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RESEARCH ARTICLE

Touchdown Remaining Lift on the Wings and Dynamic Vertical Force Transmitted to the Runway

Mario De Luca[1*], Gianluca Dell'Acqua[1]

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Abstract

Airfield pavements are designed to handle an increasing volume of conventional aircraft, but in the future they may be required to accommodate both unmanned aircraft and space vehicles; these have their own unique requirements in terms of pavement strength and durability.

This study deals with the problem of application of loads on the runway during landing. The solution of this problem, necessary for the correct construction of the decay curve, has been studied with reference to the Grip Number (GN). The experiment has been conducted on the runway of the Airport of Lamezia Terme (IATA: SUF, ICAO: LICA) - Italy.

Traffic data (from 2010 to 2014) and data on surface features (in terms of GN) for the same period (according to the Publication-ICAO Doc.9137-AN / 898, where guidelines Speed equals 65 km / h) were acquired for the goals of this study.

The analysis of the data has supplied important information about the conditions of application of the loads on the Runway. In particular, through an optimization procedure and the use of the technique OLS, a relationship of application of loads on the runway has been proposed and furthermore two different areas, in reference to the methods of the application of loads in the process of landing, have been defined: a first part x1 within which the load is applied gradually with a linear law, and a second part (L-x1), in which all the load is applied with a constant law.

Keywords

Airport Pavement Management System (APMS), runway, Grip Number (GN)

1 Department of Civil, Construction and Environmental Engineering
University of Naples "Federico II", Italy via Claudio 21, 80125 Napoli
* Correspondent author, email: mario.deluca@unina.it

1 Introduction

The average pavement is designed for a 20-year lifecycle, but increasing service lives to 40 years is now considered practical from a capital investment standpoint and because airports cannot afford to take a runway out of service for reconstruction [1]. This requires pavement designs that are stronger, more sustainable, more durable and at the same time economical. The APMS (Airport Pavement management System) includes a set of methods that can help decision makers find cost-effective strategies for providing, evaluating, and maintaining pavements in a serviceable condition [2]. The APMS is used by many airport agencies around the world [3]. Many researchers have studied this issue in recent years, producing significant results for the improvement of APMS. Khraibani et al. proposed a mixed-effects logistic model to describe the evolution law of pavement deterioration and the effects of many factors on pavement behavior were identified. This approach made optimum use of the data by taking into account unit-to-unit variability and it was more powerful than traditional regression approaches in establishing the evolution curves [4]. Drewnowski and Uta made an analysis of the possible causes of the damage to the Kinshasa airport runway, using as a basis the deterioration recorded in the concrete slabs. Deformations caused by the difference of temperature on the top surface of the slabs and the under surface, plus the overloading due to aircraft landing and take-off, were the main causes of deterioration in the Kinshasa airport runway [5]. Garg and Mounier made a comparison of US and French airport pavement hot mix asphalt (HMA). HMA design in the USA was performed in accordance with advisory circulars of Federal Aviation Administration, and in France in accordance with guide by French Civil Aviation Center [6]. Kanazawa et al. presented an evaluation for a runway to be constructed at Tokyo Haneda International Airport based on pilot's subjective judgment. Using flight simulators of a Boeing 747 and a DC 9-81, runway profiles were created to represent different magnitudes of deflection and faulting. Responses obtained from experienced pilots in the form of a questionnaire were recorded on a four-point scale [7]. Greene et al. suggested how to perform an Airfield

Pavement Condition Assessment based on pavement-condition indicators that are determined from measurement of pavement distress, structural capacity, friction, and roughness. Factors addressed in the ratings include the pavement-condition index (PCI), the structural index (ratio between the aircraft classification number (ACN) and the pavement classification number (PCN)) and friction characteristics determined through the use of measuring equipments [8]. Yager et al. report of the Joint Winter Runway Friction Measurement Program between the National Aeronautics & Space Administration (NASA), Transport Canada (TC), and the Federal Aviation Administration (FAA): the program performed instrumented aircraft and ground vehicle tests aimed at identifying a common number that all the different ground vehicle devices would report. This number, denoted as the International Runway Friction Index (IRFI), will be related to all types of aircraft stopping performance [9]. Kuo, Mahgoub and Hollyday had developed a study in which a numerical model had been designed to define the impact of load for any landing angle. The results show that the strains of traction at the base of the asphalt layer and those of compression in the upper part of the substrate may be ten times higher than bump under static load. This study show that during landing the effects due to aircraft's loads had to be considered significant in the design of airfields [10]. De luca et al conducted a study about the surface characteristics decay phenomenon related to contamination from rubber deposits. The experiment was conducted by correlating the pavement surface characteristics, as detected by Grip Tester, to air traffic before and after de-rubberizing operation and two models were constructed for the assessment of functional capacity of the runway before and after the operations de-rubberizing [11]. In many of cited works, however, the problem of the application of the load on the runway, in the landing phase, is still not resolved. The solution of this problem, necessary for the correct construction of the decay curve, has been studied with reference to the Grip Number (GN). In particular, this paper suggests some guidelines for solving this problem.

2 Air traffic load features

Supporting the pavement designs of the future are improved information about airfield topography, drainage and both pavement and soil conditions. Data collection in the future will be enabled by new means that are both quick, accurate and cost-effective. Construction methodologies are also providing new methods for enabling airfield pavements to be returned to service quickly after maintenance or reconstruction begins.

Loads caused by air traffic in static terms are made by aircraft's weight, passenger's weight, fuel weight and eventual weight of goods. Unlike land transport (trains and vehicles), these loads are influenced by lift during the phase of landing. The lift is defined as the component of the aerodynamic force calculated in the orthogonal direction of the speed. The lift influences the mode with which the loads are applied on the runway from the touch down point to the modification of flap's position for air brake. In particular, during the landing, the aircraft touches the runway with an aerodynamic configuration that allows the aircraft to descent with an angle of 3 degrees (see fig. 1). Immediately after touch down, the flaps are changed in the aerodynamic brake configuration. The variation of the flaps takes 3 or 4 seconds, therefore, keeping in mind that the plane lands with a speed of 250–300 km/h and it goes through a space of 300 meters, it is important to understand how the lift influences the loads on the runway in this space. Moreover in this phase of landing, we must also consider the high dynamic load (due to the high speed of landing) that pushes the aircraft down.

3 Hypothesis for the loads study

Considering these particular aspects to establish the distribution of loads in landing phase, it is assumed that the loads are gradually applied on the runway (starting from the area of touch down) before all the load q is applied on the runway.

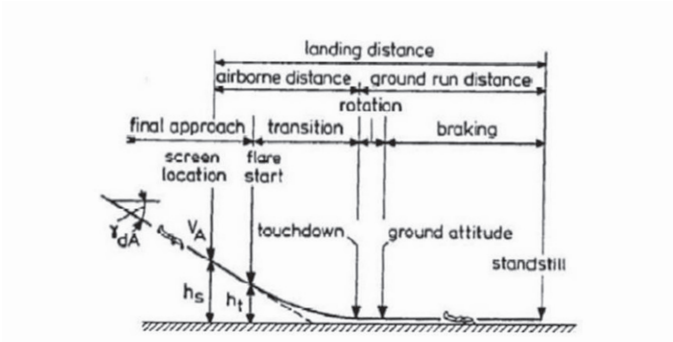

Fig. 1 Outline of the landing maneuver

It is evident that if this hypothesis is true then also the deteriorations (damage) on the runway must necessarily follow the same trend (see figure 2)

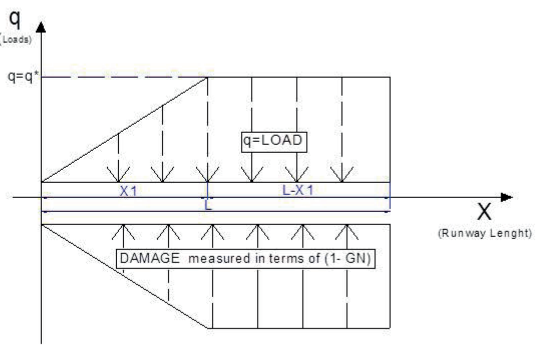

Fig. 2 Load distribution on the runway

Starting from these, hypothesis, an experiment was conducted. In particular it was built a function of load q, (to evaluate the load acting on the runway during landing) and also has been proposed a procedure to estimate the distance X1 (therefore also L-X1, L being known) . For this purpose data were collected in air traffic (2010–2014) and data relating (12) to surface deteriorations (Grip Number, GN) by Grip Tester (2010–2014). Through the analysis of the deteriorations in these five years (2010–2014) it was possible to assess the damage caused by the load.

Using this hypothesis, an experiment was conducted to build a function of load q to evaluate the load acting on the runway during landing and a procedure to estimate the distance of X1 (therefore even L-X1, because L is known). To reach this goal air traffic data (2010–2014) and data relating to surface deteriorations (Grip Number, GN) by Grip Tester (2010–2014) were collected. The analysis of the deteriorations in these five years (2010–2014) made it possible to assess the damage caused by the load.

4 Data Collection

4.1 Lamezia Terme Airport

The International Civil Airport of Lamezia Terme (ICAO: LICA, IATA: SUF) is equipped with a 4D class runway named RWY 10/28 of approximately 145,000 square meters, built with flexible pavement whose structural characteristics are identified by the code: PCN 58/F/B/W/T.

Geographic coordinates and altitude on the average sea level are as follows:

- Latitude: 38°54'30" North
- Longitude: 16°14'30" East
- Altitude: 12.31 m on the a.s.l..

The runway has a flexible pavement with a dense asphalt wearing surface. The following data were obtained for the runway during the observation period from 1 January 2010 to December 2014 (see table 1):

- GN, the Grip Number using Grip-Tester
- Loads moving on the runway during the study period (i.e, number, type and weight of the aircraft).

Fig. 3 Lamezia Terme International Civil Airport

4.2 Measurement of Surface Friction characteristics (GN)

The friction characteristics of the paved runway were determined using Grip Tester (see figure 4), according to the Publication ICAO-Doc.9137-AN/898, guidelines where speed equals 65 km/h. fifteen readings were taken (see Table 1) and for each of the readings shown in Table 1, eight different Grip tester tests were carried out as shown in Fig. 5

Fig. 4 Grip Tester Used in the survey

In the range from 2010 to 2014, 15 surveys through Grip Tester were carried out (see table 1).

Moreover Figure 5 shows the layout of the reliefs executed with Grip tester.

Table 1 Calendar of surveys

Num. Survey	Year	T (Number of day N_d)
1	2010	0
2	2010	210
3	2010	332
4	2011	380
5	2011	580
6	2011	690
7	2012	730
8	2012	876
9	2012	987
10	2013	1095
11	2013	1200
12	2013	1356
13	2014	1460
14	2014	1600
15	2014	1825

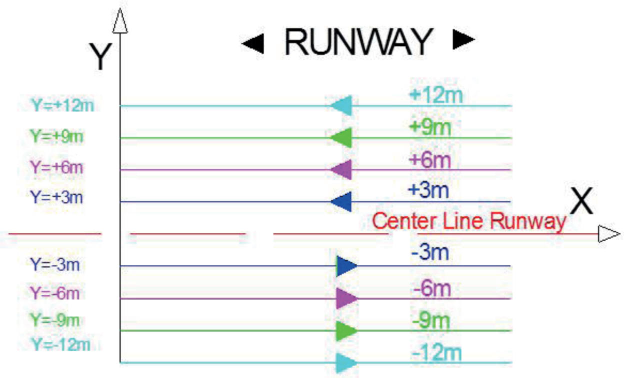

Fig. 5 Layout of Grip Tester Surveys

The traffic data (from 2010 to 2014) reference was made by the data provided by the post-holder office at the airport of Lamezia Terme.

Table 2 Lva detected by Sound level meters

Aircr. Type	Main Gear	Wheels Press. [kPa]	Year 2010 (num)	Year 2011	Year 2012	Year 2013	Year 2014
B733	S.Tandem	1346	41	33	41	38	47
B734	S.Tandem	1231	849	95	519	714	740
B737	S.Tandem	1337	1019	697	944	1733	1606
B738	S.Tandem	1414	799	2301	1705	2043	2249
B73G	S.Tandem	1275	164	69	128	133	157
M80	S.Tandem	1096	617	751	752	0	0
M82	S.Tandem	1096	751	565	724	0	0
A319	S.Tandem	856	1114	1115	1226	1288	1382
A320	S.Tandem	1164	1497	1121	1440	1408	1567
A321	S.Tandem	1231	441	960	771	952	947
A32S	S.Tandem	1366	119	1396	833	1226	1133
A330	D.Tandem	1289	17	20	20	22	23

Data Analysis

To evaluate the actions of the aircrafts on the runway that transited in the study period and to consider the characteristics of different aircrafts (see Table 3), the following relationship (Eq.1) has been designed:

$$q = \left(\frac{Load_{landing}}{Ap_{landing} * Nmain\ gear} \right) * A_p \tag{1}$$

Where :

$Load_{landing}$, takeoff weight minus the fuel used in flight;

$Ap_{landing}$, main landing gear wheels trace area at landing, defined as,

$$Ap_{landing} = \frac{P_{GearLanding}}{P_g};$$

$P_{GearLanding}$, load on single wheel of main gear;

P_g, main landing gear tires pressure (kPa);

$N_{main\ gear}$, number of wheels of the main landing gear;

A_p, is the measure of the transversal distribution of the traffic on the pavement. The reference [13] literature suggests that the steps of the wheels on the runway have a normal distribution referred to the centerline of runway (see figure 6). The degree of dispersion [14] can be characterized by the value of the standard deviation for different areas of the airport and in particular, literature suggests the following values: standard deviation σ = 773mm for traffic routes and σ =1546mm for the runways.

Therefore, putting σ = 1546mm for the runway, Y = 3500mm (where Y is the transversal degree of dispersion referred to the centerline of runway, see Fig.6)

The data acquired through the Grip Tester, in according with the layout shown in Figure 5, have been aggregated into classes (see table 3) with the same amplitude (using the distance x as variable).

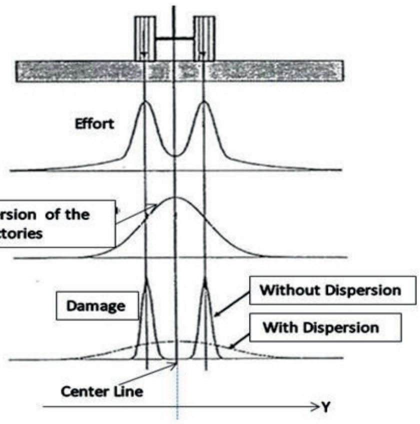

Fig. 6 Qualitative scheme of the dispersion of the trajectories

Table 3 GN aggregation in classes

Date	THR	X	Y	GN	$GN_{average}$
11/15/2010	28	10	3	0.493	
11/15/2010	28	20	3	0.497	0.48
11/15/2010	28	30	3	0.471	
11/15/2010	28	40	3	0.466	
11/15/2010	28	50	3	0.448	
11/15/2010	28	60	3	0.443	0.43
11/15/2010	28	70	3	0.419	
11/15/2010	28	80	3	0.416	
11/15/2010	28	90	3	0.387	
11/15/2010	28	100	3	0.385	0.39
11/15/2010	28	110	3	0.389	
11/15/2010	28	120	3	0.405	
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The data reported in Table 3 have been processed with OLS technique, using GN [15] as the dependent variable and the distance x as the predictor. Table 4 shows the results obtained.

Table 4 Result of data analysis

N. Survey	Equation	Determination Coefficient (R^2)
1	GN = –0.0001X + 0,540	R^2 = 0,72
2	GN = –0.0001X + 0.473	R^2 = 0.69
3	GN = –0.0001X + 0.644	R^2 = 0.10
4	GN = –0.0007X + 0.738	R^2 = 0.76
5	GN = –0.0004X + 0.571	R^2 = 0.81
6	GN = –0.0004X + 0.5778	R^2 = 0.52
7	GN = –0.0004X + 0.5882	R^2 = 0.61
8	GN = –0.0001X + 0.6498	R^2 = 0.30
9	GN = –0.0004X + 0.5882	R^2 = 0.61
10	GN = –0.0005X + 0.5847	R^2 = 0.76
11	GN = –0.0002X + 0.6518	R^2 = 0.38
12	GN–0.0005X + 0.7145	R^2 = 0.52
13	GN = –0.0003X + 0.7003	R^2 = 0.34
14	GN–0.0002X + 0.5079	R^2 = 0.50
15	GN–0.0005X + 0.5847	R^2 = 0.76

The results of table 4 show that a very close slope (trend = 10^{-4}) characterizes all equations. Moreover, it has been observed that in each of the 15 relationships of table 4 systematically the initial part (0 < x <350) of the series is characterized by a slope that is different from the rest of the series (see example Figure 7, 4, part circled in red, related to the survey n. 2).

To determine the distance x_1, i.e. the area of the runway where the load is not constant, a specific procedure of optimization has been designed.

This procedure allows to determine the value of x_1 such that R^2 (coefficient of determination) is maximum and the function of load q in this procedure has the following values:

$q = 0$ for $x = 0$;

$q = q^*$ for $x = x_1$;

$q = q^*$ per $x_1 < x < L$;

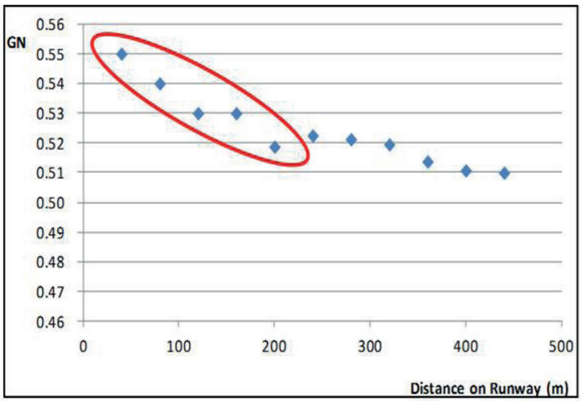

Fig. 7 Relationship between GN(Grip Number) and X (refer to survey n.2)

In particular, in the first part ($0 < \mathbf{x} < x_1$), the load q is applied with a linear law, in the second part (i.e. for values x belonging to range L-x_1), the load is constant and $q = q^*$ (i.e. all load is applied on runway). The details of the flow chart relating to optimization algorithm are shown in Figure 8.

In particular the algorithm pursues the goal of identifying a value of the distance x such that the objective function, defined by (Eq. 2), has to be maximum. Formally, the problem is defined as follows:

$$objective\ \ function \rightarrow f(x) = \rho^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i - \bar{y})}{\sum_{i=1}^{n}(y_i - \bar{y})} = Max$$

$$\begin{cases} x \le L - x_1 \\ y \le q^* \\ x, y > 0 \end{cases} \qquad (2)$$

where:

y_i, are observed values;

$\bar{y}$, is the average of the observed values;

$\hat{y}$, are the estimated values with the model obtained through the technique of OLS;

q^*, is the value of the maximum load acting on the runway defined by (Eq.1);

L, is the length of the zone where the aircraft is braking. In this case L is assumed between the most likely point to *touch down* and the beginning of the first exit ramp toward the taxiway (about 600 m).

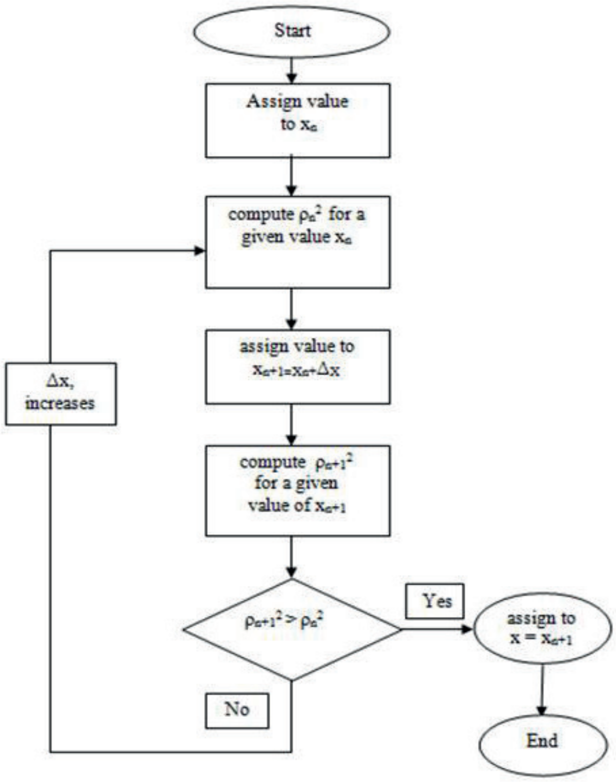

Fig. 8 Flow Chart of the optimization algorithm

5 Results of algorithm application

The results of the application of the algorithm to the 15 surveys indicated in Table 4 are reported in Table 5. In particular the penultimate column of the table 5 shows the value of x_1 such that the objective function $f(x) = r^2$ (last column) is maximum. In particular the average value for x_1 is equal to 280m.

Table 5 Final result

N. Survey	x_1 (m)	$f(x) = r^2$
1	260	0.89
2	270	0.84
3	280	0.92
4	300	0.90
5	320	0.82
6	280	0.84
7	260	0.84
8	310	0.92
9	255	0.84
10	240	0.87
11	310	0.92
12	315	0.95
13	325	0.90
14	230	0.76
15	235	0.87

6 Conclusions

In this paper, it has been analyzed the problem of the application's law of the loads on the runway during landing. The solution of this problem, necessary for the correct construction of the decay curve, has been studied with reference to the Grip Number (GN). In particular a relationship about application of loads on the runway has been proposed. The experiment has been conducted on the runway of the Airport of Lamezia Terme (IATA: SUF, ICAO: LICA) - Italy. Data collection covered the air traffic and surface characteristics (in terms of GN) in the five years (2010-2014). The analysis of the data, done by the OLS technique and by a process of optimization, has given important information about the application of loads on the runway during the landing. In particular it was found, for all 15 patterns analyzed, that the load q before being completely applied on the runway (due to the lift wing and high speed), follows a linear law (see figure 7 and table 4). This result could be an important reference for the subsequent work on the study of the actions resulting by the passage of the aircrafts on the runway and the individuation of the decay curve.

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