Design of Pavements airside at Vienna International Airport – Introduction of a new Austrian design approach

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ABSTRACT: As Vienna International Airport has intention to become a new center for mid-distance flights towards Eastern Europe a new parallel runway should be built in the next couple of years to handle the increase in the number of flights related to this expansion. In this work, the design of rigid and semi-rigid pavements, including runways and aprons, is optimized resulting in recommended multi-layer constructions with a calculated technical life span of 30 years. A new Austrian design process for pavements airside is developed using equivalent damage factors for each airplane of an aircraft mix representative for Vienna International Airport – accounting for the ratio between the damage induced by one start of a standardized aircraft (based on an Airbus A380 with a virtual maximum take-off weight of 850 t and an ACN-number of 100) and one start of an individual aircraft – to determine the number of departures the pavement has to withstand within the technical life span, which is compared to the number of departures the pavement actually resists. This approach allows to evaluate not only the damage caused by individual airplanes of the actual aircraft mix but also the deterioration of aircrafts developed in the future and its effect on the technical life span of the multi-layer pavement. Using detailed finite element modeling of the dowels and modeling the interfaces between the concrete slabs as virtual linear springs, the optimum dowel spacings in longitudinal and transverse joints were determined. The results of this design process are in good agreement with the specification according to guidelines of the Federal Aviation Administration.

KEY WORDS: Pavement design, airfield, rigid, semi-rigid, damage factor.

1 INTRODUCTION

As Vienna International Airport intends to develop for a new center for mid-distance flights towards the economically upcoming Eastern Europe, a new runway should be built in the next couple of years to handle the increase in the number of flights related to this expansion.

Because there is no universal deterministic method to design pavements airside, engineers all over the world use different, mostly empiric or semi-empiric approaches. A widespread technique is the ACN (Aircraft Classification Number) / PCN (Pavement Classification Number) method (ICAO, 2004), which may only be applied to specify the bearing capacity of airfield pavements but is not appropriate to design or evaluate a pavement construction. Each aircraft and pavement structure is related to an ACN- or PCN-value, respectively. If the PCN-value of the pavement is higher than the ACN-value of the aircraft, the airplane is allowed to land on the respective runway without any restrictions. The ACN-value is indicated by the

manufacturers of the aircrafts, while the PCN-value is determined empirically or on the basis of mechanistic models, which are not defined by the International Civil Aviation Organization (ICAO).

In this paper a deterministic method based on an analytical description of the mechanistic and climatic conditions is introduced, leading to an efficient and reliable approach for the design of rigid and semi-rigid airfield pavements.

2 METHOD

Based on the aforementioned, standardized ACN-PCN method proposed by the ICAO, a new design approach for pavements airside considering their structural fatigue is developed. In a first step, a standard aircraft is chosen to represent the forecasted aircraft mix at Vienna International Airport in the design process. According to the concept of equivalent wheel load factors, equivalent damage factors are introduced – accounting for changing loading conditions because of different landing gear configurations of the individual airplanes of the aircraft mix – to relate the damage caused by the individual airplanes of the aircraft mix with that caused by the standardized aircraft. By means of these damage factors and the standard aircraft, numerical methods can be applied for the design of airport pavements.

2.1 Definition of standard aircraft and representative aircraft mix

By default of Vienna International Airport the new airside pavements shall fulfill a required Pavement Classification Number of PCN 100 / R / A / W / T, describing a rigid pavement with a PCN number of 100, ACN support structure class A, defined in (ICAO, 2004) with no restrictions concerning the tire pressure based on a technical design method. To meet these specifications, a standard aircraft with an ACN number of 100 for ACN support structure class A has to be chosen. With the help of the tool "COMFAA 3.0" (COMFAA, 2009) released by the Federal Aviation Administration (FAA), the ACN number for a standard aircraft with a gear configuration based on an actual Airbus A380-800F (see Figure 1) was determined, raising the maximum take off weight until an ACN number of 100 was reached. This resulted in a final gross weight of 8500 kN for the standard aircraft *SAC*.
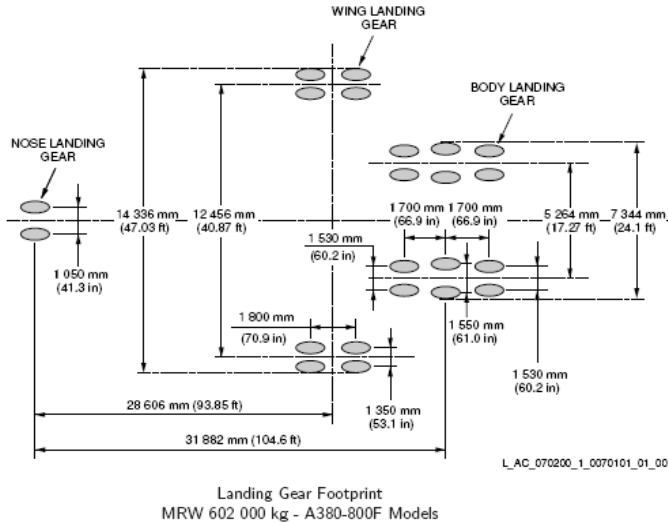

Figure 1: Main gear configuration of Airbus A380-800F (Airbus, 2008) used as standard aircraft.

The representative aircraft mix was determined on the basis of flight statistics of the year 2010 – provided by Vienna International Airport – choosing nine characteristic aircrafts. According to guidelines recommended by the Federal Aviation Administration (FAA), only the number of departures was considered within the design process.

2.2 Introduction of equivalent damage factors

The design load can be expressed by the number of departures (one departure correlates with three tire passes according to Figure 1) of the aforementioned standard aircraft, $N_{SAC,req}$, for a specified technical life span. This design load is defined as the sum of the number of annual departures of each characteristic airplane i of the given aircraft mix, $N_{CAC,i}$, multiplied with a damage factor of the specific airplane i, $DF_{CAC,i}$, as well as the number of design years, n, and an annual traffic growth factor, z:

$$N_{SAC,req} = \sum_i \left(N_{CAC,i} DF_{CAC,i} \right) \times n \times z ,$$ (1)

with

$$z = \frac{q^n - 1}{n(q-1)} , \quad q = 1 + \frac{p}{100}$$ (2)

and p as the annual growth rate.

The damage factor $DF_{CAC,i}$ describes the number of equivalent departures of the standard aircraft causing the same fatigue damage as one start of the specific airplane i. It depends on the type of construction (rigid or flexible), the subgrade reaction and the landing gear configuration of the aircraft. In the course of this work, the software tool "FAARFIELD" (FAARFIELD, 2009) (and the fatigue criterion behind it) released by the FAA, was used to specify the number of allowable departures of the standard aircraft until failure of the pavement and each specific airplane of the considered aircraft mix to determine $DF_{CAC,i}$. To be consistent with the fatigue criterions mentioned in 2.3 and 2.4, Equations (4) and (6) will be used to determine $DF_{CAC,i}$ in a next step and distributed in further publications. In order to take representative soil conditions into account, these calculations were carried out for four periods j with different subgrade reaction, as specified in Table 1 and by (Wistuba, 2003). The damage factors obtained have to be weighed according to the duration of each period within one year. $DF_{CAC,i}$ reads as

$$DF_{CAC,i} = \sum_{j=1}^{4} \frac{C_{SAC,j}}{C_{CAC,i,j}} \cdot p_j$$ (3)

with C_{SAC} and $C_{CAC,i}$ as the fatigue damages induced by one start of the standard aircraft and one start of the characteristic aircraft i, respectively. The weighing factor p_j indicates the relative duration of the subgrade reaction (bearing capacity) period.

2.3 Design of rigid pavements

The investigated rigid multi-layer construction for the new runway and aprons is depicted in Figure 2:
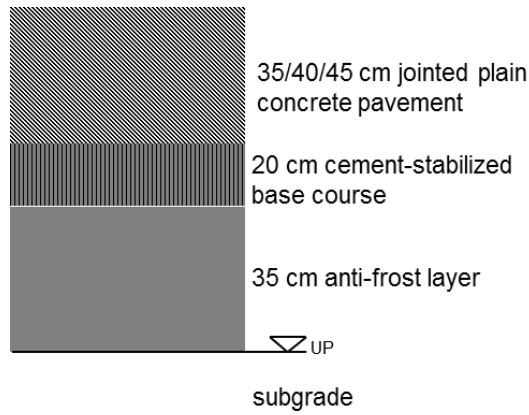
Jointed plain concrete pavement (JPCP):		
Thickness	[mm]	350; 400; 450
Modulus of elasticity	[N/mm^2]	30 000
Poissoin's ratio ν	[-]	0.15
Bending tensile strength	[N/mm^2]	5.5
Cement-stabilized base course (CSB):		
Thickness	[mm]	200
Modulus of elasticity	[N/mm^2]	5 000
Poisson's ratio ν	[-]	0.20
Subgrade (incl. anti-frost layer):		
Modulus of subgrade reaction k	[N/mm^3]	Depending on design period: 0.026; 0.035; 0.050; 0.086

Figure 2: Multi-layer construction considered in the design process and material parameters of the pavement layers.

In addition, doweled dummy joints were considered to separate the rigid pavement, resulting in square slabs with a side length of 5.5 and 6.0 m, respectively.

Introduction of the standard aircraft allows the application of numerical methods for the design process. Fatigue behavior of concrete slabs is considered through the criterion of Smith (Eisenmann, 1970), an experimentally derived criterion that relates the bending tensile stresses in the slab due to traffic and temperature loading to allowable load repetitions in respect to the bending tensile concrete strength. Equation (4) describes the relation:

$$\sigma_{tr} = \beta_{BS} \times \left\{ \left[(\log LC) - 2 \right] \times \left[0{,}0875 \times \frac{\sigma_{te}}{\beta_{BS}} - 0{,}07 \right] + 0{,}80 \right\} - \sigma_{te}. \tag{4}$$

Herein, σ_{tr} describes the stresses due to traffic load, β_{BS} is the bending tensile strength, LC denotes the number of load cycles and σ_{te} stands for the stresses due to non-uniform temperature change.

At first, finite element (FE) modeling (software "ISLAB 2000" (Islab, 2000)) was used to determine the stresses induced by the traffic load, σ_{tr}, taking subgrade reaction according to soil analysis into account (see subgrade modulus in Table 1). The CBR values were chosen according to the subgrade reaction considered within the calculation of the ACN values according to (ICAO, 2004). The results for the tensile stresses have to be weighed according to the duration p_j of assumed subgrade bearing capacity (see Table 1).

Table 1: Subgrade reaction over the course of the year (Wistuba, 2003), (ICAO, 2004).

Design period	Modulus of elasticity E [N/mm²]	CBR-value [%]	Subgrade modulus k [N/mm³]	Proportion p_j [%]
Spring	70	7	0.026	17
Transitional period	100	10	0.035	9
Summer/Autumn	140	14	0.050	50
Winter	280	28	0.086	24

Two different positions of load were investigated: (i) the relevant axis of the main gear of the standard aircraft is positioned in the middle of a slab (see Figure 3 (a)), and (ii) the relevant axis is sited at the edge of a slab (see Figure 3 (b)). Because of symmetry, only one half of the main gear was studied (compare Figure 1 and Figure 3).
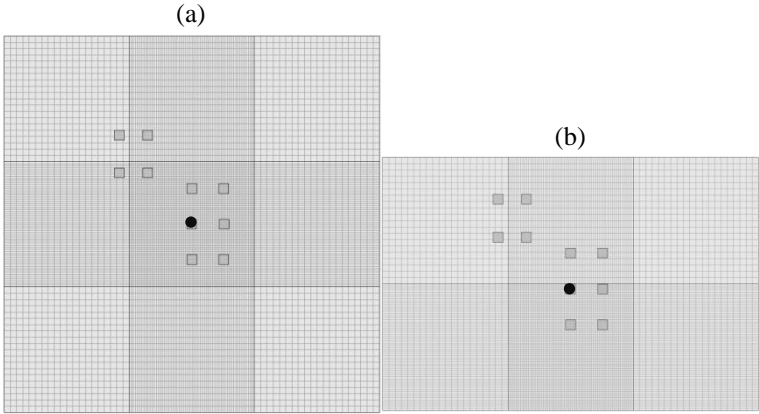

Figure 3: Two load cases investigated in the design process: (a) relevant axis (see spot) in the middle of a slab, and (b) relevant axis (see spot) at the edge of a slab.

In a first step, dowels were not modeled explicitly. The shear load transfer between neighboring slabs was considered by a constant factor of typically 60 %. In a further step, the doweled joints were studied in more detail. Within a finite element model, the dowels (20 mm diameter, 300 mm length) were replaced by vertical linear springs − the stiffness of these springs, k_f, determined for a dowel with a diameter of 30 mm and a length of 500 mm, can be obtained with the help of FE-modeling. For this purpose, a model containing two concrete slabs and one dowel was set up. While one of the slabs was restrained, the other one was allowed to perform a rigid body motion in transverse direction of the dowel (see Figure 4).
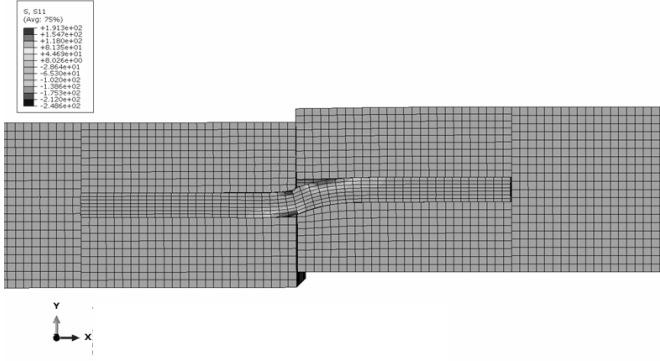

Figure 4: Finite-element model to determine equivalent spring stiffness k_f.

Since only the stiffness of the dowel is of interest, a vertical downward force was applied in the middle of the dowel's cross section at the joint. So the influence of the stiffness of the concrete above the dowel could be eliminated. With the help of the relation between force, F_y, and displacement, u_y, in vertical direction, the stiffness k_f can be determined by

$$k_f = \frac{F_y}{u_y}.$$
(5)

In a next step, the system seen in Figure 3 was modeled with "ISLAB 2000", replacing the dowels by vertical linear springs. The spacing between the dowels was varied to find the optimum spacing, for which the stresses due to traffic load were smaller than the value obtained with a shear load transfer factor of 60 %, $\sigma_{tr(60\%)}$. For dowel spacing commonly used, the stress due to traffic load does not exceed $\sigma_{tr(60\%)}$. Therefore, a spacing of 400 mm was recommended with reasonable design reserve.

Applying the maximum spring force obtained in the analysis of the whole structure on the system seen in Figure 4, a maximum concrete stress in transverse direction under the dowel of 2.16 N/mm^2 was determined and compared to the required splitting tensile strength of 2.5 N/mm^2 according to the Austrian specifications for pavement concrete (RVS 08.17.02).

In the next step, the temperature curling stresses in the slab were determined. When the temperature at the surface is higher than at the bottom of the slab (e.g. due to sun warming), the slab fibers at the top tend to expand more than the ones at the bottom and, therefore, the slab bends upwards. The dead weight of the slab is working against this effect, leading to a bending moment and inducing tensile stresses, σ_{te}, at the bottom. Additionally to the stresses due to traffic load, these temperature stresses have to be considered in the design process of rigid pavements. Solutions to estimate bending stresses due to non-uniform temperature change, given by a linear temperature gradient of $\Delta t = 0.09°C/mm$, in the middle of the slab and at its edges, respectively, are provided by Eisenmann (Eisenmann, 1970). According to available temperature data from Vienna International Airport a maximum temperature gradient of $\Delta t = 0.09°C/mm$ in the slab seemed to be reasonable. In (Eisenmann, 1970), a finite slab with length l on bearings located on the edges of the slab is considered and a critical length l_{crit} is introduced, when the middle of the slab touches the ground. Therefore three cases are taken into account: (i) if $l > 1.1 \cdot l_{crit}$, the stress in the middle of the slab can be determined according to Kirchhoff's plate theory; (ii) if $l = l_{crit}$, the stress increases by 20 %; and (iii) if $l < 0.9 \cdot l_{crit}$, the stress reduces depending on the actual length of the slab l. Due to the uniaxial stress state at the edge of the slab, in this case the stresses can be reduced by 15%. Because a temperature gradient of $\Delta t = 0.09°C/mm$ is not reasonable for a period of a whole year, σ_{te} was considered only for 5 to 15 % of a year. Thanks to this variation, not only results realistic nowadays can be obtained, but also a possible effect of global warming can be studied.

2.4 Design of semi-rigid pavements

The investigated semi-rigid multi-layer construction for the new runway is depicted in Figure 5.

To determine the allowed number of departures with the standard aircraft, the criterion of Leykauf (Leykauf, 1982) was applied. This criterion describes failure due to fatigue of the cement-stabilized base course taking the appearance of micro cracks during road operation into account:

$$LC = \left(0.57 \cdot \frac{1}{\sigma_{tr}} \right) \cdot 10^6 .$$ (6)

The bending tensile stresses induced by traffic load at the bottom of the cement-stabilized base course, σ_{tr}, were calculated using linear layered theory. As a consequence of the thermo-rheological behavior of asphalt 12 design periods with varying stiffness of the asphalt layer were considered (Wistuba, 2003).
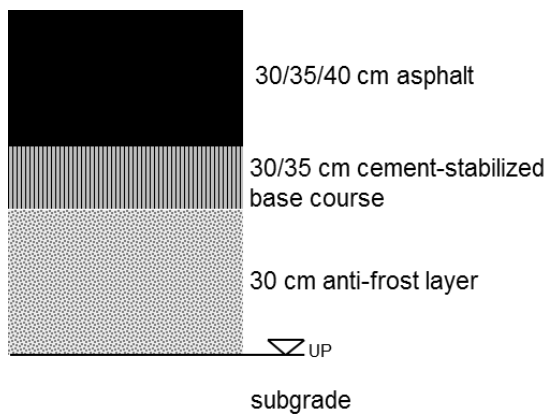
Asphalt layer:		
Thickness	[mm]	300; 350; 400
Modulus of elasticity	[N/mm^2]	f (T)
Poissoin's ratio ν	[-]	0.35
Cement-stabilized base course CSB:		
Thickness	[mm]	300; 350
Modulus of elasticity	[N/mm^2]	5 000
Poisson's ratio ν	[-]	0.20
Anti-frost layer:		
Modulus of elasticity	[N/mm^2]	Depending on design period: 140; 200; 280; 560
Subgrade:		
Modulus of elasticity	[N/mm^2]	70; 100; 140; 280

Figure 5: Multi-layer construction considered in the design process and material parameters of the pavement layers.

3   RESULTS

Inserting σ_{tr} received from the FE model and σ_{te} calculated according to Eisenmann, into Equation (4), and σ_{tr} from linear layered analysis into Equation (6), respectively, the allowed number of load cycles until fatigue failure for rigid and semi-rigid pavements could be determined.

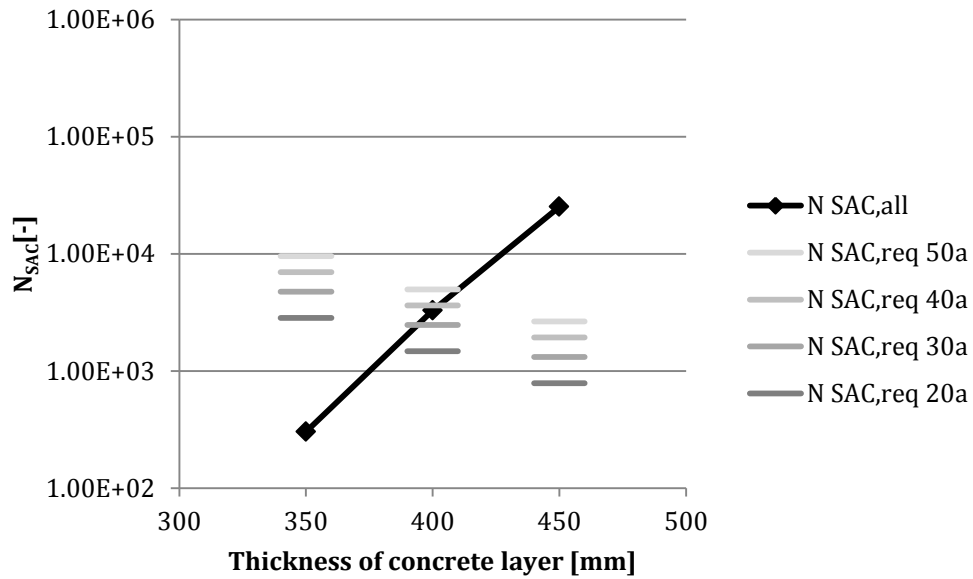Figure 6 shows a design chart for rigid pavements, while Figure 7 shows a design chart for semi-rigid pavements.

Figure 6: Allowable versus required number of departures with the standard aircraft for rigid pavements considering dimensions of a slab of 6.0 x 6.0 m, combined σ_{tr} and σ_{te} during 15% of the design period.
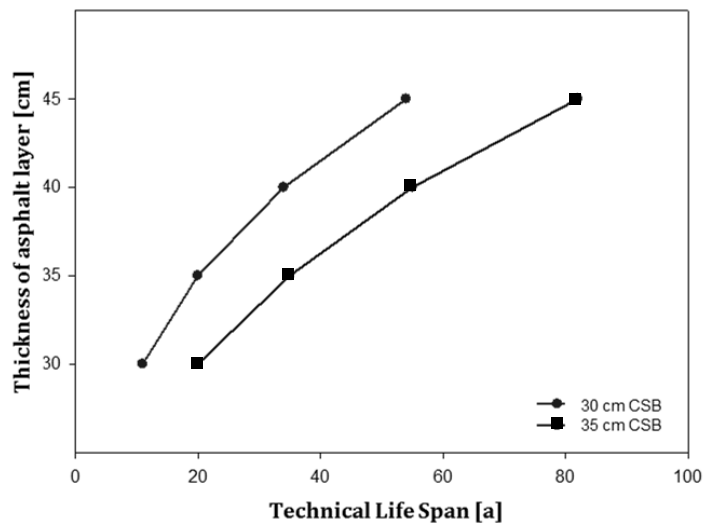

Figure 7: Thickness of the asphalt layer versus Technical life span for semi-rigid pavements considering a thickness of the cement-stabilized base course of 30 cm and 35 cm, respectively.

The recommended rigid and semi-rigid pavement constructions for the new runway and the aprons are depicted in Figure 8:
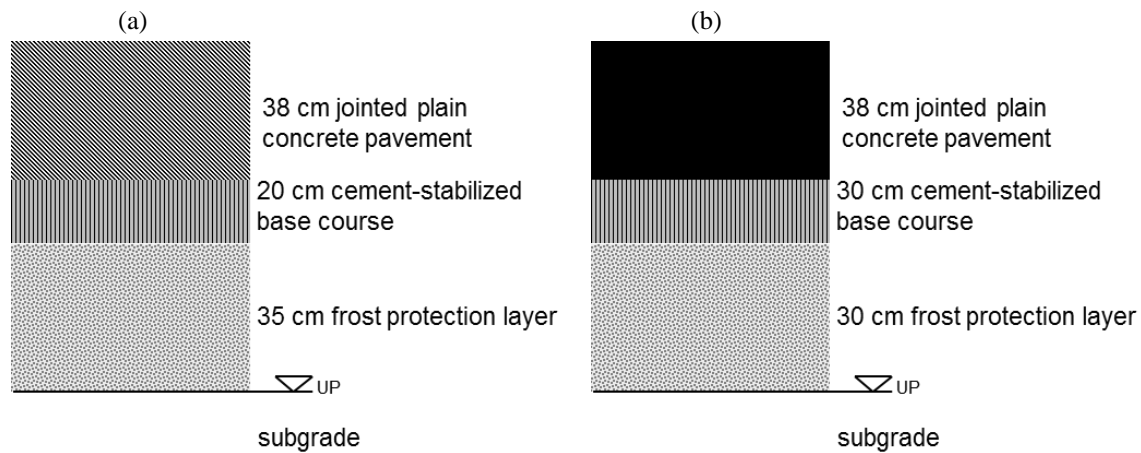
Figure 8: Multi-layer constructions to ensure a technical life span of 30 years: (a) rigid pavements, and (b) semi-rigid pavements.

4 CONCLUSIONS

In order to design the rigid pavements airside, including runways and aprons, at Vienna International Airport, a new deterministic Austrian design approach was developed. A standard aircraft was introduced that fulfills the requirements of an Aircraft Classification Number ACN 100 and is based on the landing gear configuration of an Airbus A380 with the maximum take-off weight of 8500 kN. Equivalent damage factors for each airplane of a representative aircraft mix for Vienna International Airport in the year 2010 were calculated to relate the damage induced by one start of any individual aircraft to one start of the defined standard aircraft. This approach enables the determination of the number of departures (design load) the pavement has to withstand within a specified technical life span. In addition, it allows evaluating not only the damage caused by individual airplanes of the actual aircraft mix but also the deterioration of any future aircraft type and its effect on the technical life span of the construction.

Based on Finite Element calculations to derive stresses and strains in the JPCP slabs of rigid pavements due to loading of the standard aircraft and by facilitating an analytical solution according to Eisenmann to calculate relevant curling stresses due to temperature loading, the number of allowable departures of the standard aircraft was estimated by application of the fatigue criterion according to Smith. The comparison of allowable and required departures of the standard aircraft (design load) for a design life of 30 years results in the recommendation of a rigid pavement construction consisting of a 380 mm concrete layer, 200 mm cement-stabilized base course and 350 mm anti-frost layer. Furthermore, the optimum dowel spacing of 400 mm of dowels with a diameter of 300 mm at the slab joints was determined on the basis of a finite element joint model.

Applying the fatigue criterion of Leykauf, the allowed number of departures a semi-rigid pavement actually resists was determined considering the bending tensile stresses at the bottom of the cement-stabilized base course resulting linear layered analysis. This results in the recommendation of a semi-rigid pavement construction consisting of a 380 mm asphalt layer, 300 mm cement-stabilized base course and 300 mm anti-frost layer.

Thus, the newly developed Austrian design approach, a deterministic method based on an analytical description of the mechanistic and climatic conditions, represents an efficient and reliable approach for the design of rigid and semi-rigid airfield pavements.

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