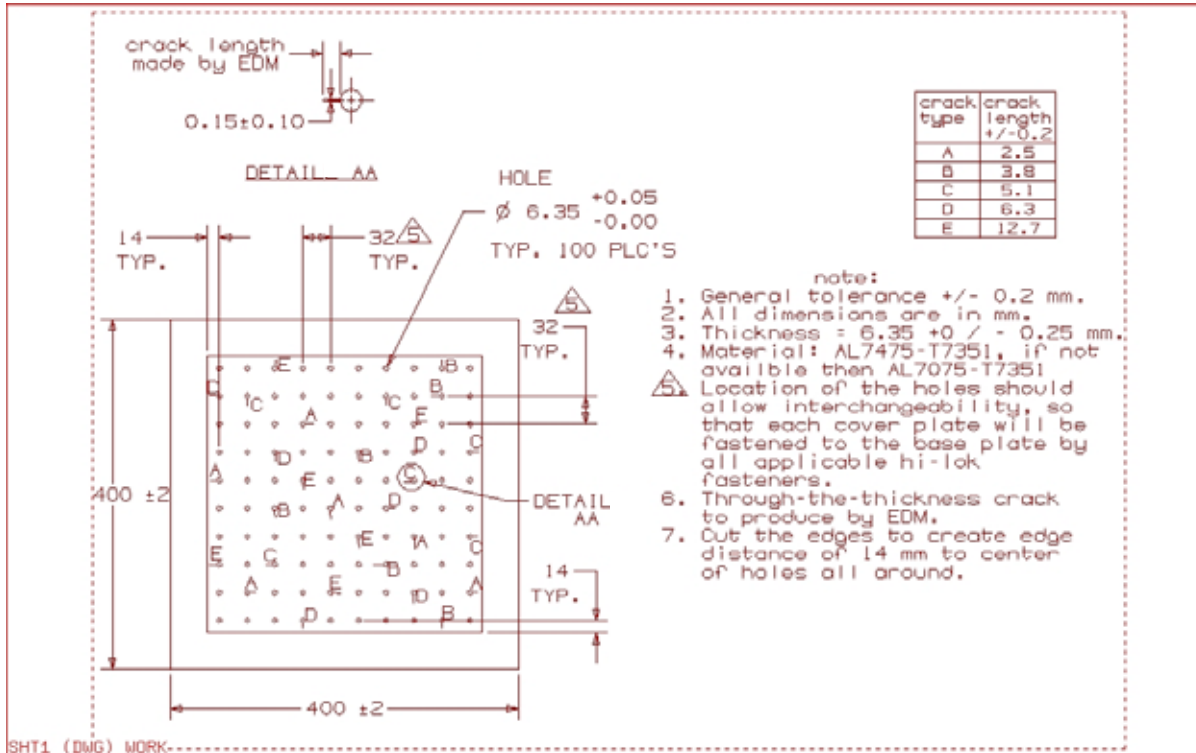


Figure 2: Base plate details

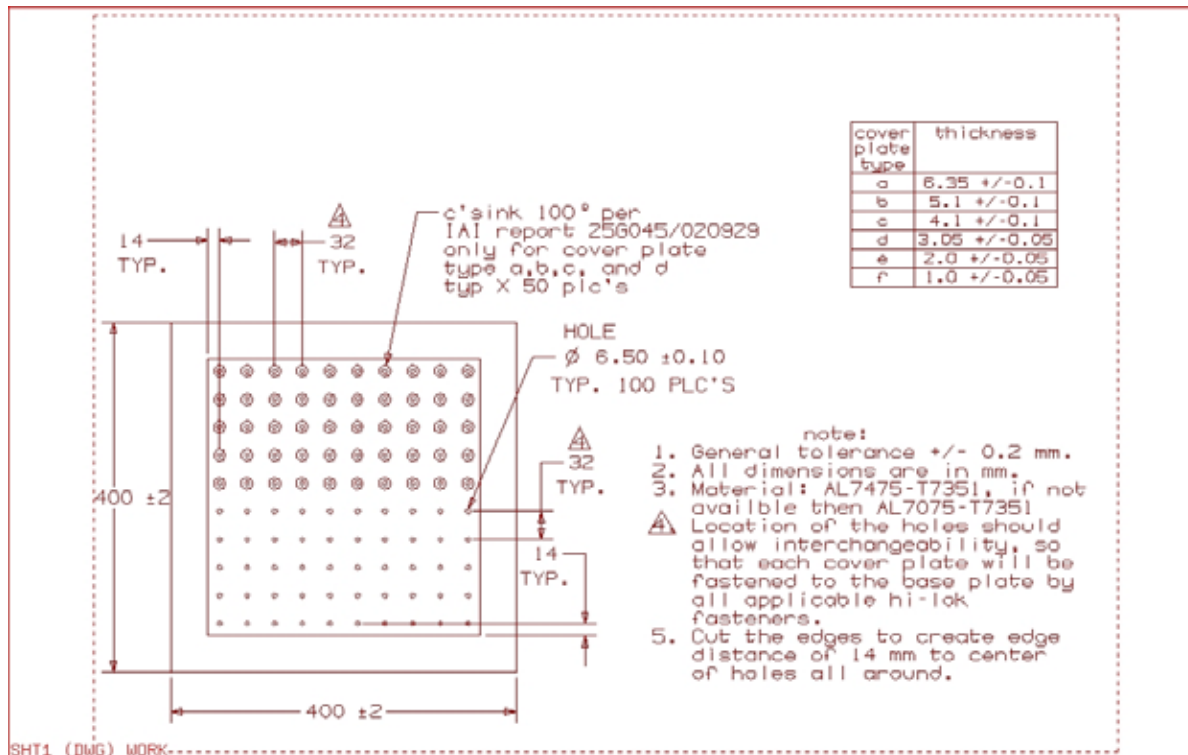


Figure 3: Cover plate details

CRACK DETECTION STATISTICAL CONSIDERATIONS FOR SETTING INSPECTION INTERVALS

Once the crack growth period to its critical length is calculated by means of damage tolerance analysis, the inspection intervals can be established by considering the inspection method and its statistical probability of crack detection. The principle of setting the inspection intervals is to ensure a valid level of in-service crack detection probability in order to discover the crack before it reaches its critical length.

There are several methods of setting the in-service crack detection inspection intervals. In this study we present a conventional method used in the aircraft industry [4]. Figure 2 illustrates the concepts of crack inspection in-service interval determination according that method.

Definitions:

- “**a_c**” - The critical crack length value, at which the structure is unable to sustain the required residual strength.
- “**a_d**” - The crack length which can be detectable by the specific NDI method with at least 90% probability and 95% confidence.
- “**T**” - The total period (flights or flights hours) from initial crack length (typical definition is 0.05”) to critical crack length.
- “**NP**” - The total available interval for detecting cracks from a crack size that can be detected by at least 90% probability to the critical crack length. (See Figure 2).

The damage tolerance analysis determines “**T**” and “**a_c**” values. The specific NDI method determines “**a_d**” value. Hence the total available interval period for detecting the crack, during routine inspections, before it reaches critical crack length value, is the “**NP**” period. Based on Ref. 4, which was established as an accepted method for determining inspection intervals, the first inspection for cracks is set at the **T/2 point**, but not later than 50% of the aircraft service life. The periodic inspection intervals during the “**NP**” period are set as per Table 2.

The statistical probabilities for crack detection capability of a specific NDI method are needed in order to implement the inspection method into damage tolerance calculations and to set the periodic inspection intervals.

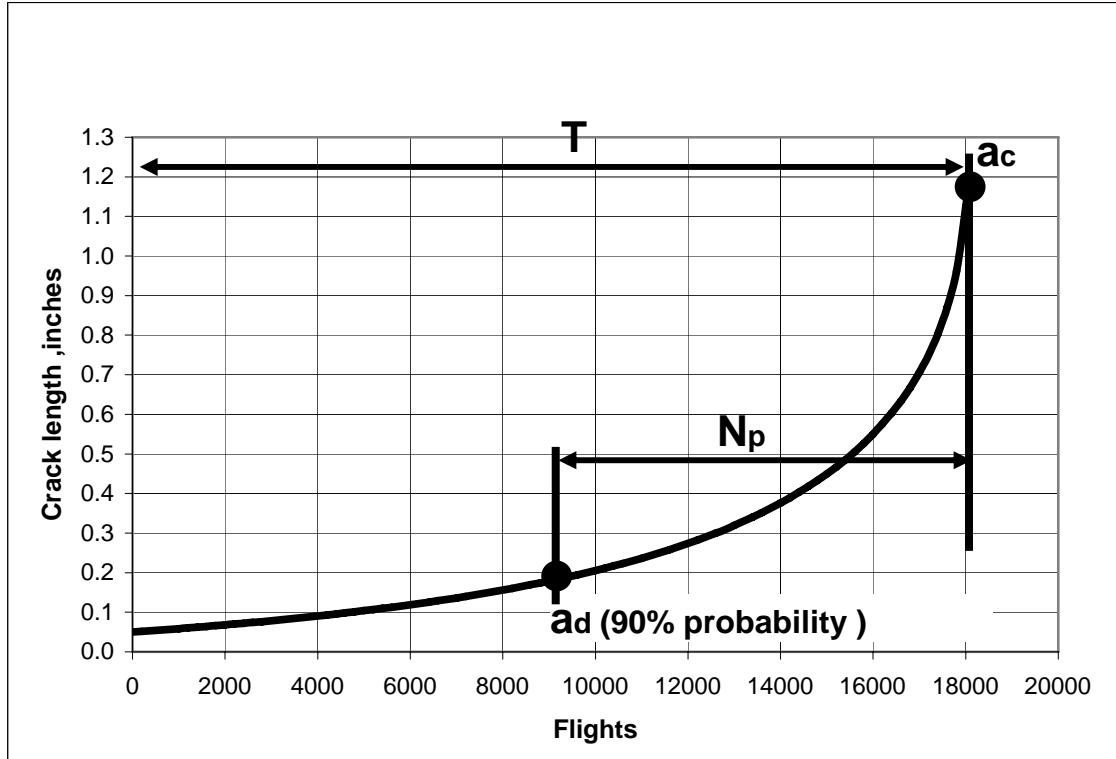


Figure 4: Crack inspection interval setting based on a conventional method

	Structural Classification of Detail	
	Multiple Load Path or Crack Arrest	Single Load Path
Periodic inspection interval	$N_P / 2$	$N_P / 3$

Table 2: Determination of the periodic inspection interval by a conventional method

The low-frequency eddy-current (LFEC) NDI method has a limited statistical database, which is not sufficient to derive statistical models to predict probabilities of crack detection. Fortunately, the high-frequency eddy-current (HFEC) NDI method is extensively used in the aircraft industry and has been extensively tested [2] [3]. The HFEC NDI method has an extensive statistical database, and a reasonably accurate and well-correlated statistical model of crack detection probability. On the basis of that model, and per the results of tests conducted in the framework of this study, we can set statistical parameters in order to establish probabilities of detection correlations to the LFEC NDI. This will allow us to implement the LFEC NDI benefits for inspection interval determination.

The HFEC NDI probability of crack detection data, gathered from extensive usage and experiments [2] [3], can be correlated either by Lognormal or Weibull three-parameter statistical distribution of crack detection per crack length.

The probability of detecting a crack of length “a” can be expressed by a three-parameter Weibull form:

$$P(a) = 1 - EXP\left(-\left(\frac{a - a_0}{\lambda - a_0}\right)^\alpha\right) \quad (1)$$

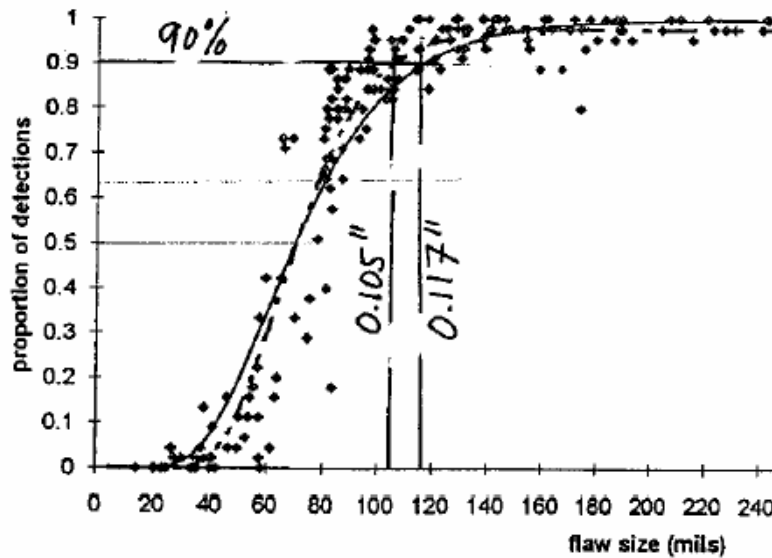
Based on the HFEC NDI experimental data [2] (sponsored by the FAA) we determined the Weibull three-parameter expression by regression and received the following parameters (see Fig. 5):

$$\alpha = 1.78 \quad (\text{Weibull distribution shape-factor})$$

$$\lambda = 0.078F \quad (\text{Crack length with probability of detection of } P = 0.632)$$

$$a_0 = 0.035F \quad (\text{Crack length with probability of detection of } P = 0)$$

where $F = 1$ for HFEC



Flaw size	P.O.D
0.035"	0%
0.070"	50%
0.078"	63.2%
0.105"	90%

Figure 5: PoD fit to HFEC NDI experimental data [2]

We can consider the HFEC NDI crack detection statistical database as a special case of inspection of a second hidden layer of which the cover plate is of a thickness of zero. We then made an assumption that the LFEC NDI crack detection probability distribution will have the same shape as the HFEC NDI crack detection probability expression, but the Weibull statistical distribution curve will be shifted as a function of the cover plate thickness.

The above Weibull statistical distribution can be used to express the correlations of the crack detection probabilities for the LFEC NDI as a function of crack length and cover plate thickness. From the statistical data gathered at the tests done in this study, we can correlate the Weibull distribution by obtaining the “F” parameter per the test results. The purpose of this study tests is to obtain the “F” parameter per each cover plate thickness. For the HFEC NDI, the “F” parameter is set to be 1. See Equation 1 parameters based on HFEC NDI experimental data [2].

This way we establish the statistical model that will predict the probability of crack detection per crack length and cover plate thickness. This will allow the use of the LFEC NDI technique with a relatively high degree of reliability for rationally determined inspection intervals. These inspection intervals will be significantly longer than those determined by the alternate inspection methods.

LFEC TESTS RESULTS

Table 3 presents the number of crack detections for each test, for the different types of ring probes and for the pencil probe. In each test, all the 100 holes were inspected by a test probe, from the cover plate side attached to the base plate. It needs to be said that there was only one false-positive, i.e. instrument indication of a crack at a hole where there was no crack. Table 3 presents the number of existing cracks in the base plate for each length, and the number of detections per each test done. The data is arranged per cover plate thickness. For each test the total number and percentage of detection is indicated, and the following parameters are presented:

- Test Probe
- Frequency of signal
- Horizontal and Vertical sensitivity

Existing Crack Length [inch]	No. Of Existing Cracks per Base Plate	Thickness:	# Detections			# Detections			# Detections			Total	
			0.04 [inch]			0.08 [inch]			0.12 [inch]				
			Test Probe:	Pencil LP	Ring s/n GO1640	Ring SPO 2030			Ring SPO 2030	Ring SPO 996			
			Frequency:	2Khz	2Khz	1Khz	700Hz	2Khz	600Hz	500Hz	500Hz		
			2	2	2	2	2	2	2	2	2	2	
			66.9	66.9	71.5	75.4	71.5	70.6					
			77.7	77.7	82.3	84.8	82.3	80.5					
		No. of tests:	1	1	1	1	1	1	23	11			
0.10	6		6	2	67	1	2	0	17	0	64	27	43
0.15	6		6	6	100	6	6	5	94	5	133	60	94
0.20	6		6	6	100	6	6	6	100	6	135	65	98
0.25	6		6	6	100	6	6	6	100	6	138	65	100
0.50	6		6	6	100	6	6	6	100	6	137	66	100
Total	30		30	26		25	26	23		23	607	283	
Total % detection			100	87		83	87	77		77	88	86	

Existing Crack Length [inch]	No. Of Existing Cracks per Base Plate	Thickness:	# Detections		# Detections		# Detections			Total	
			0.16 [inch]		0.20 [inch]		0.25 [inch]				
			Test Probe:	Ring SPO 2030	Ring SPO 2030		Ring SPO 2030				
			Frequency:	600Hz	450Hz	350Hz	350Hz	400Hz	350Hz		
			1	1	1	1	1	1	1	3	
			71.5	74.5	63.8	72.6	69.5	70			
			85.9	84.6	81.3	85	84.3	84.1			
		No. of tests:	1	1	1	1	1	1	1	3	
0.10	6		2	33	0	1	8	0	1	1	11
0.15	6		6	100	4	4	67	2	2	1	28
0.20	6		6	100	5	5	83	4	5	5	78
0.25	6		6	100	5	6	92	4	5	5	78
0.50	6		6	100	6	6	100	5	5	6	89
Total	30		26		20	22		15	18	18	
Total % detection			87		67	73		50	60	60	

Table 3: Ring and pencil probe detection results

Table 4 presents the number of crack detections for each test, for the two types of ring probes, separately for the plain holes and for the countersunk holes. The table presents the number of existing cracks per each length, that are covered by a plain hole at the cover plate, and that are covered by a countersunk hole at the cover plate. For each test, the total number and percentage of detection is indicated separately for the plain holes and for the countersunk holes.

Existing Crack length [inch]		No. Of Existing Cracks		NUMBER OF CRACK DETECTIONS													
				t = 0.12 inch		t = 0.16 inch		t = 0.20 inch				t = 0.25 inch					
				Ring SPO 2030		Ring SPO 2030		Ring SPO 2030				Ring SPO 2030					
				600Hz		600Hz		450Hz		350Hz		350Hz		400Hz		350Hz	
C'sink	Plain	C'sink	Plain	C'sink	Plain	C'sink	Plain	C'sink	Plain	C'sink	Plain	C'sink	Plain	C'sink	Plain	C'sink	Plain
0.10	0.10	4	2	0	0	1	1	0	0	1	0	0	0	1	0	1	0
0.15	0.15	3	3	2	3	3	3	1	3	2	2	1	1	1	1	0	1
0.20	0.20	2	4	2	4	2	4	2	3	1	4	1	3	1	4	2	3
0.25	0.25	3	3	3	3	3	3	2	3	3	3	2	2	2	3	2	3
0.50	0.50	3	3	3	3	3	3	3	3	3	3	2	3	2	3	3	3
TOTAL		15	15	10	13	12	14	8	12	10	12	6	9	7	11	8	10
Total % of detect				67	87	80	93	53	80	67	80	40	60	47	73	53	67

Table 4: Ring probe detection results for plain holes and countersunk holes

Table 5 presents the number of crack detections for each test for the sliding probe. The sliding probe can be used only on the countersunk holes containing flush fastener heads. Table 5 presents the number of existing cracks in the base plate per each length that is covered by a countersunk hole. The data is arranged per cover plate thickness. For each test the total number and percentage of detection is indicated, and the following parameters are presented:

- Test Probe
- Frequency of signal
- Horizontal and Vertical sensitivity

NUMBER OF CRACK DETECTIONS USING SLIDING PROBE (SPO 1893)						
Existing Crack Length [inch]	Number Of Existing Cracks at Countersunk Holes	Plate Thickness	t = 0.12 inch	t = 0.16 inch	t = 0.20 inch	t = 0.25 inch
		Frequency	350 Hz	350 Hz	350 Hz	350 Hz
		Horz. Sen.	54.4	58.4	53	57.1
		Vert. Sen.	66.9	69.9	70.5	74.6
0.10	4		2	2	2	2
0.15	3		3	3	3	2
0.20	2		2	2	2	2
0.25	3		3	3	2	3
0.50	3		3	3	3	3
Total	15		13	13	12	12
Total % detection			86.7	86.7	80.0	80.0

Table 5: Sliding probe detection results for the countersunk holes

ANALYSIS OF THE LFEC TEST RESULTS

Figure 6 presents the total percentage of crack detection for all the tests and all the crack lengths for all holes (plain & countersunk) done with ring & pencil probes per cover plate thickness. A tendency can be seen that as the cover plate is thicker, the total percentage of crack detection decreases. It can be seen that as the cover plate is thicker, a lower testing frequency is needed in order to maintain a reasonable crack detection percentage. It is noted that the ability of crack detection of the pencil probe for cover plate of 0.04 inch is outstanding, but that probe did not give any indication for the other cover plate thicknesses.

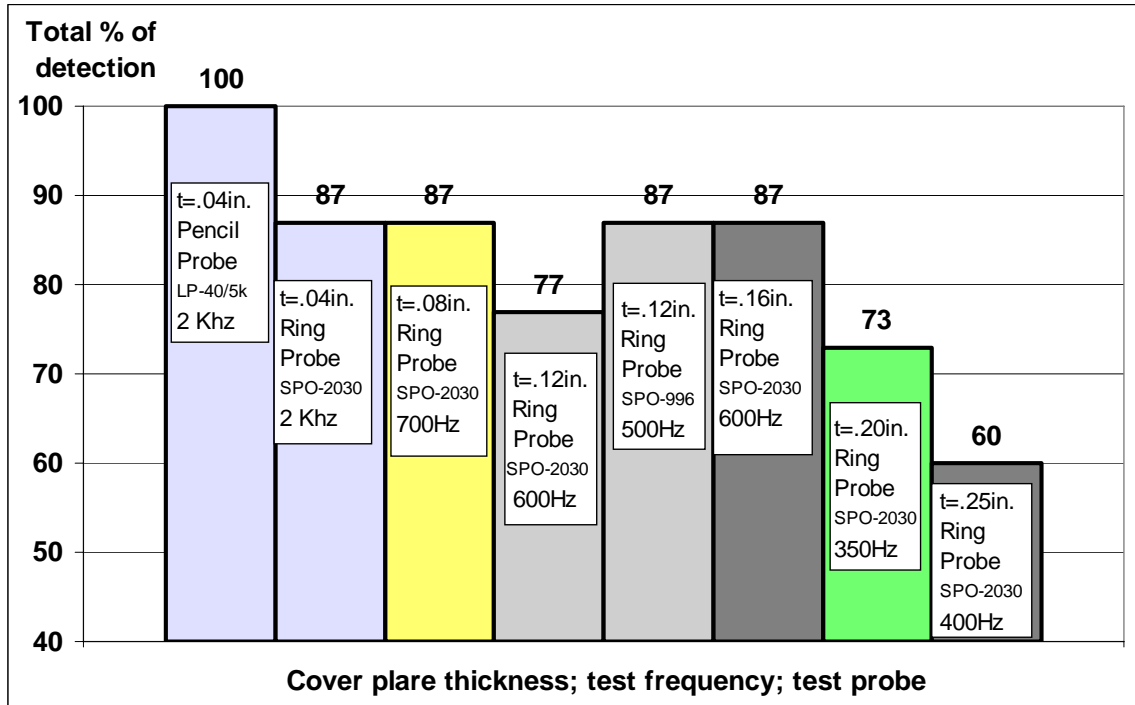


Figure 6: Total percentage of crack detection for all tests all crack lengths and all holes (plain & countersunk) done with ring & pencil probes per cover plate thickness

Figure 7 presents the total percentage of crack detection for the IAI tests, for all the crack lengths, for plain holes versus countersunk holes, done with ring probe per cover plate thickness. It can be seen that the ability of crack detection of the ring probe on the countersunk holes is significantly lower relative to the detection for the plain holes. A suspected cause for that phenomenon is the existence of a small thin groove in-between the countersunk edge and the fastener flush head that induces some disturbance to the ring probe signal.

Figure 8 presents the total percentage of crack detection for the IAI tests, for all the crack lengths, for countersunk holes only, done with sliding probe for each cover plate thickness. Comparing the results presented in Figure 7 for the ring probe detection on countersunk holes, to the results presented in Figure 8, it can be seen that the ability of crack detection of the sliding probe on the countersunk holes is significantly higher than the ability of the ring probe.

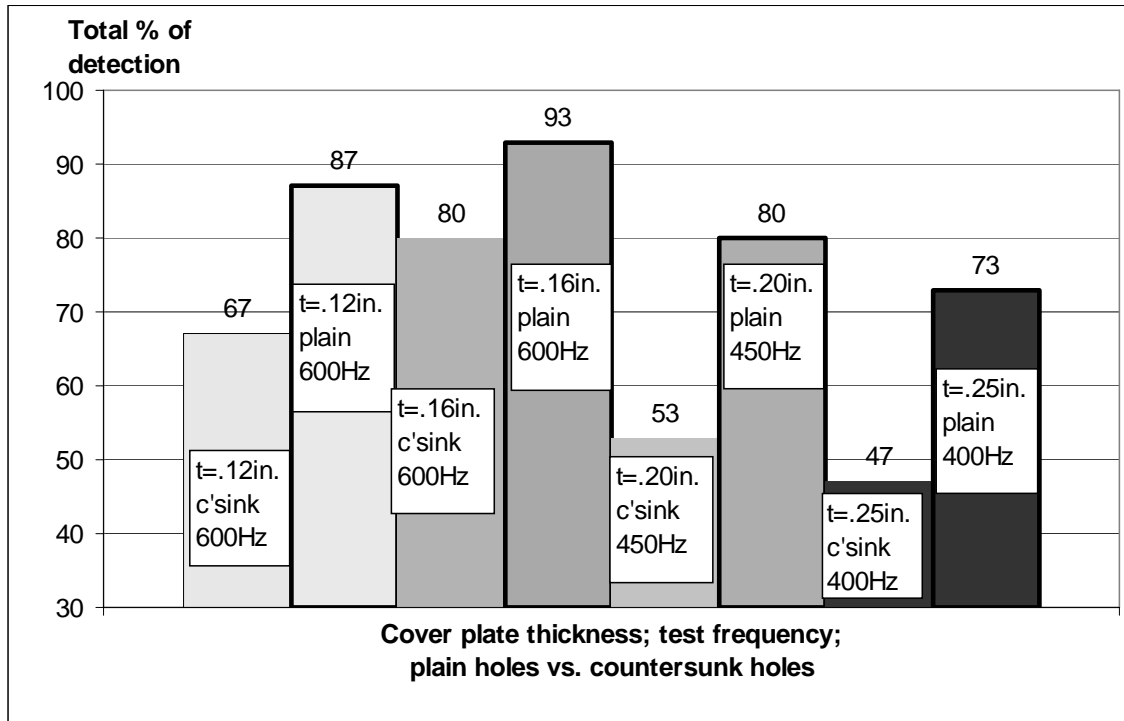


Figure 7: Total percentage of crack detection for IAI tests, for all crack lengths, for plain holes versus countersunk holes done by ring probe per cover plate thickness

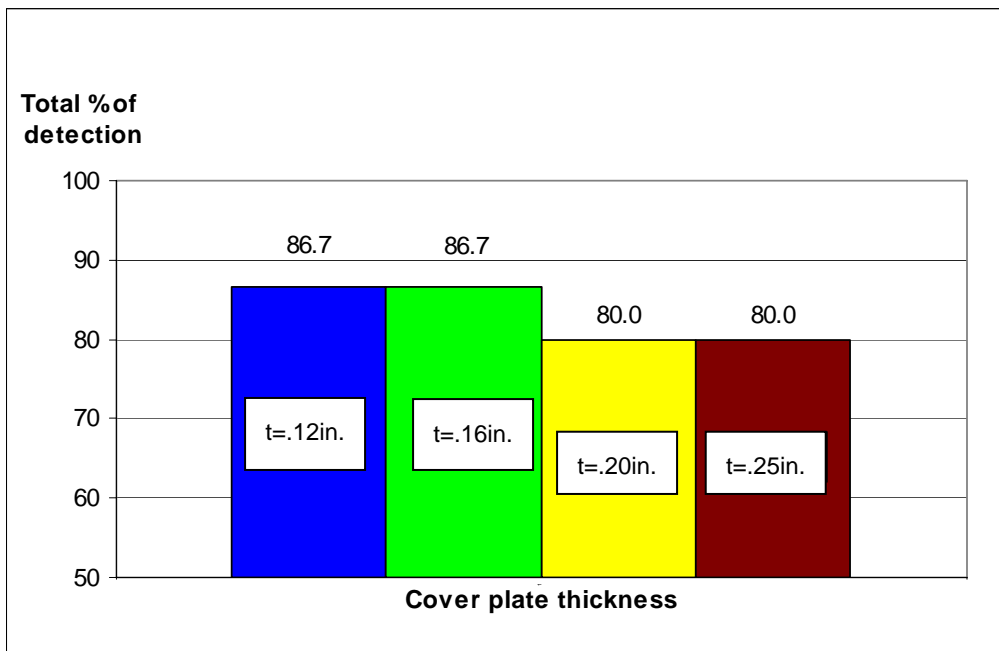


Figure 8: Total percentage of crack detection for countersunk holes with sliding probe

Figure 9 presents all the tests (all probes used, all hole types) together with the percentage of crack detection results, arranged as a map per crack length and per cover plate thickness. This presentation of percentage of detection for each combination of crack length and cover plate thickness as resulting from the tests performed, can set a criterion for non-reliable crack detection conditions. That criterion means that a curve describes a constant percent of crack detection can be drawn according to tests results (let's say 90% of crack detection criterion). Each combination of crack length and cover plate thickness that will appear at the upper and/or right side of that curve on the map means that this combination has less probability of detection than the criterion that had been set, and is defined as "no reliable detection" condition for the LFEC NDI capability.

It is important to emphasize that the extent of tests are planned to be enlarged, by applying more inspections on the plates to be performed by more and different inspectors. Enlarging the statistical database will refine the resolution of the PoD results for each combinations of crack length and cover plate thickness.

For the Figure 9 map, we made an approximation for a 90% crack detection criterion curve, and it is drawn on the map for illustration purposes. Once the statistical database will be large enough, the criterion for non-reliable crack detection conditions curve may be drawn more accurately.

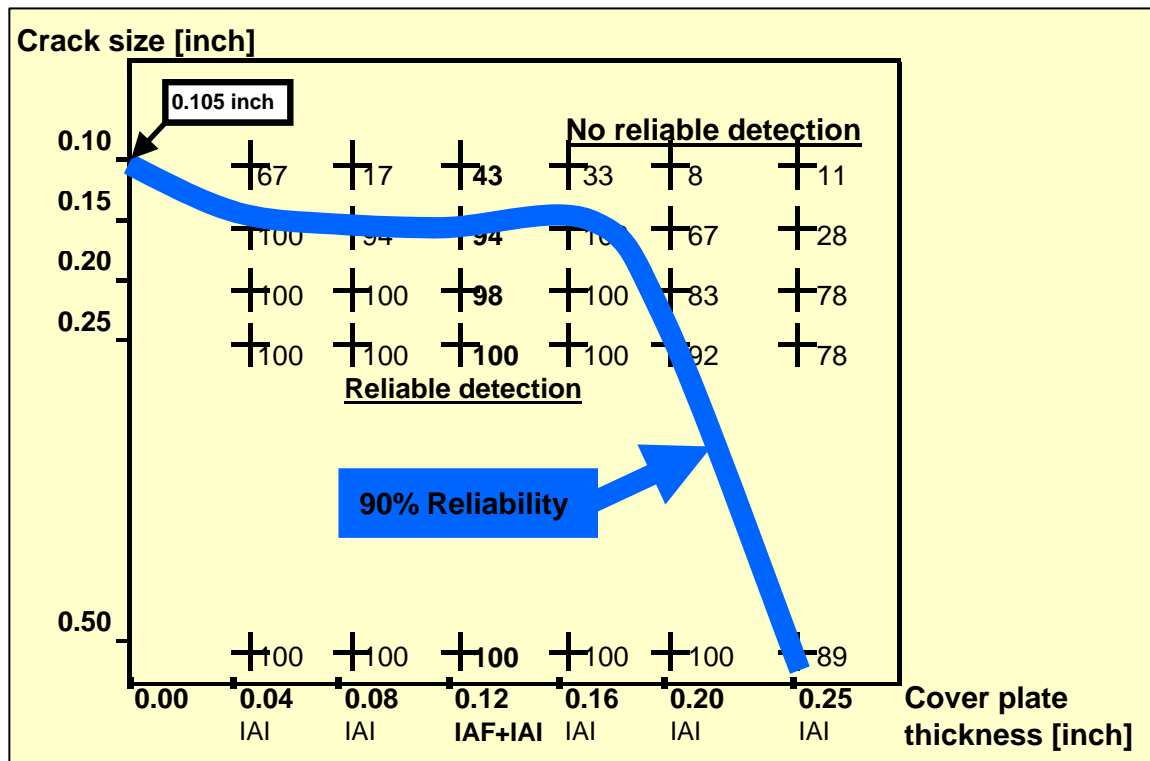


Figure 9: Percentage of crack detection for all tests (for all probe types) per crack length and per cover plate thickness

Figure 10 presents for each of the cover plate thickness, the probability of crack detection per crack length for the following:

- The tests results.
- The Weibull distributions correlated to LFEC NDI tests as per the F parameter obtained from the tests results.
- The Weibull distributions for HFEC NDI (i.e. crack detection inspections for an uncovered layer).

According to all the tests results for each cover plate thickness, we “calibrated” the well-established Weibull distribution for HFEC NDI crack detection probabilities (for an uncovered crack detection), to correlate with the test results. That “calibration” is done by “tuning” the “F” parameter for the Weibull distribution expression (for HFEC NDI the $F=1$). For each cover plate thickness, we obtained a different “F” parameter. Examining the resulting correlations for each cover plate thickness, we can establish a reasonably accurate Weibull distribution.

Figure 11 presents the “F” parameter obtained from the tests conducted for the different cover plate thickness. We obtained a reasonable correlation between the “F” parameter and the cover plate thickness. This correlation enables the Weibull three-parameter expression to predict the probability of detecting a crack in a second layer for any desired cover plate thickness, in the range of “0” inch to 0.25 inch.

CONCLUSIONS

1. The testing database gathered up to now, indicates a statistical correlation that can be expressed and implemented in damage tolerance analyses. This will allow us to implement the benefits of the LFEC NDI technique in the inspection interval determination and to enjoy the potential of significantly increasing inspection intervals for some structural details.
2. There is a need to continue the tests on the plates with additional inspectors, to collect more data, in order to establish a more reliable set of statistical parameters required by the Weibull distribution for the crack detection probability analysis. An accurate statistical analysis of the LFEC crack detection capability is essential for a valid inspection interval determination based on damage tolerance analysis.
3. As expected, for the thicker cover plates, the crack detection ability decreases. Naturally, the shorter crack lengths (0.10 inch, 0.15 inch) are those most difficult to detect.
4. For the thicker cover plates, the probe crack detection ability increases by using a lower frequency (up to a limit, adjusted by the NDI expert).
5. The sliding probe increases dramatically the crack detection ability for countersunk holes, but is inapplicable for plain holes.
6. The ring probe has lower crack detection ability for countersunk holes, relative to plain holes.
7. The pencil probe has an excellent crack detection ability (the best), for the lowest cover plate thickness ($t=1\text{mm}$), but is inapplicable for all other cover plate thicknesses.
8. The small cracks (0.10 inch), which are oriented perpendicularly towards the plate edge, were the most difficult to detect.

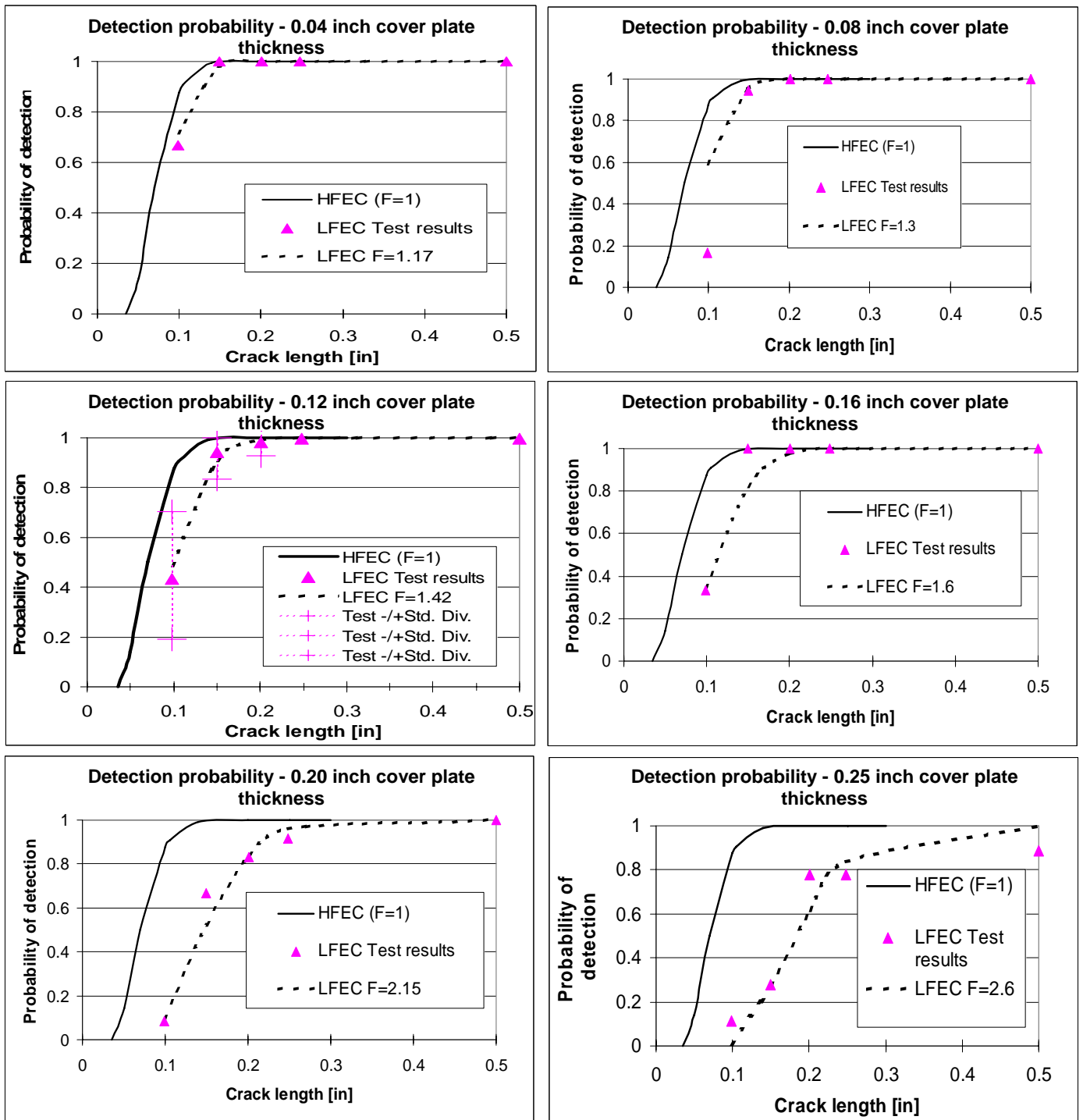


Figure 10: Probability of detection correlations to test results per cover plate thickness as function of crack length

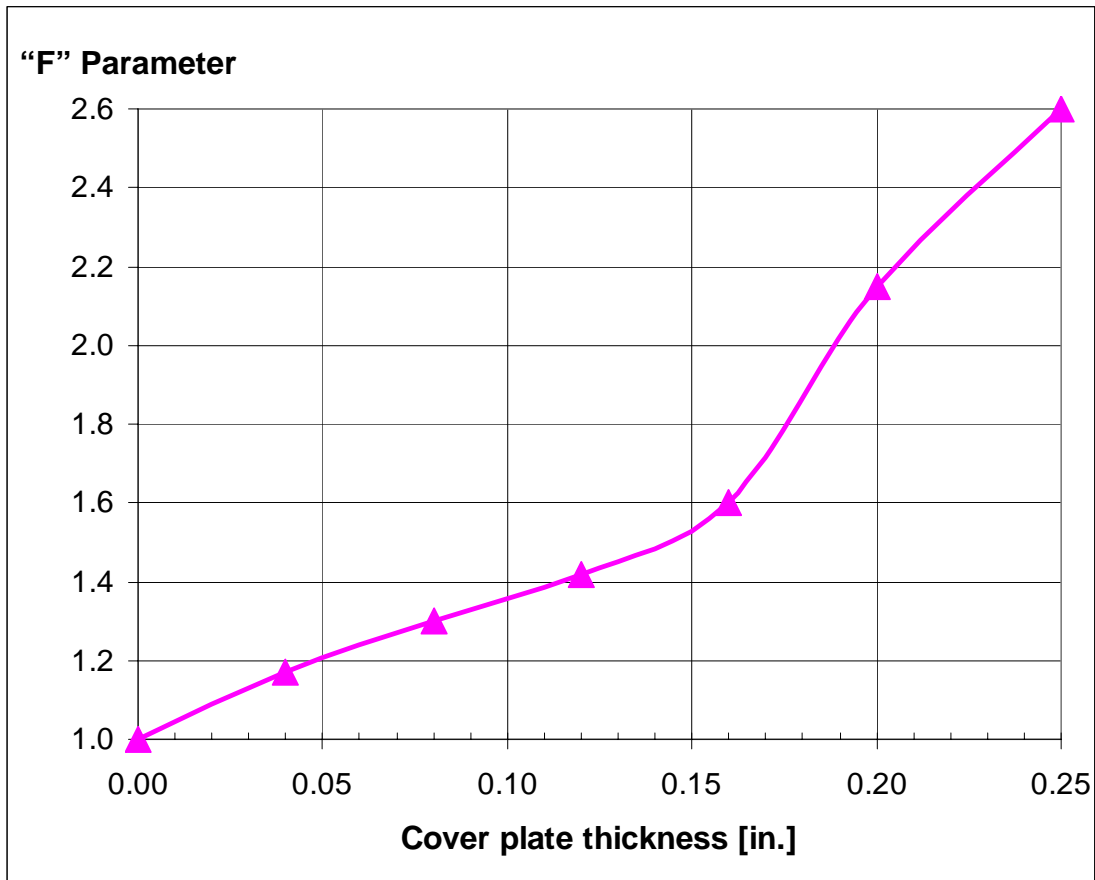


Figure 11: "F" parameter obtained from tests as a function of cover plate thickness

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