A new mechanistic design procedure for flexible airfield pavements

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Abstract

Empiricalbased approaches for pavement design have shown their limitations, particularly as far as material characterization and landing gear consideration are concerned. The current trend is to move towards new design methods based on mechanistic approaches. Such a method has been used for highway pavement design for more than 30 years in France, and as regard to airfield pavements, the French Technical Service of Civil Aviation released its new design procedure for flexible pavements in 2013. This procedure includes an accurate description of the pavement structure and the loadings through various parameters, which makes itbeing an optimizing tool for pavement designs. The main point of interest of this paper consists of a description of the different steps of the calculation process involved in this new procedure. The proposed description is illustrated by the implementation of a basic pavement design example.
A long-term improvement of this design procedure will be proposed in the future using experimentations and user's feedback.

*Keywords:*Pavement design; asphalt material; fatigue law; damage.

Résumé

Les méthodes de dimensionnement des chausséesbaséessur des principesempiriquesontmontréleurslimites, en particulieren ce qui concerne la caractérisation des matériauxainsique la considération des nouvelles configurations de trains d'atterrissage. La tendanceactuelleest à l'utilisation de nouvellesméthodesbaséessur des approchesmécanistiques ; de tellesméthodessontappliquéesdans le domaineroutierdepuis plus de 30 ans en France.Pour les chausséesaéronautiques, le Service Technique de l'AviationCivile a développéetmis à disposition uneméthodebaséesurcesprincipes en 2013. La procédureintègreune description précise de la structure de chausséeet des chargements à l'aide de différentsparamètres, ce qui permetune optimisation des dimensionnements. Cet article a pour but principal de décrire les différentesétapes de calculimplémentéesdanscette nouvelle méthode ;cette description estillustréepar un exempled'application.
Le perfectionnement à long terme de cetteprocédure de dimensionnement sera proposéedans le futur à l'aided'expérimentationsainsiqu'aurecueil de différents retours d'expérience.

*Mots-clé:*Dimensionnement de chaussée ; matériaux bitumineux ; loi de fatigue ; dommage.

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Nomenclature

E	Young's modulus
ν	Poisson's ratio
h	Thickness of a layer
f	Frequency of loading
V	Speed of aircraft
Mrw	Maximum ramp weight
Mlw	Maximum landing weight
S_{bal}	Standard deviation of the lateral wander distribution
$RESWL$	Rational equivalent single wheel load
ε_t	Horizontal strain at the bottom of the base layer
ε_{zz}	Vertical strain at the top of the subgrade
$s_{\max}$	Maximum amplitude of the strain
N	Number of cycles to failure
K	Fatigue law parameter
β	Fatigue law parameter
ΔD	Elementary damage

1. Introduction

The former French design methodology for flexible airfield pavement was based on the empirical CBR (California Bearing Ratio) approach, initially developed by the US Corps of Engineers. The limitations of thishistoric method are widely recognized today. Among other limits, one main deficiency is due to the equivalent thickness concept related to the CBR approach. This concept is not appropriate for characterisinginnovative high-performance materials and to account for the relatively frequent use of cement treated capping layers. Another restriction is the use of the empirical equivalent single load concept, inappropriate for modelling new types of aircraft landing gears (e.g. Boeing 777 or Airbus 380).

In order to improve the design of airfield pavements, the French Civil Aviation Technical Centre (STAC) and the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) launched a research program aiming at working out a new method for structural design of airfield pavements. The result of this program is a design manual which is now available on the STAC's website (www.stac.aviation-civile.gouv.fr) (STAC, 2014). This new design method is mainly based on the application to airfield structures of the French rational design method for roads and highways used since more than thirty years, with the release of the first version of the Alize-LCPC software (Alize-Lcpc, 2001). Despite its mechanistic nature, the rational pavement design approach also has strong empirical aspects and needs to be calibrated and evaluated by means of experimentations and feedback from real pavement. The AIRBUS full-scale tests on flexible and rigid pavement (STAC, 2001), (Fabre et al, 2003) performed between 1998 and 2003 atToulouse-Blagnac airport by AIRBUS in partnership with IFSTTAR and STAC significantly contributed to the development of a wide experimental database. These full-scale data were essential for the development of the new design method, which is now implemented in the dedicated software "Alize-Airfield Pavement".

A presentation of this design methodology is proposed in this paper. The first part describes the computation process used for assessing the resilient strains and stresses induced by the traffic mix on the pavement structure. Secondly, a presentation of the damage calculation process including various parameters such as lateral wandering of aircrafts is shown. The design methodology is then implemented on a real case, the results of which are presented in the last paragraph.

2. Calculation of the resilient strains/stresses

2.1. Theoretical approach

Several approaches are available in the literature in order to assess the distribution of strains and stresses in a multi-layer pavement structure subjected to loads on its surface (Boussinesq, Westergaard, finite elements…). This newdesign procedure is based on the theoretical analysis of pavement using the Burmister model (1943). The pavement structure is represented as a multilayered semi-infinite linear elastic model (figure 1). Each layer is characterized by a modulus value E which depends on the temperature and the loading frequency, and a Poisson's ratio ν with a fixed value of 0.35 (quite representative of the pavement material to a first approximation).

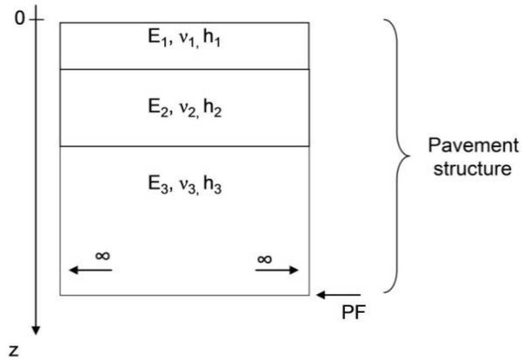


Figure 1: Description of the pavement structure

The calculation of strains and stresses in the pavement are performed with a static load. Thus, dynamic effects such as stress rotationare not considered. However, the speed of aircrafts is an input parameter of the methodology, which allows adjusting the modulus value of asphalt materials accordingly using typical susceptibility curves. Indeed, moduli values of visco-elastic materials are very much dependent on the frequency of loading applied. So as to assess the frequency of loading f in the asphalt pavement from the speed of the aircraft V, the following rule applies:

$$f\left(Hz\right)=\frac{V\left(km/h\right)}{10} \quad (1)$$

It is important to mention that this is a simplified relationship which should theoretically take into account the load spreading pattern in the pavement as well as a specific depth in the pavement. However, it is considered as representative of airfield pavement structures as a first approximation.

Three types of section are considered in the methodology, corresponding to a defined speed, as shown in table 1 and figure 2.

Table 1. Design speeds for the three types of section

Pavement section	Speed considered (km/h)
High speed sections (runway)	100
Intermediate speed sections (taxiways)	30
Low speed sections (aprons)	10

For low speed sections, the selected calculation speed is 10 km/h (corresponding to 1 Hz) whereas aircrafts are static on these sections. This would otherwise lead to consider a frequency of loading equal to zero, which is not adapted to the calculation process. However, the design procedure requires a "static" verification on these sections, which is not detailed in this paper.

The temperature selected for computations (called "equivalent temperature") is an important parameter which may be set accordingly to the climate. This equivalent temperature is defined as the constant temperature for which the damage value in the pavement is identical to that obtained with the monthly averaged temperature distribution. Recommendations are provided in the STAC's design manual (STAC, 2014) for typical climate types (e.g. 15°C for France).

2.2. Traffic description

A major improvement has been made in this design procedure compared to the empirical CBR based one for which the equivalent single wheel load was used. A much more complete description of landing gears is now proposed. Every single load of every landing gear is modelled as a circular contact area on which a uniform vertical pressure is applied (figure 2). The pressure magnitude is assimilated to the tire pressure, which is a fairly good description as a first approximation. The radius of the circular contact area is determined easily knowing the load on each wheel as well as the tire pressure. All these data are listed in the STAC aircraft characteristic database, namely Ficav, updated in 2013.

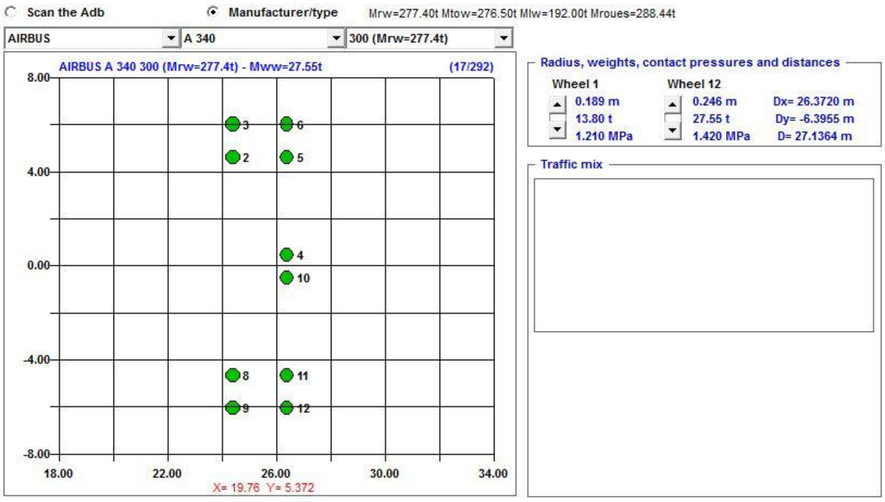


Figure 2: Description of landing gear loads

The other necessary traffic data include the design period, which is set to 10 year by default for flexible pavements, the number of passes for each aircraft and their weight. It is important to mention that aircraft weights are parameters which have an important impact on the design results. This is the reason why the new design procedure requires, if possible, to distinguish take-offs and landings so as to adjust the aircraft weight accordingly (Maximum ramp weigh – Mrw – used for take-offs, maximum landing weights – Mlw – used for landings, unless more accurate data is available).

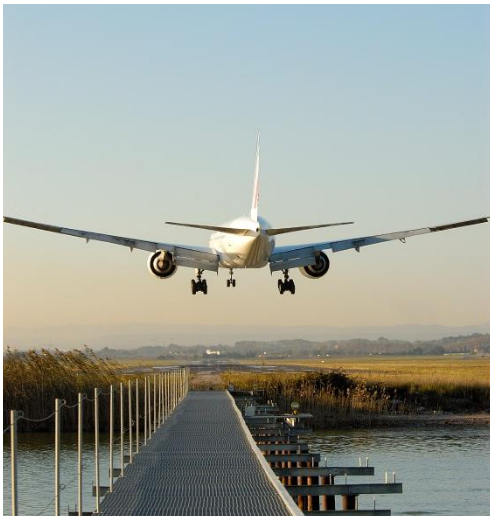


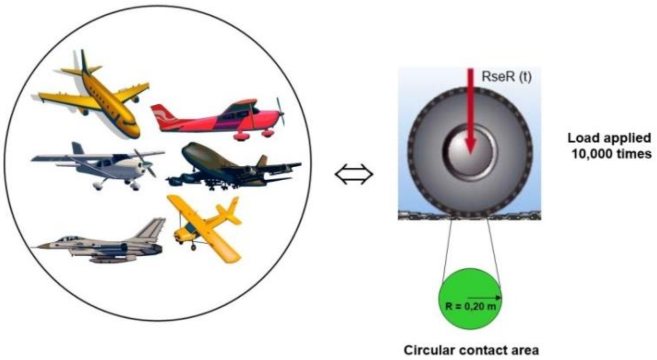
Figure 3: Illustration of lateral wander

The description of the traffic mix takes another parameter into account:the lateral wander,which is illustrated in figure 3. The consideration of this parameter allows modelling the lateral offset from the pavement axis of aircrafts on the pavement structure. Indeed, lateral wander implies the reduction of the number of coverages applied at a specific location in the pavement since these coverages are distributed laterally.Lateral wander is characterised by a parameter S_{bal} used for the pavement design whose definition is detailed in paragraph 3. Its value depends on the pavement section considered, and the following recommendations are provided in the design manual (table 2 below).

Table 2.Lateral wander parameter for the three types of section

Pavement section	S_{bal} (m)
High speed sections (runway)	0.75
Intermediate speed sections (taxiways)	0.5
Low speed sections (aprons)	0

The aggressiveness of the loads induced by the traffic mix is a global parameter which is tricky to be determined, but which has major effects on the pavement thickness design. A classification is proposed in the "Guide to the application of standards" (STAC, 2009), taking into account the aircraft tire pressure, number of wheels on the main landing gear, and number of passes, allows determining a "Traffic Class" (from 1 for low traffic to 5 for high traffic). However, with this new design procedure based on multi-layered elastic theory, it was possible to define a new parameter called the rational equivalent single wheel load (RESWL) using damage equivalency. This parameter is defined as the single wheel load applied 10,000 times on the pavement structure (contact pressure = 1.5 MPa) giving the same asphalt damage as the whole traffic mix (figure 4).



This RESWL is used in the design method as a parameter for the calibration of the procedure. This will be detailed in paragraph 3.

Figure 4: Definition of the rational equivalent single wheel load (RESWL)

2.3. Strain/Stress calculation

Calculation of strains and stresses in the pavement are performed at several critical locations corresponding to the two modes of failure considered in the design process. These two modes of failure are the fatigue of asphalt mixes, characterised by the tensile strain at the bottom of the base layer (ε_t), and the permanent deformation (subgrade failure) characterised by the vertical strain at the top of the subgrade (ε_{zz}).

Therefore, evaluation of the strain distribution are performed at these two locations on horizontal planes, at each node $P(x_i, y_j, z_k)$ of a grid defined by Δx and Δy (figure 5).

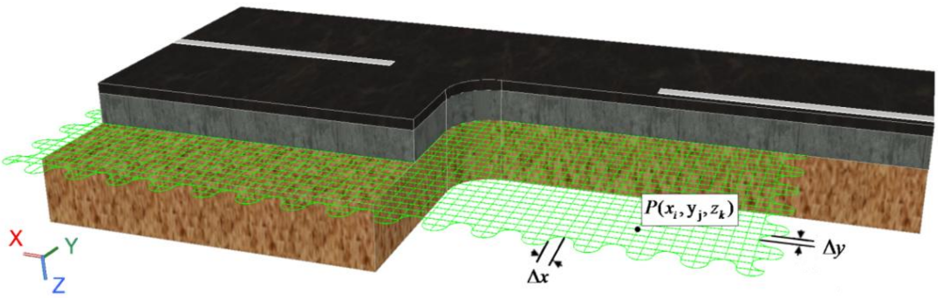


Figure 5 : Definition of the calculation grid

An example of results of such calculations are shown in figure 6 for the aircraft defined in figure 2, and for the fatigue tensile strain ε_t. Due to the symmetry of landing gears, calculations are performed only one side of the aircraft longitudinal axis.

The next step of the design procedure is the assessment of the damage for the two design criterion due to the whole traffic mix which is done from these strain calculation.

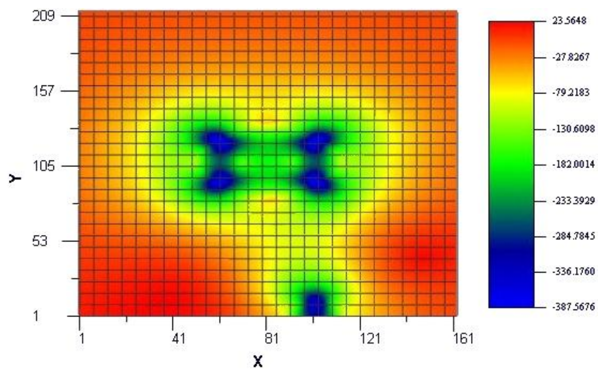


Figure 6: Example of fatigue tensile strain calculation for an A330-300 aircraft

3. Evaluation of the damage

A damage parameter is introduced in the pavement design process and it allows comparing the allowable strains in the pavement due to the structure "strength" to the actual traffic mix induced strains. Those are computed in several steps, with the consideration of two physical phenomena: the consecutive effects of the moving wheels of the landing gear (for multiple wheel landing gear), and the lateral wandering, which are detailed in the following paragraphs. Firstly, the basic damage calculation process is presented.

3.1. Damage law – Elementary damage

The classical Wöhler damage law is used in this procedure for both design criteria. It relates the actual maximum strain level $(s_{\max})$ to the number of cycles to failure (N). $s_{\max}$ is equal to ε_t for fatigue damage, and to ε_{zz} for permanent deformation damage.

$$N(s_{\max}) = \left(\frac{K}{s_{\max}}\right)^{\beta} \tag{2}$$

where β and K are the damage parameters, detailed below for asphalt materials and granular materials.
The elementary damage is defined as a fraction of the number of cycles to failure, and one pass of an aircraft creating a strain level $\varepsilon_{\max}$ at a particular location in the pavement contributes to a damage value of:

$$\Delta D = \frac{1}{N(\varepsilon_{\max})} = \left(\frac{\varepsilon_{\max}}{K}\right)^{\beta} \tag{3}$$

Damage values are then added using Miner's law. A damage of 1 means the pavement is failed.

- Damage parameters for asphalt materials

It is important to note that relation (2) is partially calibrated from laboratory tests for asphalt materials, for which the maximum strain level and the number of cycles to failure are defined in the test procedure (50% decrease of the modulus for the failure). It is considered that this formalism is extendable to pavement structure models as defined in paragraph 2.
Laboratory tests database allow setting the coefficient β equal to 5. As for the coefficient K, it is expressed as follows:

$$K = 10^{6/\beta} k_{\theta f}\, k_S\, k_r k_c \bar{\varepsilon}_6 \tag{4}$$

with $\bar{\varepsilon}_6$ the strain level for 10^6cycles (for the fatigue test) at 25 Hz/10°C, $k_{\theta f}$ a temperature and frequency parameter, k_S a parameter taking into account the heterogeneity of the subgrade bearing capacity, k_r linked to probabilistic aspects (fatigue test results scattering and pavement base layer thicknessvariability).

As for the k_c coefficient, it is a calibrating factor taking into account the differences between field observation and theoretical description. Its value is function of the traffic aggressiveness, defined by the RESWL. Figure 7 shows the variation of this parameter.
Values of k_c for low RESWL are calibrated so as to match with that of the highway design procedure. As for high RESWL, experimental results from the two research programs "Pavement Experimental Program"(STAC, 2001) and "High Tire Pressure Test" (STAC, 2011) were used, among others, to calibrate this coefficient.

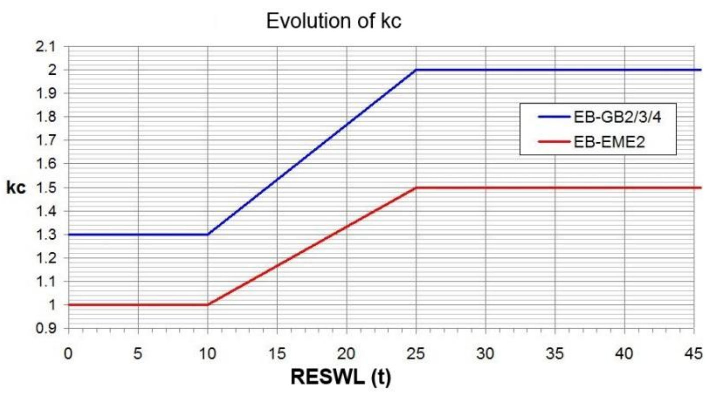


Figure 7: Evolution of the calibration factor k_c

- Damage parameters for granular materials

Contrarily to asphalt materials, damage parameters do not come from laboratory tests, but are the results of observations of many pavement sections, highways or airfield pavements at a lower extend. The damage parameters are equal to:

$$K = 16000 \text{ and } \beta = 4.5 \quad (5)$$

3.2. Continuous integration of Miner's rule

Damages induced in the pavement structure by the traffic mix are cumulated using Miner's rule, and take into account the strain amplitudes associated to each aircraft. Also, an improvement was made to this calculation process for the consideration of complex landing gears. For a particular longitudinal profile of the pavement structure, the strain history (all the strains values undergone by a pavement element) is used to compute the damage. This is illustrated by the longitudinal profile in figure 8. The "peak" strain values are counted as a positive damage whereas the "trough" strain values are counted negatively.

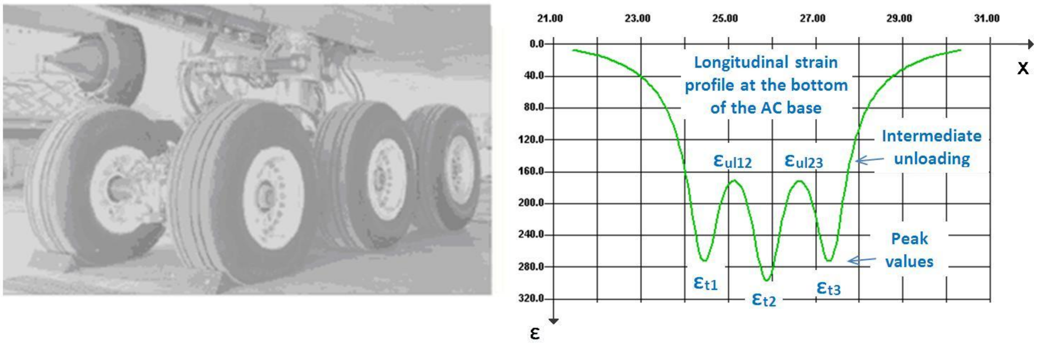


Figure 8: Illustration of the continuous integration of Miner's rule

The continuous integration of Miner's rule is the mathematical integration of a longitudinal strain profile used to determine the damage of the whole landing gear, and not only that calculated with the unique maximum strain value. More detail about this may be found in the STAC's new pavement design manual.

3.3. Lateral wander consideration

With the implementation of the continuous integration of Miner's rule, the damage calculation without wandering effect can be computed. This last calculation step enables considering wandering effect.
The parameter S_{bal} , part of the traffic description, is the actual standard deviation of the lateral aircraft position distribution relative to the pavement axis. This distribution is assumed to be Gaussian, and centred. Figure 9 shows the distribution as well as landing gear positions and damage calculation principle.

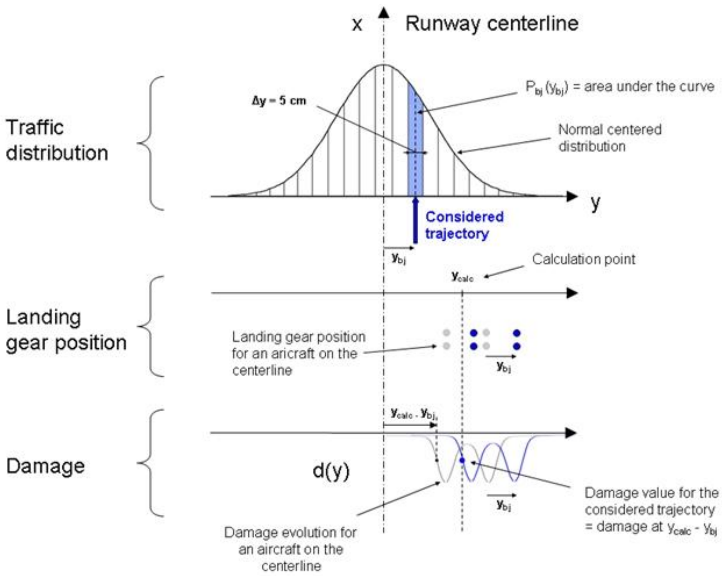


Figure 9: Consideration of lateral wandering for damage calculation

For a considered trajectory of calculation, corresponding to a lateral position on the pavement, the damage calculation result of the aircraft passing on every "real" trajectory from the distribution is used. All these damages are weighted by coefficients equal to the area between two calculation trajectories (in blue on figure 9), and then summed. This gives the damage value with wandering. More detail may also be found in the new STAC's pavement design manual.

4. Implementation of the procedure

The different steps of the flexible pavement design procedure were presented in the last two paragraphs. This paragraph shows an example of calculation based on real data from a taxiway of a large airport in France. The computations are not performed "by hand", but with the dedicated pavement design software Alizé-Airfield Pavement.

4.1. Design inputs

The aim is to design over a period of 10 years the thickness of the pavement's layers for the traffic forecast as shown in figure 10.

Other traffic data, design life, wandering and frequency

Title: **no name**

Design life of the pavement (years): 10.00

Aircraft of the traffic mix	Mass (t)		Aircraft passes Number	Units	Ta(%)	Cumulated traffic	Wandering (m)	Speed (km/h)	Equivalent temperature Option	TetaEq
1-AIRBUS A 320 100 (Mrw=68.4t)	Mrw	68.400	12792	Passes/year	0.00	127 920	1.00	30.0	Teq	15.00
2-AIRBUS A 321 200 (Mrw=93.4t)	Mrw	93.400	4888	Passes/year	0.00	48 880	1.00	30.0	Teq	15.00

Figure 10: Traffic data

The pavement section to be designed is a taxiway, which means that a speed of 30 km/h and a wandering parameter of twice the standard deviation ($2 \times S_{bal} = 1\ m$) are selected.

The equivalent temperature is set to 15°C since no more accurate data are available.

Also, both aircraft of the traffic mix are considered as take-offs because the proportion of take-offs/landings are not known. Therefore, the weights used are the Maximum Ramp Weights.

The soil investigations lead to use a pavement foundation with rigidity properties of $E = 80\,MPa$.

4.2. Calculation

An initial pavement structure is selected so as to define the type of materials to use, and in order to do the first damage calculation. If the damage is higher than 1, the thickness of the designed layer (subbase layer in this case) is increased; if it is lower than 1, the thickness is decreased. An iterative process enables repeating these calculations automatically until the damage reaches 1 by lower value. The pavement design is then optimised. The global results of the calculation for the taxiway considered are shown in figure 11 below.

Display the pavement structure

Titre : **AC flexible pavement - Mf1 template**

Interface	thick. (m)	Young (MPa)	Nu	Material type	Design criterion	Risk (%)	Sig6 or Epsi6 or A	-1/b	SH	SN	Kr	1/Ks	1/Kd	Kc
	0.06	f(T,F)	0.350	eb-bbsg3										
bonded	0.14	f(T,F)	0.350	eb-eme2	EpsilonT-inf	2.5	130.0	5.0	0.022	0.25	0.740	1.0		f(RseR)
bonded	0.044	600	0.350	gnt1										
bonded	0.25	240	0.350	gnt1										
bonded	infinite	80	0.350	subgrade	EpsilonZ-sup		16000	-0.222						

Hgnt= 0.294 m   Gnt1/Gnt1

Restore initial thicknesses   Restore standard values of the Material library

Memo-results | K Details | Initial thicknesses | Library values

Figure 11: Design results

A subbase layer thickness of 24 cm made of granular material GNT category 1 is obtained. Surface and base layers are made of asphalt material BBSG3 and EME2 respectively.
In order to go a bit more into detail of this calculation, a "unique calculation" mode is proposed.

Figure 12 below shows the damage profiles for both design criteria, (a) with lateral wandering effect and (b) without lateral wandering effect.

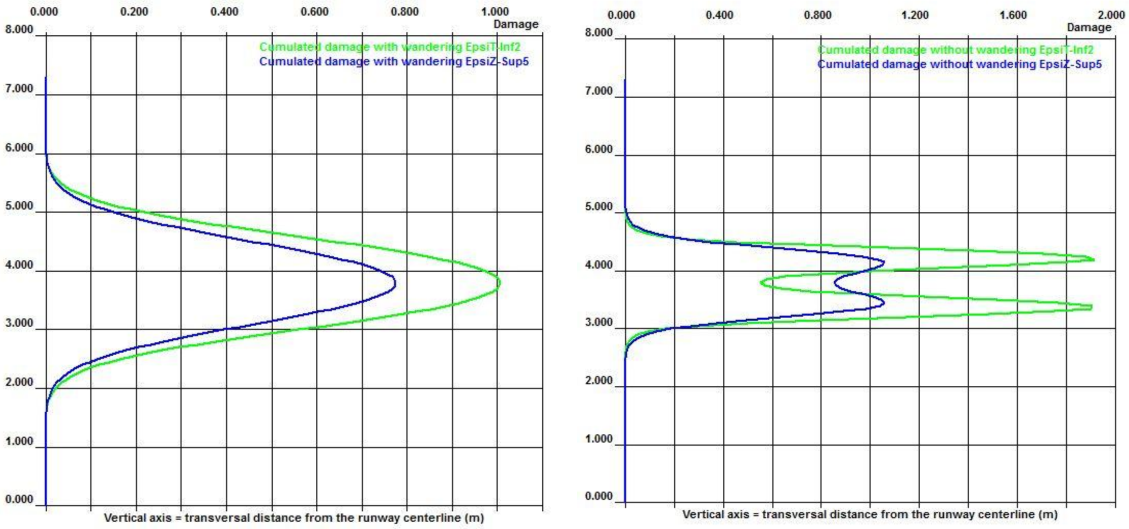


Figure 12: (a) Damage profile with wandering; (b) Damage profile without wandering

The profile without wandering allows seeing the wheel paths of the aircrafts. Since the two aircrafts of the traffic mix have exactly the same landing gear configuration, the traffic is very much channelized.

5. Conclusion

In this paper, a description of the new airfield pavement design method is proposed, along with an implementation on a case study. The improvements compared to the CBR based procedure are quite significant, and allow detailed landing gear configurations. The pavement structure is described with a rational model with the subgrade modulus as the bearing capacity parameter, which is more appropriated than the CBR value.

The damage model, based on the traditional Wöhler approach, is quite interesting in the fact that there is a rational consideration of lateral wandering as well as landing gearmulti-pic effect due to the successive passes of each wheel added to it. This overcomes the main drawbacks of the previous empirical design method, which is greatly appreciable.

In addition, the use of the new design method is more flexible than the CBR based one in the sense that it is very easily adaptable to future evolutions (new materials, new aircraft landing gear configurations). Also, since the materials are characterized by fundamental properties, this new method may be used in every country whatever the standard materials.

Finally, future research is being led from this design methodology to be applied to rigid pavements, but also to develop rational ACNs and PCNs.

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