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Replacement of FAARFIELD Tandem Factors With Cumulative Damage Factor Methodology

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16. Abstract

The United States Federal Aviation Administration (FAA) adopted FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) as its standard thickness design procedure for airport pavements in September 2009. FAARFIELD includes a layered elastic analysis routine for flexible pavement design and a three-dimensional finite element structural analysis routine for rigid pavement design.

The current FAARFIELD design procedure for flexible pavements accounts for the effect of aircraft gears in tandem as part of the pass-to-coverage (P/C) ratio computation. The result is a two-part P/C ratio consisting of a wander-related factor multiplied by a tandem factor. The tandem factor is computed as a straight-line interpolation between the number of wheels in tandem (for shallow structures) and unity (for deep structures).

The objective of this report is to accompany the source code implementation of replacing the current method using a tandem factor with an alternative calculation, in which the cumulative damage factor (CDF) due to wheels in tandem is computed based on the subgrade linear elastic strain response.

The report contains a comparison of CDFs for flexible pavements under tandem axle gear loads (two dual-gear and three dual-gear configurations), as computed by the current method (FAARFIELD Version 1.4) and by the new method. The report also contains a comparison of CDF computed by the new method with the CDF computed for multiple wheel sets in tandem using the Alizé-Aircraft program, which was developed by the Institut français des sciences et technologies des transports, de l'aménagement et des réseaux - French Institute of Science and Technology for Transport, Spatial Planning, Development and Networks (IFSTTAR) and the French Directorate General for Civil Aviation (DGAC).

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2D	Two dual-gear configuration (four wheels)
3D	Three dual-gear configuration (six wheels)
AC	Advisory Circular
CDF	Cumulative damage factor
C/P	Coverage-to-pass ratio
D	Dual-gear configuration (two wheels)
DGAC	Direction générale de l'aviation civile (Directorate General for Civil Aviation (France))
FAA	Federal Aviation Administration
FAARFIELD	FAA Rigid and Flexible Iterative Elastic Layered Design
IFSTTAR	Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (The French Institute of Science and Technology for Transport, Development and Networks)
LEDFAA	Layered Elastic Design—FAA
P/C	Pass-to-coverage ratio

EXECUTIVE SUMMARY

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1. INTRODUCTION.

In September 2009, the United States Federal Aviation Administration (FAA) issued Advisory Circular (AC) 150/5320-6E, "Airport Pavement Design and Evaluation," which adopted FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) (version 1.3) as the approved design standard for airport pavement thickness [1 and 2]. FAARFIELD 1.3 replaced the previous standard, Layered Elastic Design–FAA (LEDFAA) 1.3.

FAARFIELD includes a layered elastic analysis routine for flexible pavement design and a three-dimensional finite element structural analysis routine for rigid pavement design.

Currently, the FAARFIELD design procedure for flexible pavements accounts for the effect of aircraft gears in tandem as part of the pass-to-coverage (P/C) ratio computation. The result is a two-part P/C ratio, consisting of a wander-related factor multiplied by a tandem factor. The tandem factor is computed as a straight-line interpolation between the number of wheels in tandem (for shallow structures) and unity (for deep structures).

This report accompanies the source code implementation of replacing the current method using a tandem factor with an alternative calculation, in which the cumulative damage factor (CDF) due to wheels in tandem is computed based on the subgrade linear elastic strain response.

2. ALGORITHM MODIFICATION.

For flexible pavements, the interaction between n_t tires in a tandem gear assembly may be significant. FAARFIELD 1.3 includes a tandem gear factor to consider the interaction between the front and rear tires in an assembly, as earlier implemented in LEDFAA [3]. Let b be the net distance between the front and rear tires (i.e., the center-to-center tandem spacing minus the length of the tire contact patch), and let h be the total pavement thickness to the top of the subgrade. Then the tandem factor F_{tnd} is defined as follows:

$$\begin{aligned} F_{tnd} &= 1 && \text{when } h/b \geq 2 \\ F_{tnd} &= n_t - (n_t - 1)(h/b - 1) && \text{when } 1 < h/b < 2 \\ F_{tnd} &= n_t && \text{when } h/b \leq 1 \end{aligned}$$

The variation of F_{tnd} with nondimensionalized tandem spacing h/b is illustrated in figure 1.

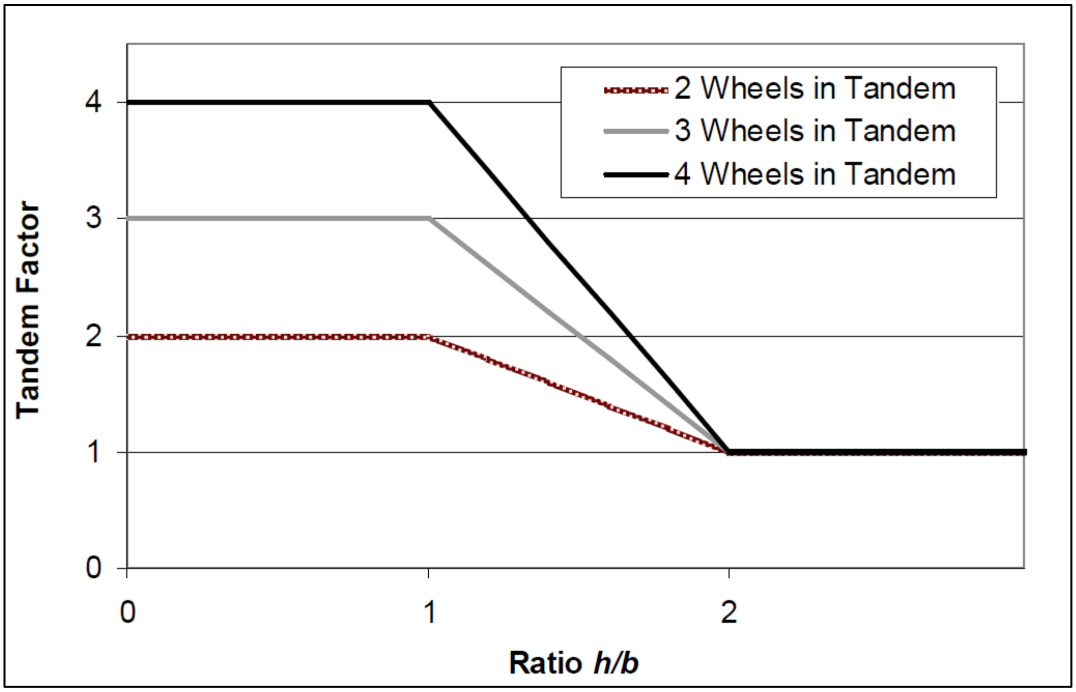


Figure 1. Tandem Gear Factor in FAARFIELD 1.3 as a Function of Tandem Spacing [4]

In the current design procedure, the pavement surface is divided into 81 10-inch-wide longitudinal strips for a total pavement width of 810 inches. The offset of each strip is measured from the pavement centerline to the center of the strip. The present method of calculating the CDF at the i^{th} strip is as follows [2]:

$$CDF_i = \sum_{A=1}^{m} \left(\frac{C}{P}\right)_i^{(A)} \frac{P_A}{N_A} F_{tnd}^{(A)} \tag{1}$$

where $\left(\frac{C}{P}\right)_i^{(A)}$ denotes the C/P ratio for offset *i* and aircraft *A* before considering the tandem adjustment, *m* is the number of aircraft types in the traffic mix, N_A is the number of coverages (repetitions of maximum vertical subgrade strain values) to failure for aircraft *A*, and P_A is the total number of passes of aircraft *A* in the design period. The CDF value for the design is determined by taking the maximum value of CDF_i over all 81 strips:

$$CDF = \max(CDF_i) \tag{2}$$

To simplify, consider the case $m = 1$ (single aircraft mix) and omit the summation index *A*, so equation 1 reduces to a single term:

$$CDF_i = \left(\frac{C}{P}\right)_i \frac{P}{N} F_{tnd} \tag{3}$$

Equation 3 can be rewritten as follows:

$$CDF_i = \left(\frac{C}{P}\right)_i PD(y_i) \tag{4}$$

where $D(y_i)$ is the damage computed along the offset y_i.

In the current FAARFIELD design method, the damage is proportional to the tandem factor F_{tnd} and does not depend on the offset coordinate. Once the maximum value of vertical strain $\varepsilon_{max} = \max \varepsilon(x, y)$ is found, the damage is equal to:

$$D = F_{tnd}/N(\varepsilon_{max}) \tag{5}$$

This approach is different from the more general approach in the Alizé-Aircraft program [5 and 6], which uses integration of elementary damages $D_e(\varepsilon)$ to calculate the damage at offset y_i:

$$D(y_i) = \int_{-\infty}^{\infty} H\left(\frac{d\ \varepsilon(x,y_i)}{dx}\right) d\ D_e(\varepsilon(x, y_i)) = \int_{-\infty}^{\infty} H\left(\frac{d\ \varepsilon(x,y_i)}{dx}\right) d\ \left(\frac{1}{N(\varepsilon(x,y_i))}\right) \tag{6}$$

Here, $\varepsilon(x, y_i)$ is vertical strain calculated at longitudinal coordinate x and lateral offset y_i, $N(\varepsilon)$ is the number of repetitions to failure at strain level ε, and

$$H(x) = \begin{cases} 1, & x > 0 \\ 0, & else \end{cases}$$

the Heaviside function. Unlike the current FAARFIELD method, the integral approach of equation 6 allows calculation of multiple-peak damage directly from strain, without the need to determine the distance between tires in tandem and the thickness of the structure.

Note that for a single peak, the integral of equation 6, when evaluated along the profile containing the maximum value ε_{max} of vertical strain, reduces to the current FAARFIELD concept, as expressed by equation 5:

$$D = \int_{-\infty}^{\infty} \frac{d\ D_e(\varepsilon)}{d\varepsilon} \frac{d\ \varepsilon(x)}{dx} H\left(\frac{d\ \varepsilon(x)}{dx}\right) dx = \int_{-\infty}^{x_{peak}} \frac{d\ D_e(\varepsilon)}{d\varepsilon} \frac{d\ \varepsilon(x)}{dx} dx = \tag{7}$$

$$= \int_{\varepsilon(-\infty)}^{\varepsilon(x_{peak})} \frac{d\ D_e(\varepsilon)}{d\varepsilon} d\varepsilon = D_e\big(\varepsilon(x_{peak})\big) - D_e(\varepsilon(-\infty)) = \frac{1}{N(\varepsilon_{max})}$$

The damage D computed by equation 7 is then used in equation 4 to compute CDF_i at the i^{th} offset.

For the case of multiple peaks, the cumulative damage from all peaks can be calculated as follows:

$$D = \int_{-\infty}^{\infty} \frac{d\ D_e(\varepsilon)}{d\varepsilon} \frac{d\ \varepsilon(x)}{dx} H\left(\frac{d\ \varepsilon(x)}{dx}\right) dx = \sum_{k=1}^{n} s_k D_e(\varepsilon_k) \tag{8}$$

where n is the total number of extremum points, ε_k are critical strain values, and s_k is a factor characterizing the *k*th extremum:

$$s_k = \begin{cases} 1 & if\ \varepsilon_k\ is\ maximum \\ -1 & if\ \varepsilon_k\ is\ minimum \\ 0 & if\ \varepsilon_k\ is\ not\ extremum \end{cases}$$

It should be noted that integration (equation 8) needs to be done in FAARFIELD only on the strip where the maximum strain for a given gear configuration is located. Integration along the other strips is not necessary.

The proof of equation 8 is the following: let the strain profile under consideration decompose by intervals $(x_k, x_{k+1}), k = 1 \dots n,$ where strain is a monotonically behaving function of coordinate x. In other words, the coordinates x_k are extremum points where the strain changes its character from increasing to decreasing or vice-versa. Using the additive property of integration, one may write:

$$D = \int_{-\infty}^{\infty} H\left(\frac{d\,\varepsilon(x)}{dx}\right) d\,D_e(\varepsilon) = \int_{-\infty}^{x_1} H\left(\frac{d\,\varepsilon(x)}{dx}\right) d\,D_e(\varepsilon) + \\ + \sum_{k=1}^{n-1} \int_{x_k}^{x_{k+1}} H\left(\frac{d\,\varepsilon(x)}{dx}\right) d\,D_e(\varepsilon) + \int_{x_n}^{\infty} H\left(\frac{d\,\varepsilon(x)}{dx}\right) d\,D_e(\varepsilon) \quad (9)$$

Apparently at the interval $(-\infty, x_1)$, the strain derivative is positive, so $H\left(\frac{d\,\varepsilon(x)}{dx}\right) = 1$. Then,

$$\int_{-\infty}^{x_1} H\left(\frac{d\,\varepsilon(x)}{dx}\right) d\,D_e(\varepsilon) = \int_{-\infty}^{x_1} d\,D_e(\varepsilon) = D_e(\varepsilon(x_1)) - D_e(\varepsilon(-\infty)) = D_e(\varepsilon_1) \quad (10)$$

Similarly, the last term in equation 9 can be calculated at the interval (x_n, ∞). The strain derivative is negative, so $H\left(\frac{d\,\varepsilon(x)}{dx}\right) = 0$ and

$$\int_{x_n}^{\infty} H\left(\frac{d\,\varepsilon(x)}{dx}\right) d\,D_e(\varepsilon) = 0 \quad (11)$$

Terms $\int_{x_k}^{x_{k+1}} H\left(\frac{d\,\varepsilon(x)}{dx}\right) d\,D_e(\varepsilon)$ in equation 9 have sign depending on x_k. If x_k is a maximum point, then the next point x_{k+1} is a strain minimum point, so at the interval $(x_{k,} x_{k+1})$ the derivative is negative, and by the definition of the Heaviside function:

$$H\left(\frac{d\,\varepsilon(x)}{dx}\right) = 0$$

This implies:

$$\int_{x_k}^{x_{k+1}} H\left(\frac{d\,\varepsilon(x)}{\mathrm{dx}}\right) \mathrm{d\,D}_e(\varepsilon) = 0 \quad (12)$$

If x_k is a minimum point, then next point x_{k+1} is a strain maximum point, so on the interval $(x_{k,}x_{k+1})$ the derivative is positive:

$$\mathrm{H}\left(\frac{\mathrm{d}\ \varepsilon(\mathrm{x})}{\mathrm{dx}}\right) = 1$$

This implies:

$$\int_{x_k}^{x_{k+1}} H\left(\frac{d\ \varepsilon(x)}{dx}\right) d\ D_e(\varepsilon)\ = \int_{x_k}^{x_{k+1}} d\ D_e(\varepsilon) = \ D_e(\varepsilon_{k+1}) - D_e(\varepsilon_k) \qquad (13)$$

When equations 10-13 are substituted into the appropriate terms in equation 9, the result is:

$$D = D_e(\varepsilon_1) + \sum_{\substack{k=2, \\ k\ is\ point\ of\ minimum}}^{n-1} (D_e(\varepsilon_{k+1}) - D_e(\varepsilon_k)) \qquad (14)$$

Rearranging the sum in equation 14, with respect to all extremum points (not only minima), results in equation 8.

3. PROGRAM MODIFICATIONS.

The FAARFIELD source code was modified to implement a new method of computing damage based on equation 8. In the modified source code, the newly created subroutines were given names similar to their parent subroutines. For example, in the current FAARFIELD version, `Sub CoverageToPassFlexible` calculates the C/P ratio. The existing subroutine was retained with no changes, while changes in C/P calculations were made in a newly created subroutine `Sub CoverageToPassFlexibleK`. This approach allowed the developers to roll back to the original subroutines as needed during testing.

3.1 DELETION OF TANDEM FACTOR.

The first major modification was deleting the tandem factor, represented by the variable `multiplier1`, from the process of calculating the C/P ratio. This modification was done in subroutine `CoverageToPassFlexible`. As a result, reported P/C values now represent the influence of aircraft wander only.

3.2 DETERMINATION OF CRITICAL LONGITUDINAL PROFILE.

In the modified FAARFIELD, subroutine `ComputeResponse2` forms an array of vertical strains along a longitudinal axis at some chosen offset value. The particular offset is chosen as follows: Subroutine `ComputeResponse2` starts the same way as its parent subroutine `ComputeResponse`. Strains are evaluated at points along the critical response path (figure 2) for the gear type. Then from among those evaluated strains, the maximum strain is selected. The modified subroutine `ComputeResponse2` stores both the value of the maximum strain and the offset at which that maximum strain is detected (variable *offsetMax*).

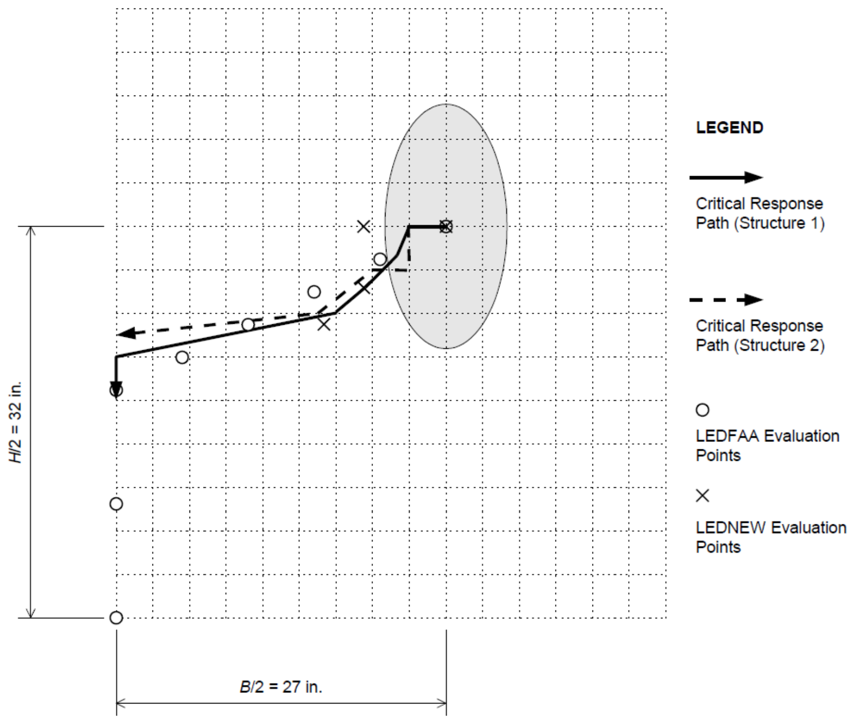


Figure 2. Critical Response Locus for McDonnell-Douglas DC-10-10 Aircraft (Only one wheel is shown due to bidirectional symmetry.)

As implemented, the length of the vector of evaluation points for the longitudinal profile is chosen as 100. This choice is based on the typical characteristic length of the mesh size and is sufficient for accurate integration.

In theory, the longitudinal coordinate extends from -∞ to ∞, but practically, the interval needs to be truncated at finite distances from the tandem gear center. The choice of truncation limits is determined by the magnitude of strains. At sufficiently far distances from the contact tire area, the strains are negligible, and there is no need to integrate them.

An effective way to calculate the integration limits (-*a*, *a*) is to double the interval (-*a*, *a*) of the integration (equation 8) repeatedly, until the difference between two successive iterations becomes smaller than the given tolerance Δ:

$$\left| \int_{-2a}^{2a} \frac{d\,D_e(\varepsilon)}{d\varepsilon} \frac{d\,\varepsilon(x)}{dx} H\left(\frac{d\,\varepsilon(x)}{dx}\right) dx \Big/ \int_{-a}^{a} \frac{d\,D_e(\varepsilon)}{d\varepsilon} \frac{d\,\varepsilon(x)}{dx} H\left(\frac{d\,\varepsilon(x)}{dx}\right) dx \right| < 1 + \Delta$$

Another approach is based on an a priori estimate of vertical strain in the far-field region for the given structure. As implemented in FAARFIELD 1.4, the limits of integration were chosen as follows: the upper limit is equal to the forward-most wheel coordinate plus 160 in. (406 cm), and the lower limit is equal to the rearmost wheel coordinate minus 160 in. (406 cm). The strain profile obtained in this way is referred to as the critical longitudinal profile. Similar logic determines the choice of the interval between mesh points. If no information is available about functional behavior within integration limits, numerical integration is run starting from a sparse mesh. Then the number of evaluation points is increased (generally doubled) within the limits of integration, integrated again, and the result is compared to the previous integration. If the difference between the two successive integrals is less than a given tolerance, the procedure is stopped. Typically, an array of 1800 evaluation points provides sufficiently accurate results for damage integration. Consider a gear for which the distance between the forward-most and rearmost wheels is 200 in. (508 cm). For this hypothetical (and highly conservative case), the discretization interval would be calculated as (200 + 160 + 160) / 1800 = 0.29 in. (0.73 cm). In most real cases, such as the examples in this report, the discretization interval is shorter. For comparison, in the Alizé software, the limits of integration are between two and three times the total height of the pavement structure (with the exact limits depending on the thickness), and the discretization interval is generally between 1 - 2 inches (2.5 - 5 cm).

4. COMPARISON OF CURRENT AND NEW METHODS.

The results shown in the following sections compare the current CDF calculation procedure to the new procedure incorporating integration along a longitudinal profile. As the flexible design procedure is an iterative process, it was necessary to compare only the CDF curves resulting from the first iterations. Experience shows that if the CDF curves from the first iterations are in agreement, then the CDF curves produced in subsequent iterations will also agree.

4.1 DUAL-GEAR CONFIGURATION.

If the gear loading (single (S) or dual (D) gear configurations) results in a single peak, the new method should not deviate from the old method for any structure. Consider the sample structure in figure 3, loaded by a traffic mix consisting of 1200 annual departures of the generic D-200 aircraft (200,000 lb gross weight). The D-200 characteristics are displayed in figure 4.

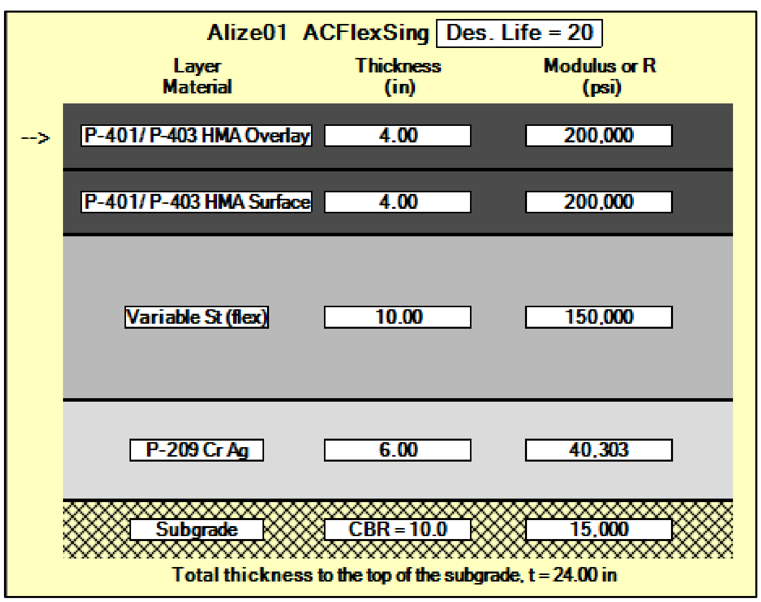


Figure 3. Sample HMA-on-Flexible Overlay Structure Loaded by Generic D-200 Aircraft Gear

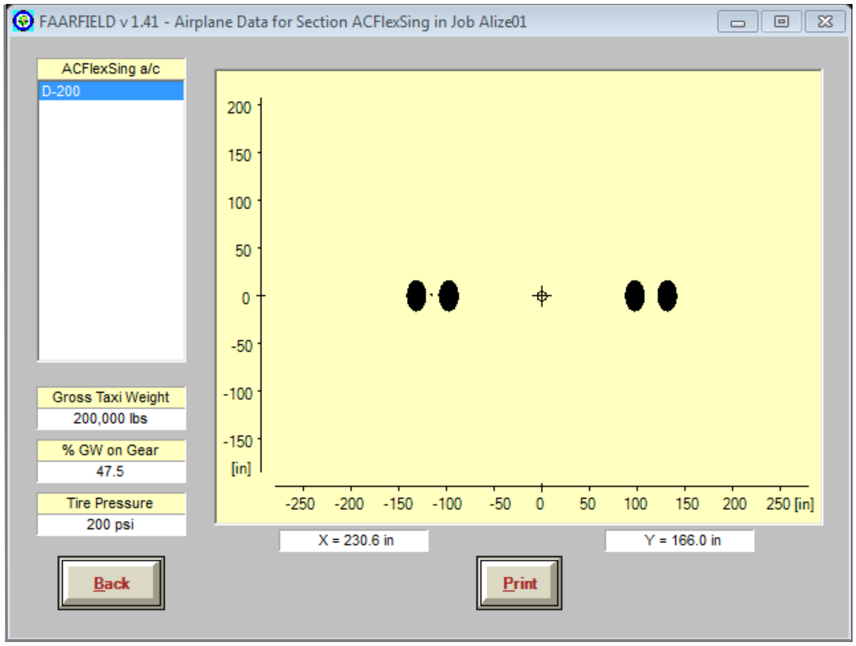


Figure 4. D-200 Aircraft Footprint as Displayed in FAARFIELD

In figure 5, the blue solid curve is the CDF calculated by the new damage integration method based on equation 8. The red crosses represent the current CDF calculation method. As expected, the two curves exactly coincide for the considered D gear configuration.

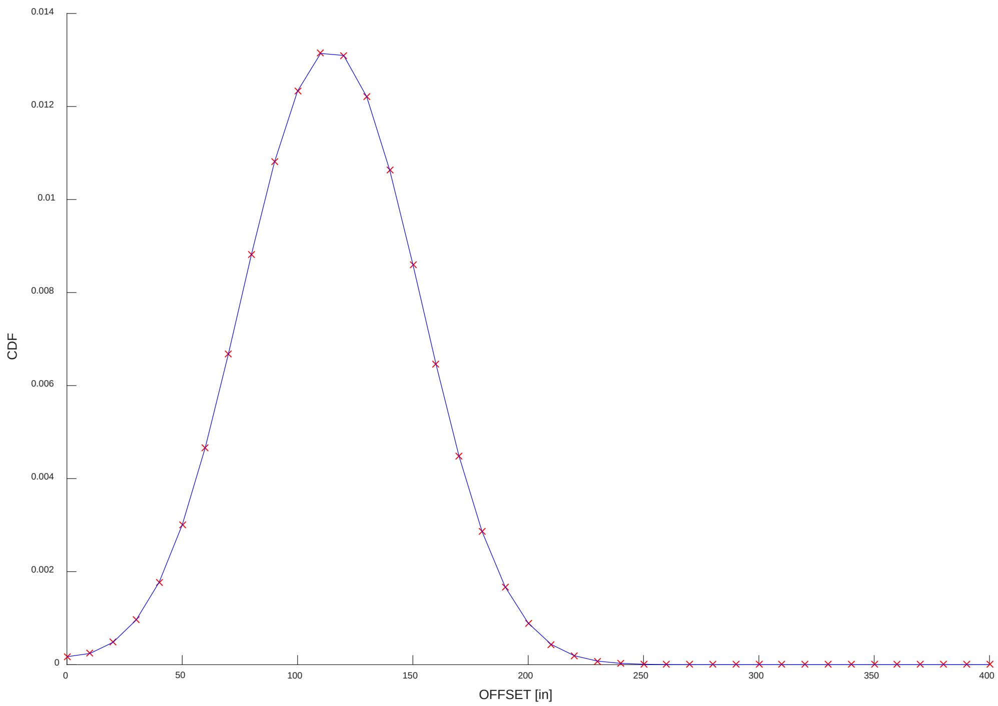


Figure 5. Comparison of CDF for Current and Proposed Methods for D-200 Gear

4.2 2D GEAR CONFIGURATION.

Consider the same structure as in figure 3, but loaded instead by 1200 annual departures of the generic 2D-400 aircraft (400,000 lb gross weight). The 2D-400 gear characteristics are shown in figure 6. In this case, the tandem factor is 2 for the current procedure. The new method automatically takes into account the double peak in strain profile during the integration procedure. The computed CDF curves for the two methods are nearly identical, as shown in figure 7.

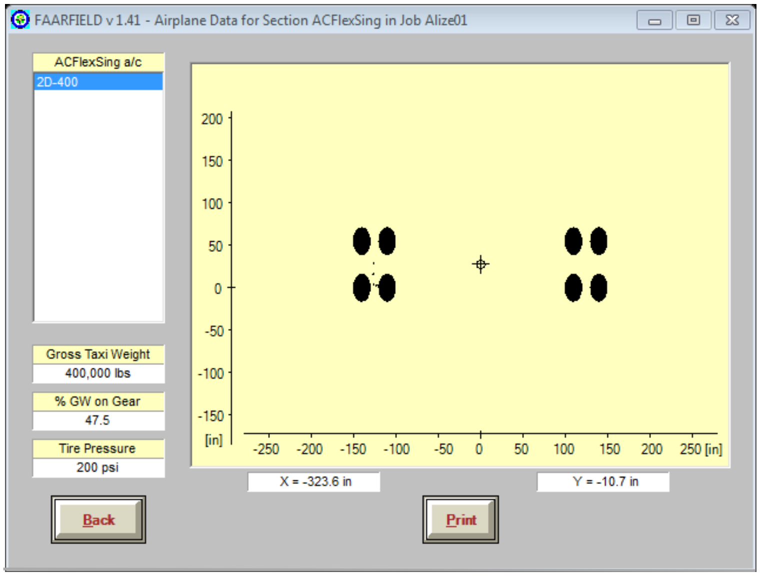


Figure 6. 2D-400 Gear Footprint as Displayed in FAARFIELD

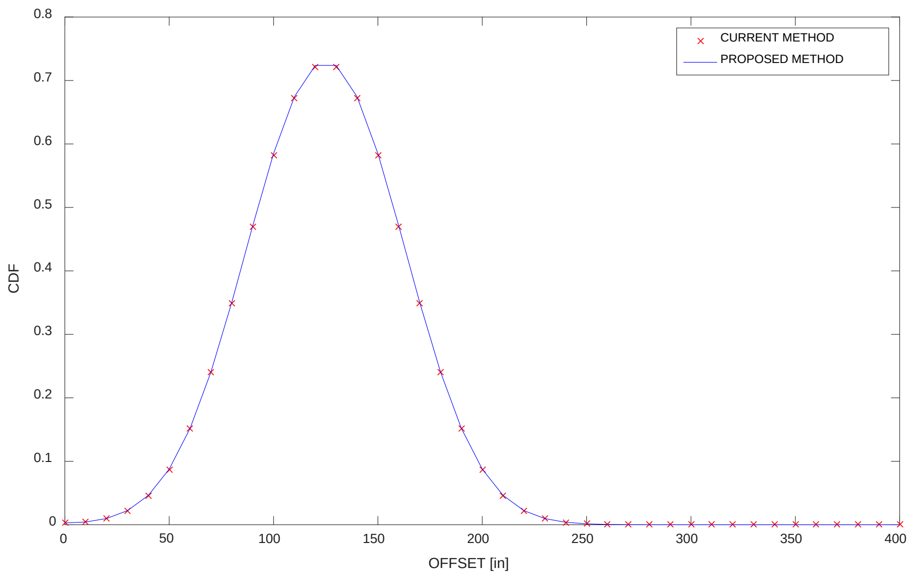


Figure 7. Comparison of CDF for Current and Proposed Methods for 2D-400 Gear

4.3 3D GEAR CONFIGURATION.

Next, consider the same overlay structure as in figure 3, but loaded instead by 1200 annual departures of the 6-wheel (3D) Boeing B777-200ER gear (658,000 lb gross weight). The B777-200ER characteristics are shown in figure 8.

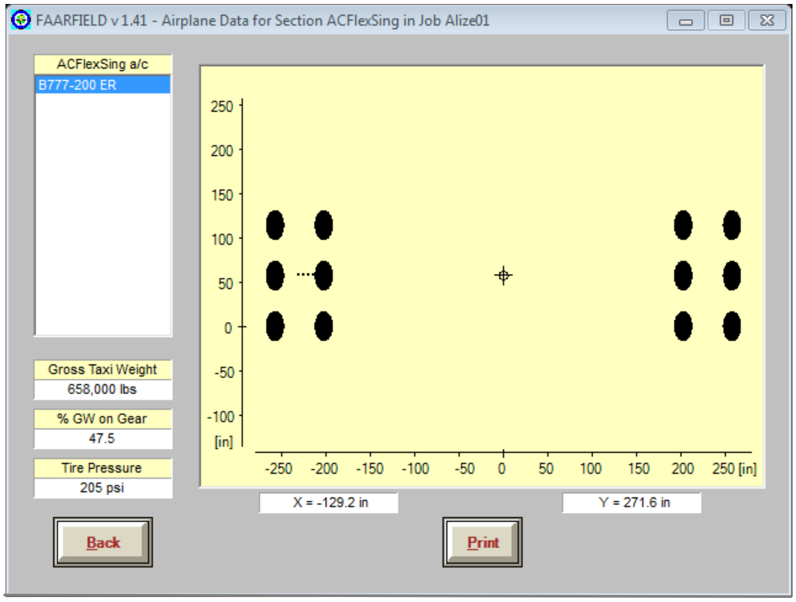


Figure 8. B777-200ER Gear Footprint as Displayed in FAARFIELD

The blue solid curve in figure 9 is the CDF calculated by the proposed damage integration method. The red crosses represent the current CDF calculation method. The difference in CDF curves is explained by the fact that in the considered example, the second and third strain peaks (figure 10) do not start from a negligible level of strain damage. Therefore, the damage contribution caused by passage of the second and third wheels in tandem is not as large as caused by the first wheel. This phenomenon is not taken into account in the current CDF calculation, where the damage for the considered example is simply tripled damage caused by the highest strain peak.

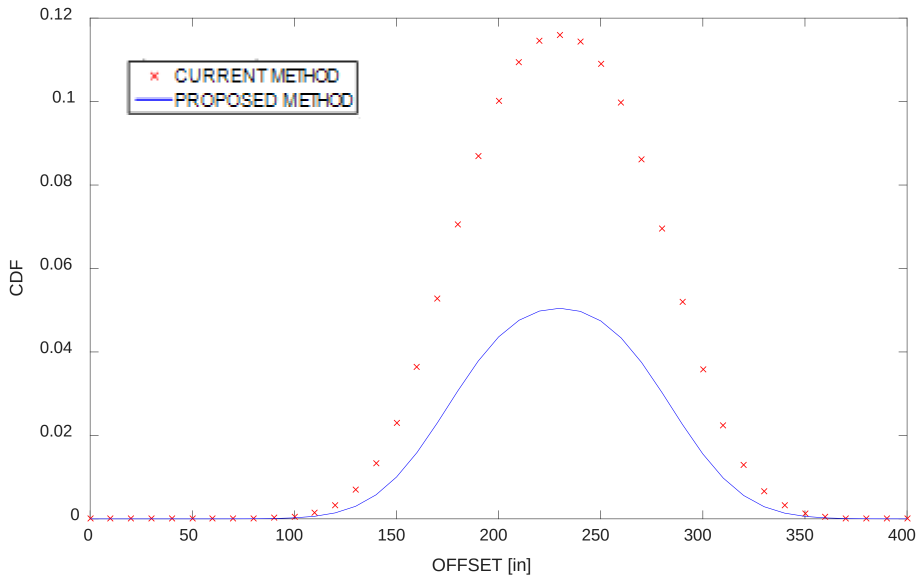


Figure 9. Comparison of CDF for Current and Proposed Methods for B777-300ER

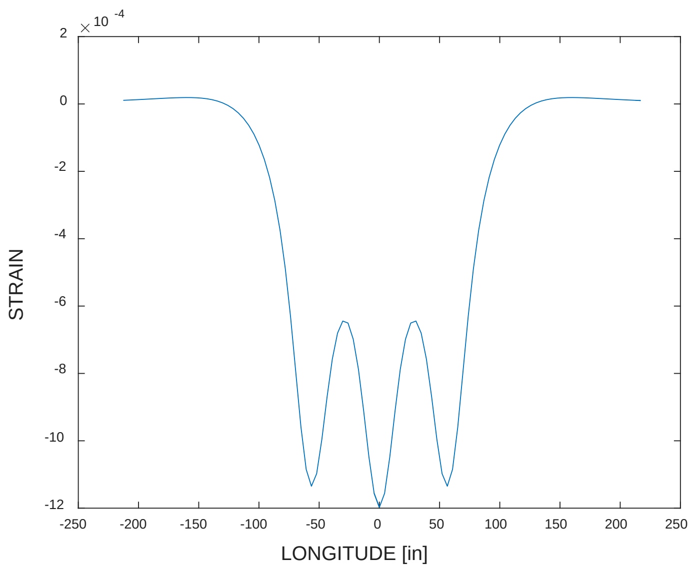
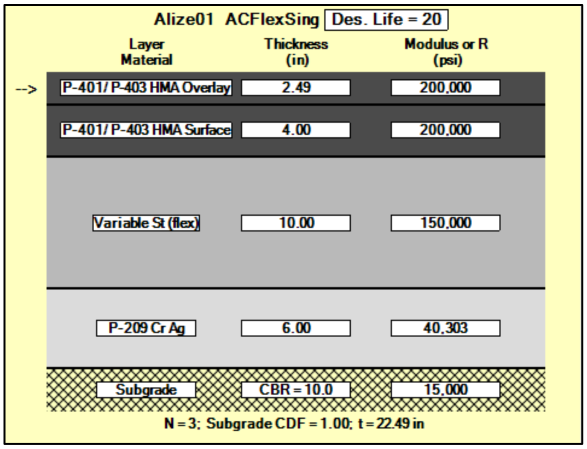
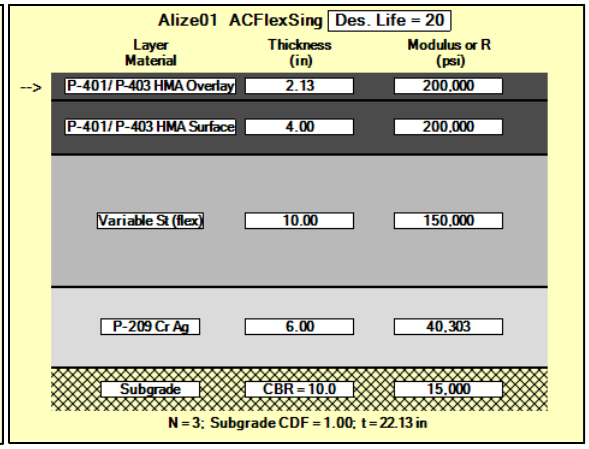


Figure 10. Vertical Strain at Critical Profile, B777-200ER From Example

The difference in computed CDF, as shown in figure 9, leads to a corresponding difference in thickness design results, as shown in figure 11.





(a) Current method with tandem factor (b) Proposed method with damage integration

Figure 11. Comparison of Overlay Thickness Designs for B777-300ER

Figure 11 shows that the overestimation of CDF in the current method leads to a thicker overlay design requirement (2.49 in. versus 2.13 in.).

5. COMPARISONS FOR THE CASE OF DEEP STRUCTURES.

Consider the generic 2D gear load in section 4.2, the new method recovers not only the limit case where the tandem factor would be equal to 2 under the existing method but also the limit case for deep structures, where the tandem factor would be equal to 1, and gives comparable results for intermediate cases.

The following examples compare the current method of computing flexible pavement CDF using the tandem factor with the new method, in which the tandem factor is replaced by integration along the strain profile, for a range of pavement structural thicknesses. The basic structure used for comparisons is shown in figure 12. The depth of structure in these examples is varied by changing the thickness of the stabilized flexible layer. All cases assumed the same traffic, 1200 annual departures of a generic 2D-400 aircraft (figure 6). The graphic comparisons are given in figures 13 through 18. As shown in figures 5, 7, and 9, the computed CDF is plotted as a function of the offset from the centerline. In each figure, the red crosses represent the CDF, as computed using the current (tandem factor) method using the values of the tandem factor given below the figures. For comparison, the blue solid lines represent the CDF computed by the new integration method. Note that for both thin (figure 13) and very thick (figure 18) structures, the two curves exactly coincide for the given 2D gear configuration. For intermediate thicknesses (figures 14-17), the CDF computed by the new method is less than that computed using the tandem factor.

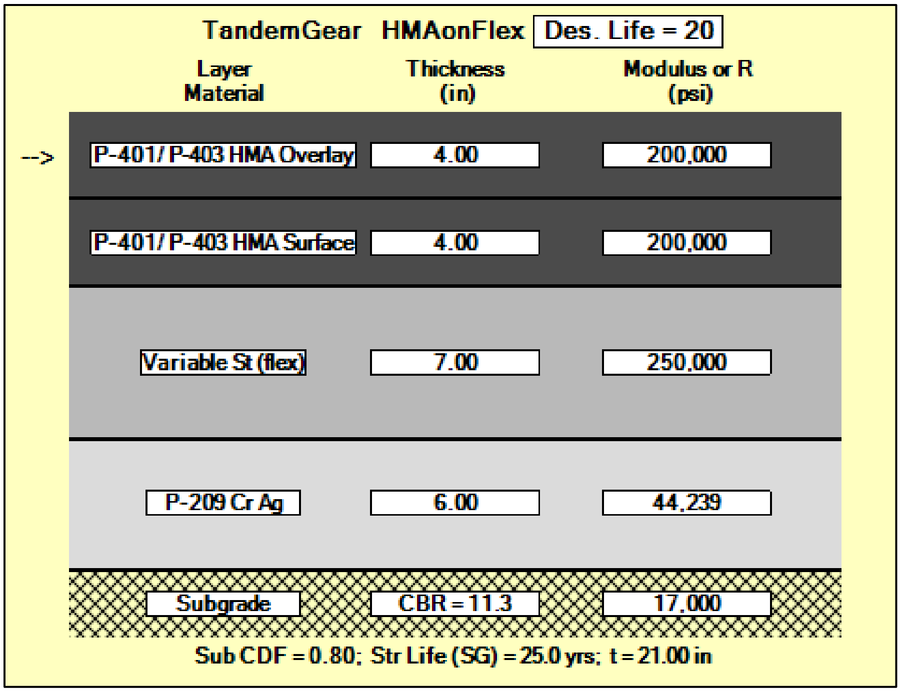


Figure 12. Structure Used for CDF Comparisons for 2D Gears

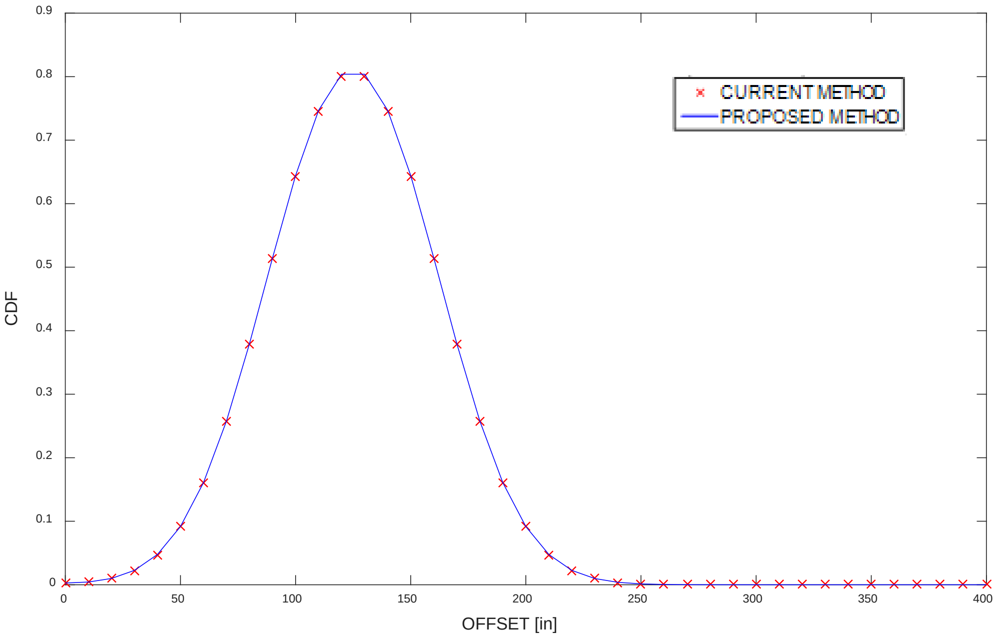


Figure 13. Comparison of CDF for Current and Proposed Methods for 2D-400 Gear, Total Thickness = 21 in., Tandem Factor for FAARFIELD 1.3 = 2.0

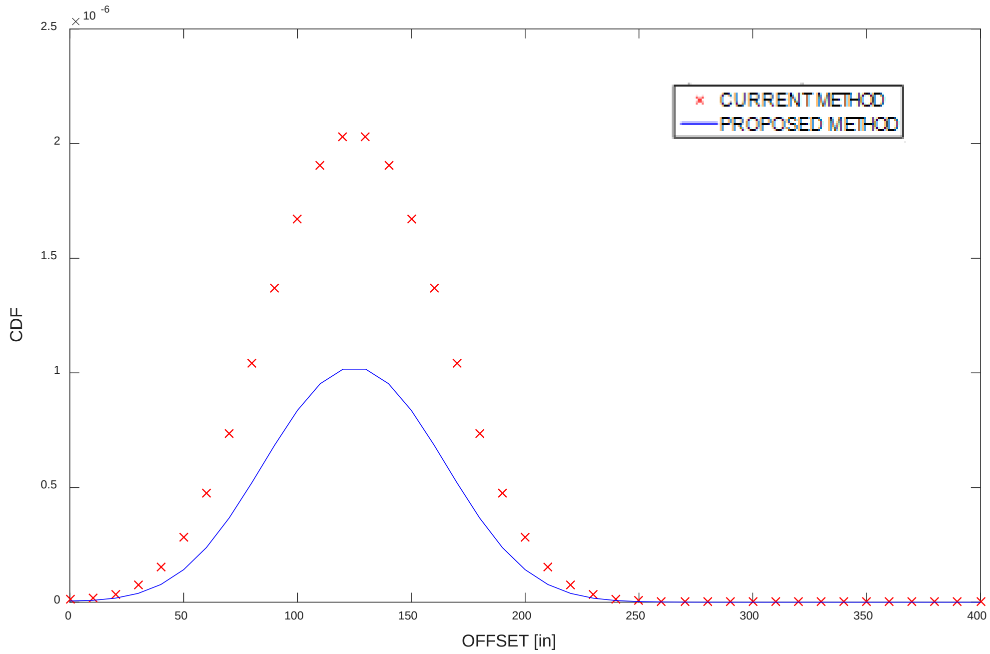


Figure 14. Comparison of CDF for Current and Proposed Methods for 2D-400 Gear, Total Thickness = 31 in., Tandem Factor for FAARFIELD 1.3 = 2.0

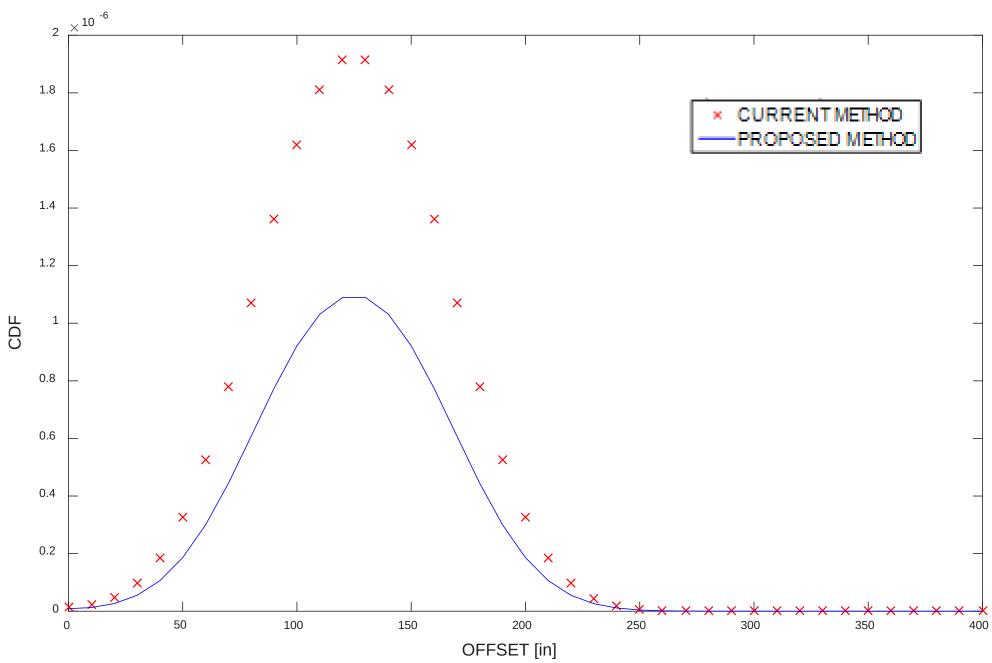


Figure 15. Comparison of CDF for Current and Proposed Methods for 2D-400 Gear, Total Thickness = 41 in., Tandem Factor for FAARFIELD 1.3 = 1.758

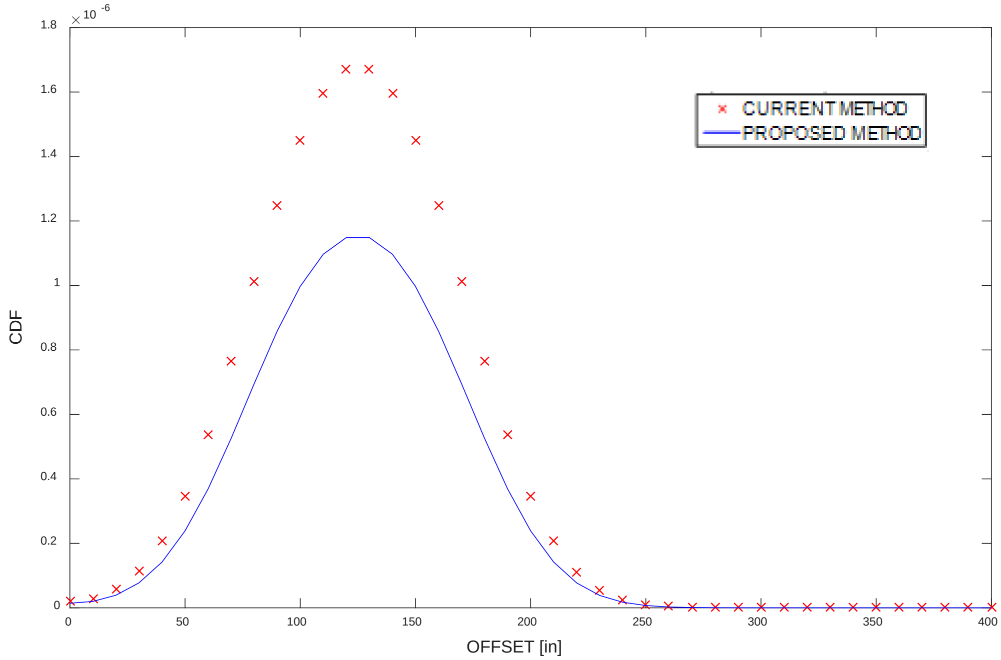


Figure 16. Comparison of CDF for Current and Proposed Methods for 2D-400 Gear, Total Thickness = 51 in., Tandem Factor for FAARFIELD 1.3 = 1.455

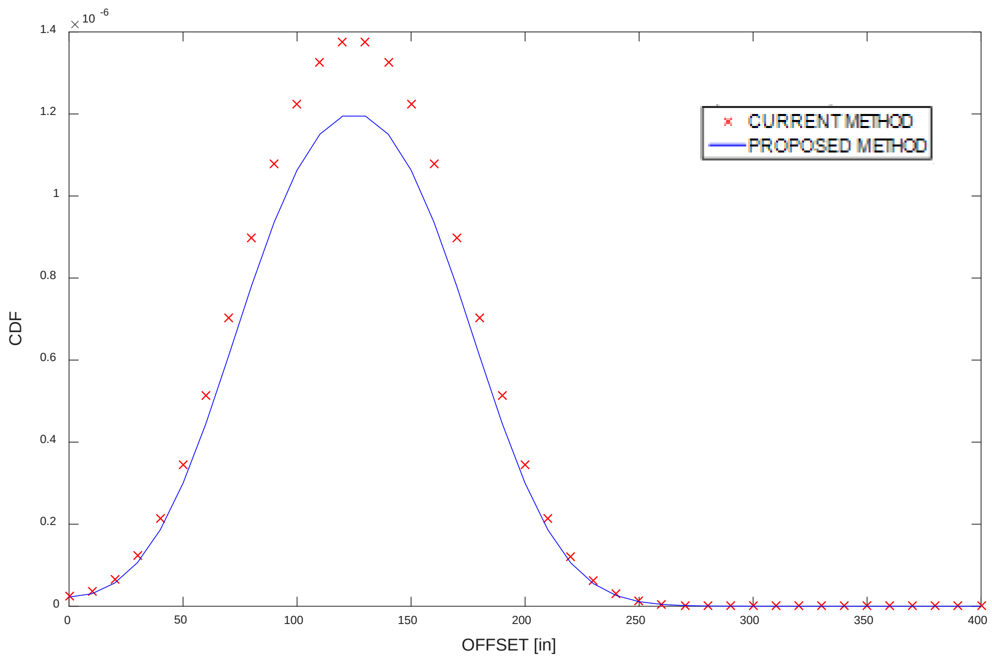


Figure 17. Comparison of CDF for Current and Proposed Methods for 2D-400 Gear, Total Thickness = 61 in., Tandem Factor for FAARFIELD 1.3 = 1.152

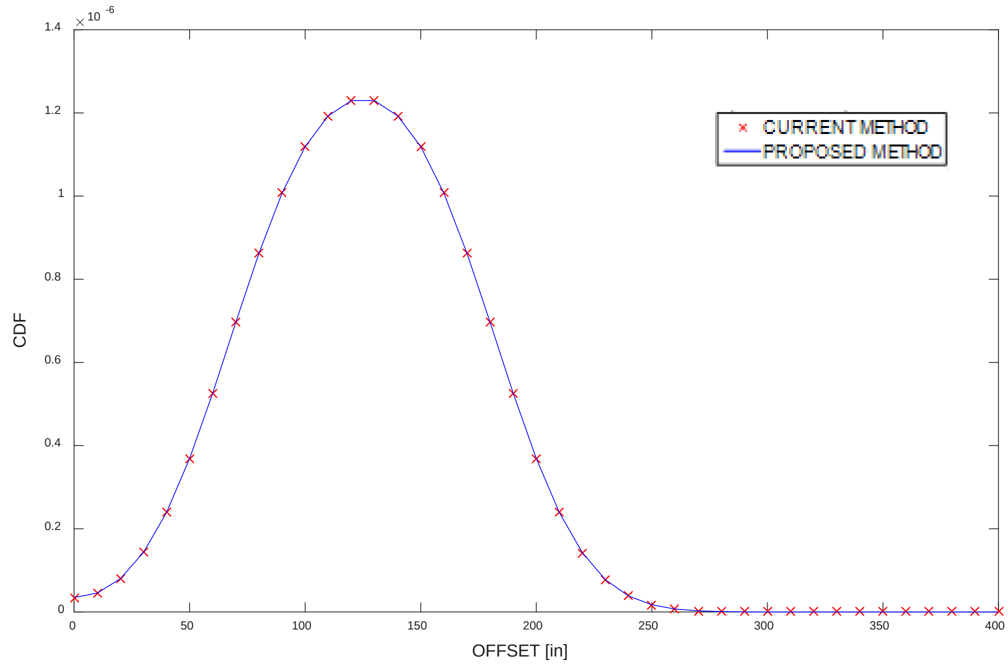


Figure 18. Comparison of CDF for Current and Proposed Methods for 2D-400 Gear, Total Thickness = 71 in., Tandem Factor for FAARFIELD 1.3 = 1.0

6. COMPARISONS WITH CDF FROM ALIZÉ-AIRCRAFT.

A Microsoft® Excel® spreadsheet was provided to the FAA by IFSTTAR [7]. That spreadsheet included an array of evaluation points of the strain integral, the values of vertical strain at those points for a sample evaluation of an Airbus A380 main gear (figure 19), and a macro implementation of the CDF calculation in Alizé-Aircraft design program. The macro attached to the spreadsheet does not determine limits of integration or intervals between evaluation points. The algorithm in the provided macro implements a particular numerical method of integration—namely, the trapezoidal rule for a uniform grid.

It could not be determined from the spreadsheet precisely how the spreadsheet implementation determines integration limits and mesh step increments. However, based on an examination of figure 19, and on further information obtained from IFSTTAR [8], the limits of integration were chosen at longitudinal coordinates 79 in. (2 m) beyond the gear limits, at which distance strains become negligibly small with respect to their maximum values. Furthermore, the interval between integration points is taken as 1.8 in. (4.5 cm).

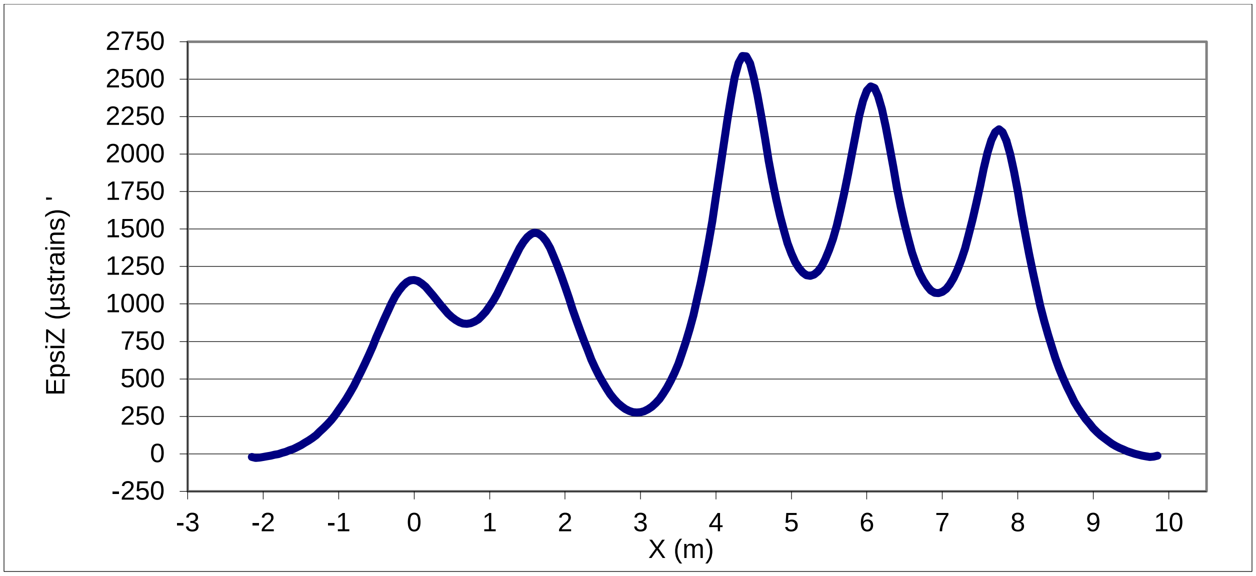


Figure 19. Alizé-Aircraft-Generated Vertical Strain Profile [7]

To compare the new FAARFIELD CDF calculation method with the method used by Alizé-Aircraft, the following Visual Basic code was written and added to the Alizé-Aircraft-produced spreadsheet, shown in figure 20.

```
Public Function fminerintegralK() As Double 'kairat
Dim sigma1, sigma2, totaldamage, damage1, damage2 As Double
Dim j1, toto As Integer

sigma1 = 0
damage1 = 0
totaldamage = 0
'-----
For j1 = 2 To nbpoint - 1

damage2 = 0

If stress(j1 - 1) < stress(j1) And stress(j1) > stress(j1 + 1) Then ' Maximum
sigma2 = stress(j1)
damage2 = 1 / faafailure1_4(sigma2)
End If

If stress(j1 - 1) > stress(j1) And stress(j1) < stress(j1 + 1) Then ' Minimum
sigma2 = stress(j1)
damage2 = -1 / faafailure1_4(sigma2)
End If

totaldamage = totaldamage + damage2
Next j1

fminerintegralK = totaldamage
'----
End Function
```

Figure 20. Visual Basic Code Added to the Alizé-Aircraft-Produced Spreadsheet

This macro function code is just an adaptation for Microsoft® Excel® of the new FAARFIELD CDF calculation, as expressed in equation 8. The result of calculation using the FAARFIELD method coincides with the trapezoidal rule adopted in the Alizé-Aircraft program. In both cases, for the example profile in figure 17, the computed damage is equal to 0.04700, as shown in figure 21.

	A	B	C	D	E
1	**JM. Balay (Ifsttar) to David Brill (Faa)**				
2	October 23, 2014				
3	The Miner continous integration of damages as implemented in th Alize-Lcpc soft				
4	See the VBA macro linked to this Excel worksheet				
5					
6	Example of computation				
7	For this example, Alize-Lcpc software gives : Damage= 0.0470012				
8	Vertical strain profile at top of subgrade (example)				
9	X (m)	EpsiZ (µstrains)			
10	-2.15	-20.45123		Result :	
11	-2.1	-27.10757		From line no :	10
12	-2.05	-24.26565		to line no :	250
13	-2	-20.81258		**Total damage =**	0.047001202
14	-1.95	-16.79713		FF damage=	0.047001202
15	-1.9	-12.18735			

Figure 21. Alizé-Aircraft CDF vs Proposed CDF Method (denoted as FF Damage) [8]

The damage integration method based on equation 8 requires less computational effort than the full trapezoidal integration method presented for Alizé-Aircraft, since equation 8 calculates integrand values only at extremum strain points. However, it should be noted that for simpler applications (i.e., those following Miner's Law), Alizé-Aircraft does implement a simplified (and faster) numerical integration function essentially equivalent to equation 8.

7. CONCLUSIONS.

A new method of accounting for the influence of multiple aircraft wheels in tandem in flexible pavement thickness design has been implemented and tested in the Federal Aviation Administration (FAA) computer program, FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD). The proposed method avoids the use of tandem gear multipliers on the pass-to-coverage ratio, and computes cumulative damage factor (CDF) directly by integration of the subgrade linear elastic strain profile. The proposed method is similar in concept and produces results similar to Alizé-Aircraft, the French pavement thickness design program. Comparisons between the existing and proposed methods in FAARFIELD show no differences for very deep and for very shallow flexible pavement structures, and a reduction in computed CDF for medium-thickness structures using the new approach.

8. REFERENCES.

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7. Email communication from Balay, Jean-Maurice, Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (IFSTTAR) to David Brill, FAA, October 23, 2014.

8. Email communication from Balay, Jean-Maurice, IFSTTAR, to David Brill, FAA, May 11, 2016.