ФИЗИЧЕСКИЕ НАУКИ

УДК 537.9
DOI 10.25587/2222-5404-2024-21-4-45-55

Numerical analysis of flexible airfield pavements behaviour submitted by large aircraft: influence of the position and configuration of the landing gear

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Abstract. Finite Element numerical program applied to the airfield pavement behavior to determine the damage mechanisms of pavement structures under high intensity loads and to determine the critical response has been investigated. This investigation on airfield pavements confirms that six-wheels bogies for aircraft or tridem axles of heavy weights on road pavement mainly create longitudinal cracking due to the maximum transverse strains, while four-wheels bogie for aircraft or tandem axles mainly create transverse cracking due to the maximum longitudinal strains such as in road pavements. The modelling was based on quasi-static comparisons of landing gear configurations. These analyses provided data on the effects of interference when changing the distance between wheels or supports, comparisons between different landing gear configurations of the A340, B777 and their main competitors. A multi-layer linear model is proposed considering the design of flexible pavement, which will be more rational than the current CBR method.
Keywords: finite element, airfield pavement, damage mechanism, six-wheels bogies, four-wheels bogies, tricycle axles, longitudinal deformations, critical response, deformation, tandem axis.
For citation: Z. Ambassa, R. Medjo Eko, Safonova M. N., Fedotov A. A., Ammosova N. E. Numerical analysis of flexible airfield pavements behaviour submitted by large aircraft: influence of the position and configuration of the landing gear. *Вестник СВФУ.* 2024, Т. 21, № 4. С. 45–55. DOI: 10.25587/2222-5404-2024-21-4-45-55

Численный анализ поведения гибких аэродромных покрытий при воздействии крупногабаритных воздушных судов: влияние положения и конфигурации шасси

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Аннотация. Исследована численная программа методом конечных элементов, применяемая к поведению аэродромных покрытий для определения механизмов повреждения конструкций дорожных покрытий при нагрузках высокой интенсивности и определения критического реагирования. Данное исследование на аэродромных покрытиях подтверждает, что шестиколесные тележки для самолетов или трехколесные оси тяжелых грузов на дорожном покрытии в основном создают продольные трещины из-за максимальных поперечных деформаций, а четырехколесные тележки для самолетов или тандемные оси в основном создают поперечные трещины из-за максимальных продольных деформаций, например, в дорожных покрытиях. Моделирование проводилось на основе квазистатических сравнений конфигураций шасси. Эти анализы предоставили данные о влиянии помех при изменении расстояния между колесами или опорами, сравнения между различными конфигурациями шасси A340, B777 и с их основными конкурентами. Предложена многослойная линейная модель, рассматривающая конструкцию гибкого покрытия, которая будет более рациональной, чем текущий метод CBR.

Ключевые слова: конечный элемент, аэродромное покрытие, механизм разрушения, шестиколесные тележки, четырехколесные тележки, трехколесные оси, продольные деформации, критическое реагирование, деформация, тандемная ось.

Для цитирования: З. Амбасса, Р. Меджо Эко, Сафонова М. Н., Федотов А. А., Аммосова Н. Е. Численный анализ поведения гибких аэродромных покрытий при воздействии крупногабаритных воздушных судов: влияние положения и конфигурации шасси. *Vestnik of NEFU.* 2024, Vol. 21, No. 4. Pp. 45–55. DOI: 10.25587/2222-5404-2024-21-4-45-55

Introduction

For decades, the flexible airfield pavements design analyses performed in practice still use ICAO empirical CBR based on Equivalent Single Wheel Load (ICAO, 2005). The issue of pavement compatibility was considered to be fundamental to the programme, especially as the current ACN/PCN method, was shown to have reached its limit of reability with the unpredicted cracks of pavements subject to 6 wheel bogie loads. These airfield pavements will deteriorate rapidly if subjected to aircraft loads that exceed the structural strength of the pavement (Ambassa and Ossendé, 2024). To prevent them from being overloaded and sustaining structural damage, their strength should be assessed and reported of which the aircraft mass should not exceed the strength of the pavement (Priyanka and Tutumluer, 2018; Wei and Guo, 2022). Allowing operations with overloads risks causing accelerated damage of the structure and reduction of the service life of the pavement. Pavements are designed to support a defined load for a predictable number of applications during their lifetime (DGAC-STBA, 1988). The evolution of airport traffic and aircraft architecture create new stress conditions, such as multi-peak loading with large strains (Kerzrého et al., 2012; Broutin, 2010). New generation aircraft, large carriers, relatively restrictive for flexible pavements require a detailed analysis of the behaviour of materials under this type of stress and to better quantify the effect of the large amplitudes of stress caused by these aircraft which exceed those applied by an axle of heavy weight on road pavement (Kabo, 2002; Kerzrého et al., 2012; Broutin, 2010, Ménagé et al., 2020). The Finite Element Method represents a powerful alternative approach for pavement response mechanistic analysis submitted by various loads configurations. In this paper, we combine the practicality of empirical methods with the technical soundness of mechanistic solutions and uses mechanistic analysis, to determine the pavement response to imposed load, then applies "empirical" formulations (i.e. "transfer functions") to determine the development of distress due to the load-induced pavement response. The pavement modelling is representative of the internationally recognised subgrade categories A for flexible structures. The modelling performed on quasi-static comparisons of Landing Gear configurations. These analyses provided data on effects of interference when wheels or legs spacing changed, comparisons between various A340, B777 Landing Gear configurations and with their main competitors. A multi-layered linear model addressing flexible pavement design has be proposed, which will be more rational than the current CBR method. The initial aim was to provide a design method for flexible pavement structures based on quasi static and fatigue (cumulative damage) factors.

Table

Characteristics of the structure analysed

Таблица

Характеристики проанализированной структуры

Type	Designation	Materials	Thickness	E (MPa): Young modulus	Poison's ratio
Structure 1					
Type A	Surface layer	BB (bottom of bituminous)	80 mm	5400	0.35
	Base layer	GB2 (gabbro-basalt)	220 mm	9300	
	Subbase layer	UGM (unbound granular materials)	120 mm	300	
	Subgrade	CBR=15 (gabbro-basalt)	3000 mm	120	

Pavement structure

The mechanical and geometrical characteristics of the pavement structures selected according to the subgrade obtained by the ACN/PCN method, are represented in table 1. For this structure, we opted for a subbase layer in unbound granular materials of 12 cm in order to reduce the number of finite elements and to reduce the calculation time on Cast3M (Cast3M, 2022).

The surface course is 8 cm thick of aeronautic asphalt concrete (BB), which is a standardised material (standard NF P 98 131). The mean value of the in situ compaction had to be between 94% and 97%. The specifications required a 0/14 continuous grading with the characteristics recommended by the GAN (2012). The base course is divided in two layers of 11 cm thick each of bituminous gravel (GB3). GB3 is a standardised material (standard NF P 98 138). The specifications required a 0/20 continuous grading with the characteristics recommended by the GAN (2012).

A number of successive layers of the subbase, depending of the final thickness constitute the course. The material used is unbound granular materials (UGM). The specifications required a 0/20 graded UGM with the following characteristics (GTR, 2000 ; GAN, 2012).

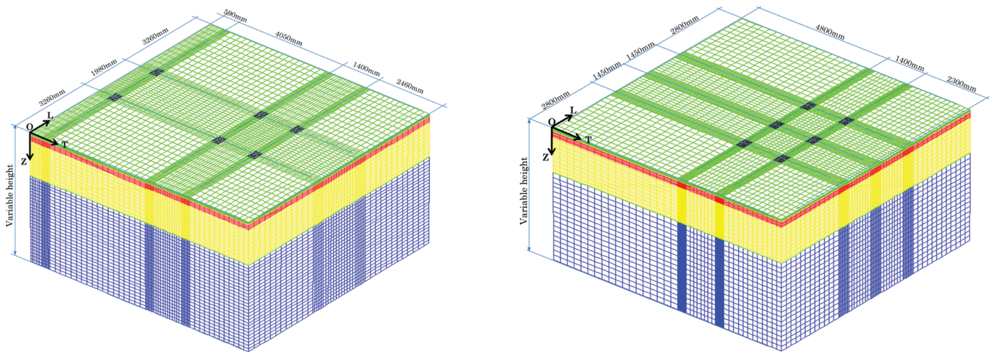
Subgrades are classified according to the supporting soil from the recommendations of the ICAO (2005) and the GTR (French subgrade classification for transportation geotechnic) (2000).

Finite elements modelling of pavements on Cast3M

A few finite elements modeling have been made, based on previus parameters, with Cast3M code to control the strain amplitude for the structure loaded in accordance with all landing gear configuration of aircraft analysis. The analyse has been therefore covered by a Cast3M finite elements code for those static parameters. Nevertheless, it has been necessary to compare the A340 with competitors, as the B777, on flexible pavement, for a concrete positioning.

Numerical calculation results

We found high level of tensile strain at the bottom of base layer and very high vertical compressive strain ot the top of unbound granular materials and subgrade, compared to "road" values. At the base of GB2, the signal of transverse and longitudinal strains is very clearly different (Figures 2 to 3 and 6 to 7). In the transverse direction, the bottom of GB2 is always in extension. The signal presents three or two peaks corresponding to the successive positions of the three or two axles composing the 6 or 4 wheels bogie. For three peaks in transverse direction, the inequality between the peak values is well marked. In this direction, the strain corresponding to the position of the second wheel is in almost cases appreciably higher than those corresponding to the position of the first and third wheel. A perfectly elastic behaviour of



a) b)

Fig. 1. 3D View of Cast3M FE of pavement structure:
a) under landing gear of a A340 ; b) under landing gear of a B777

Рис. 1. 3D-вид Cast3M FE структуры дорожного покрытия:
а) под шасси самолета A340; б) под шасси самолета B777

materials would lead involve indeed, a symmetry of the signal about the axis of the load (equality of the strains relative to the first and the third load). In the longitudinal direction, the base of GB2 presents on the contrary successive shape of extension and compression: extension at the position of the wheels and compression between two wheels. The strain corresponding to the position of the second wheel is lower than the other 2 peaks. The tensile strains in the longitudinal direction corresponding to the position of the 6 wheels bogie is lower than the strains in transverse direction in general. It is the opposite effect which is observed for the tensile strains generated for 4 wheels bogie. At the top of the unbound granular materials (UGM), the signal presents compression strains comprising per direction two (4 wheels) or three separated peaks (6 wheels) (Figures 4 and 8). In the case of the 6 wheels bogie, the central peak, has the greatest amplitude in general. At the top of the unbound granular materials and the top of the subgrade, the signals of the vertical strains have similar forms. They show a general compression with the position of the load, with peaks under the wheels all the less marked as much than the layer of unbound granular materials is thick. Figures 2 to 9, illustrate 3D view and shading of the strains at the base of the GB2 layer, at the top of the unbound granular materials and subgrade layers. The number of peaks in each 3D map indicate the position, the types and number of wheels bogie analysed on the pavements. These 3D shading provide all the necessary informations at the base or at the top of each layer according to the design criteria considered.

The flexible pavements response under landing gear of a A340-600

Strains at the base of the GB3 layer (fatigue criterion)

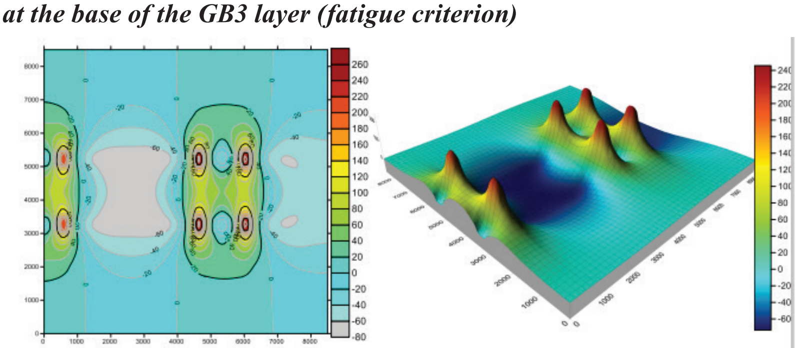


Fig. 2. Transverses tensile strains (x 10^6) at the bottom of bituminous (GB) layer on the pavement

Рис. 2. Поперечные деформации растяжения (×10^6) в нижней
части битумного слоя (GB) дорожного покрытия

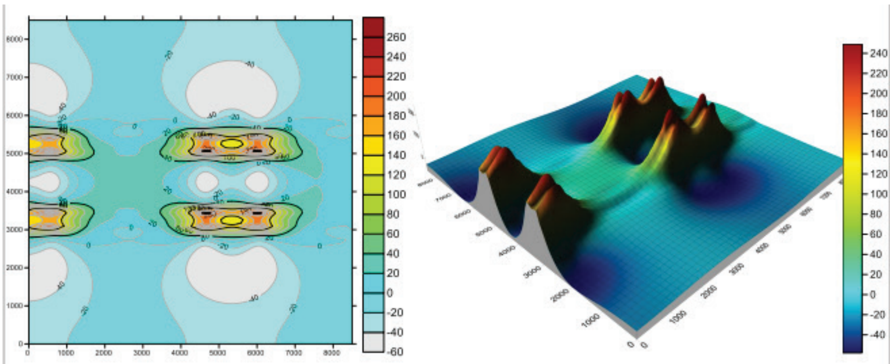


Fig. 3. Longitudinals tensile strains (x 10^6) at the bottom of bituminous (GB) layer on the pavement
Рис. 3. Продольные деформации растяжения (×10^6)
в нижней части битумного слоя (GB) дорожного покрытия

Strains at the top of the* unbound granular materials *layer (rutting criterion)

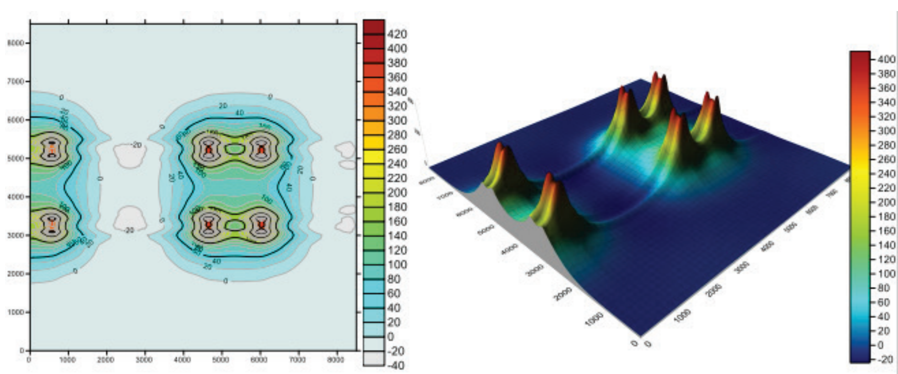


Fig. 4. Vertical compressives strains (x 10^6) at the top of the
unbound granular materials layer on the pavement
Рис. 4. Вертикальные деформации сжатия (×10^6) в верхней части слоя
не связанных гранулированных материалов дорожного покрытия

Strains at the top of the subgrade layer (rutting criterion)

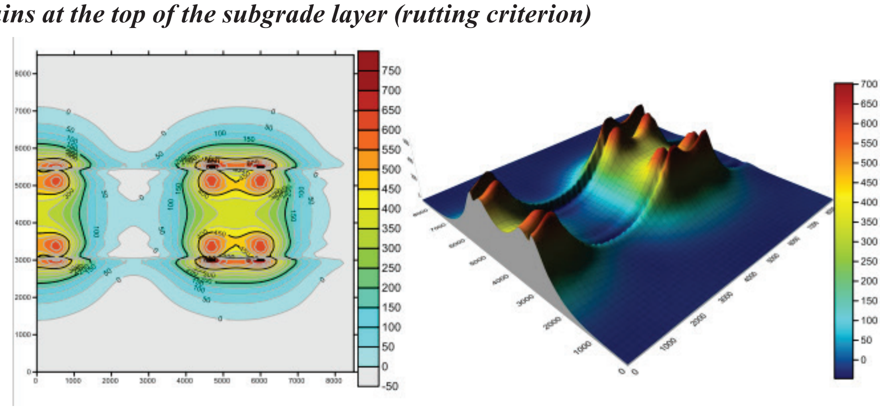


Fig. 5. Vertical compressives strains (x 10^6) at the top of subgrade layer on the pavement
Рис. 5. Вертикальные деформации сжатия (×10^6) в верхней
части слоя основания дорожного покрытия

The flexible pavements response under landing gear of a B777-300ER

Strains at the base of the GB3 layer (fatigue criterion)

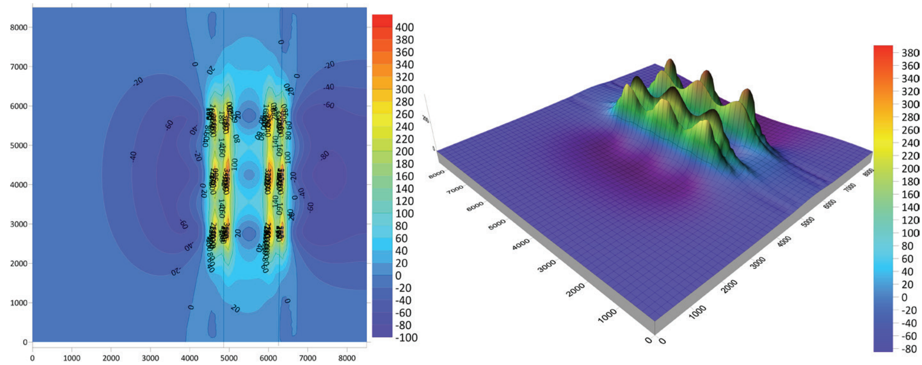


Fig. 6. Transverses tensile strains (x 10⁶) at the bottom of bituminous (GB) layer on the pavement

Рис. 6. Поперечные деформации растяжения (×10⁶) в нижней части битумного слоя (GB) дорожного покрытия

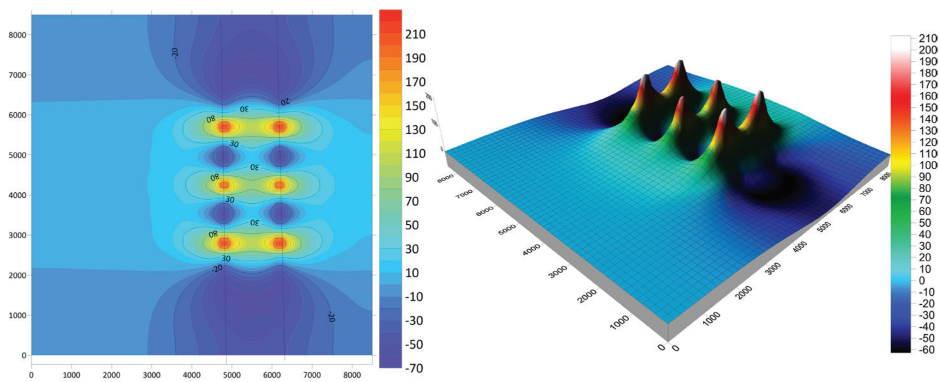


Fig. 7. Longitudinals tensile strains (x 10⁶) at the bottom of bituminous (GB) layer on the pavement

Рис. 7. Продольные деформации растяжения (×10⁶) в нижней части битумного слоя (GB) дорожного покрытия

Strains at the top of the unbound granular materials ***layer (rutting criterion)***

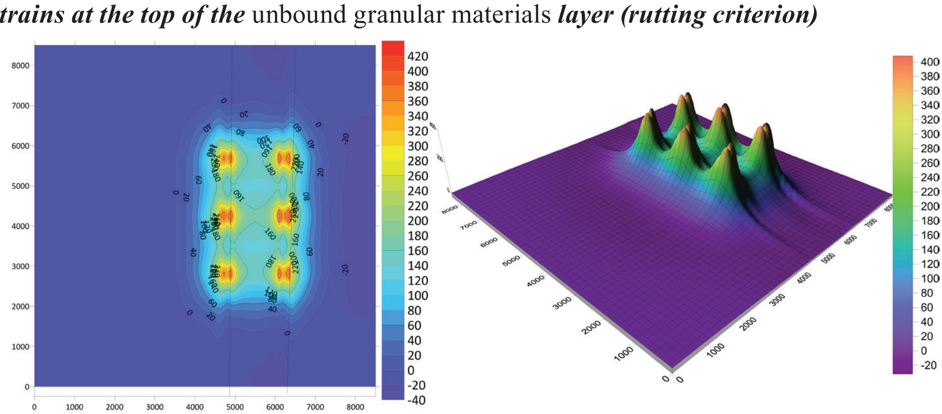


Fig. 8. Vertical compressives strains (x 10⁶) at the top of the unbound granular materials layer on the pavement

Рис. 8. Вертикальные деформации сжатия (×10⁶) в верхней части слоя несвязанных зернистых материалов дорожного покрытия

Strains at the top of the subgrade layer (rutting criterion)

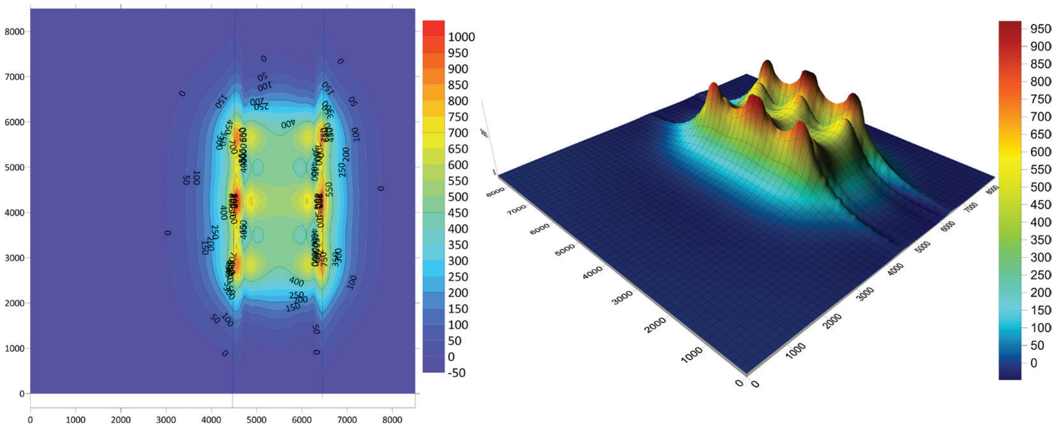


Fig. 9. Vertical compressives strains (x 10^6) at the top of subgrade layer on the pavement

Рис. 9. Вертикальные деформации сжатия (×10^6) в верхней поверхности слоя основания дорожного покрытия

Pavements damage calculation

Top down and bottom up on airports flexible pavements cracking are evaluated in this section by new French Rational Design airports flexible pavements method (DGAC-STBA, 2014), based on the concept of Rational Equivalent Simple Wheel Load (RseR).

- For fatigue criteria on the bituminous layers:

$$\Delta D\left(x, z_k\right)=\frac{1}{K^{\beta}}\left[\varepsilon_{t_1}^{\beta}-\varepsilon_{u_{1-2}}^{\beta}+\varepsilon_{t_2}^{\beta}-\varepsilon_{u_{2-3}}^{\beta}+.....+\varepsilon_{t_n}^{\beta}\right] \tag{1}$$

where: $\beta=-\frac{1}{b}$, $K=10^{6/\beta}.k_{\theta f}.k_r.k_s.k_c.\overline{\varepsilon_6}$, $\overline{\varepsilon_6}=90\mu strains$ for GB materials,

$$k_{\theta f}=\sqrt{\frac{E\left(10°C, 10Hz\right)}{E\left(\theta_{eq}, f\right)}},\quad k_r=10^{-ub\delta}\quad \delta=\sqrt{S_N^2+\left(\frac{c.S_h}{b}\right)^2}$$ and k_c = *2 for RseR > 25t*

$$k_s=\begin{cases} \frac{1}{1.2} => E_{subgrade}<50MPa \\ \frac{1}{1.1} => 50MPa<E_{subgrade}<80MPa \\ \frac{1}{1.065} => 80MPa<E_{subgrade}<120MPa \\ 1 => E_{subgrade}\geq 120MPa \end{cases}$$

- For rutting criteria at the top of the unbound granular materials and subgrade layers:

$$\Delta D\left(x, z_k\right)=\frac{1}{K^{\beta}}\left[\varepsilon_{zz_1}^{\beta}-\varepsilon_{u_{1-2}}^{\beta}+\varepsilon_{zz_2}^{\beta}-\varepsilon_{u_{2-3}}^{\beta}+.....+\varepsilon_{zz_n}^{\beta}\right] \tag{2}$$

K = 16000 and β = 4.5

Where: ε_6 - *(10 °C, 25Hz)* tensile strain, at which fatigue failure of a sample of asphalt mix occurs upon 10^6 loading cycles (at 50% probability) under the following test conditions: bending of beam specimen at 10 °C, at frequency of 25 Hz; ε_t - tensile strain, at which fatigue failure of a base the bituminous layer; ε_{zz} compressive strain, at which rutting failure of a top of the unbound granular materials and the subgrade layers; *b=-0.2* - the slope of the fatigue line of asphalt mix; *E(10°C)* - the modulus of the bituminous material at 10 °C; *E(θ_{eq})* - the modulus of the bituminous material at equivalent design temperature; k_r – factor to account for variability of test results and calculation risk; S_N - The dispersion of the results of the fatigue tests on the asphalt concrete described by the standard deviation; S_h - the thickness of the layers made of bituminous binders is variable, with a dispersion that is expressed by the standard deviation; k_s – factor to account for errors in preparation of underneath asphalt layers; k_c – factor to account for the type of asphalt mix.

The analysis of the damage results of the different structures while determining the value of the Rational Equivalent Simple Wheel Load (RseR) is very revealing: (1) Regardless of the type of aircraft bogie considered in this paper, the main mode of damage is the fatigue of the bituminous layers. On these bituminous layers, the elementary damage caused by bogie stress on the runway is much greater than the damage obtained on the layers of unbound materials (UGM and the subgrade) which is linked to rutting (Ambassa, et al., 2012; 2013[a] ; 2013[b]; Ambassa, and Amba, 2017). (2) This investigation demonstrates that the trend which aims to reduce the load of the 4 and 6-wheel bogies of an undercarriage to an Equivalent Single Wheel in order to determine the thickness of the pavement according to the rutting criterion of the material layers is not always suitable; especially for the stresses of large aircraft whose preponderant effect on bituminous pavements is rather the fatigue damage of the bituminous layers. (3) Analysis of the results of 3D numerical modelling and damage calculations through strains shows that the load transfer mechanism is very different from one pavement to another and is a function of the position and composition of the bogies.

Conclusion

This airfield pavement study confirms that six-wheeled aircraft trolleys or heavy-weight three-axle bridges on the road surface mainly create longitudinal cracks due to maximum transverse deformations, while four-wheeled aircraft trolleys or tandem axles mainly create transverse cracks due to maximum longitudinal deformations. For this purpose, a numerical program using the finite element method applied to the behaviour of airfield surfaces has been studied to determine the mechanisms of damage to airfield pavement surface structures under high-intensity loads and to determine critical response. The modelling was based on quasi-static comparisons of landing gear configurations. These analyses provided data on the effects of interference when changing the distance between wheels or supports, comparisons between different landing gear configurations of the A340, B777 and their main competitors. In the case of heterogeneous traffic in aicraft, Miner's (1935) additivity law is applied to have an equivalent damage. The representation of the strain shapes was done with 3D and 2D profiles to improve the quality of response and to clearly identify the critical areas when passing an aircraft bogie. From an aircraft consideration, the 4 and 6-wheel bogies of the B777 are more destructive to flexible pavements than the bogies of the other aircraft tested in this study. The calculation of damage according to the new French rational method for aeronautical flexible pavements revealed that the main damage to these pavements is due to the fatigue of the bituminous layers and not to the bearing or rutting of the platform and the unbound granular materials layers as recommended by the empirical ICAO design method of aeronautical flexible pavements with abacus.

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