Evaluation of rigid pavement on apron of terminal 3 Soekarno-Hatta International Airport using finite element method

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Abstract. The development of transportation technology is indicated by the appearance of a new aircraft gear configuration, dual trim. The load repetitions of the movement of aircraft with dual-tridem gears, such as B-777-300ER aircraft with MTOW 28 tons, on Terminal 3 Soekarno-Hatta International Airport (SHIA) apron may cause pavement deformation, resulting in long-term fatigue and structural failures. Therefore, the performance of the existing rigid pavements to hold the loads for the next 20 years should be evaluated. Firstly, the equivalent annual departure and coverage of the aircraft in the airport up to 2037 is calculated. Next, the existing rigid pavement structure of the apron in the airport is modeled using a finite element method to calculate thermal stress and fatigue analysis for either the dowel or the slab. Our study result shows that the coverage value for the next 20 years is 86,534 with the maximum deflection of 0.055 mm and the maximum stress of 0.496834 MPa. The calculated thermal stress is 1.55 MPa, resulting in load repetition for the slab 1,241,484 and an infinite load repetition for the dowel.

1 Introduction

1.1 Background

Indonesia’s aviation industry has been growing rapidly for the past few years, for both domestic and international travels. It is characterized by the introduction of various types of larger aircraft into the industry. One of the aircraft is dual-tridem gears-based Boeing 777-300ER, operated by PT. Garuda Indonesia since 2013 to serve long-haul international routes from/to Terminal 3 Soekarno-Hatta International Airport (SHIA). The use of heavier aircraft raises concern regarding the capability of the apron’s pavement structure on handling the additional loads.

Unfortunately, the current existing airport pavement design guidelines only specify pavement thickness output. The pavement thickness capability gained in restraining the structural response (stress, strain, and deflection) generated by the aircraft load on the landing gear is not covered yet. Therefore, finite element methods are needed to overcome this problem. In addition, the basic theory of pavement loading developed by Westergaard in 1926 can only be applied to single-wheel aircraft and two-layer pavements. This study is conducted to address the limitations of current existing theories that have not accommodated current technology developments.

This study focuses to measure the ability to exist pavements in the apron of Terminal 3 SHIA to resist structural responses due to temperature and load variation. The analysis was performed using a finite element method with the help of Abaqus software version 6.11.

1.2 Objective

The objective of this research is to evaluate of existing rigid pavements on the apron of Terminal 3 Soekarno-Hatta International Airport in support the loads that pass through it during the design life.

2 Theoretical framework

2.1 Calculation of equivalent annual departure and coverage

1. Determine the annual departures expressed in design aircraft landing gear (R2). 
   \[ R_2 = Annual \text{ Departure} \times Conversion \text{ Factor} \] (1)

2. Determine the wheel load of design aircraft (W1) B-777-300ER. 
   \[ W_1 = \% \text{ load on main gear} \times MTW \times \frac{1}{N} \] (2)
   where: \( W_1 \) = wheel load of design aircraft (kg),
3. Determine the wheel load of the aircraft in question \((W_2)\)

\[
W_2 = \% \text{ load on main gear} \times MTW \times \frac{1}{N} \quad (3)
\]

where:
- \(W_2\) = wheel load of the aircraft in question (kg),
- \(N\) = the number of design aircraft landing gear.

4. Determine equivalent annual departures by the design aircraft (\(R_1\)) B-777-300ER.

\[
\log R_1 = \log R_2 \times \left(\frac{W_2}{W_1}\right)^{1/2} \quad (4)
\]

where:
- \(R_1\) = equivalent annual departures by design aircraft,
- \(R_2\) = annual departures expressed in design aircraft landing gear,
- \(W_1\) = wheel load of design aircraft (kg),
- \(W_2\) = wheel load of the aircraft in question (kg).

5. Coverage

\[
\text{Coverage} = \frac{R_1 \times (1 + I)}{\text{Pass To Load Repetition}} \quad (5)
\]

where:
- \(R_1\) = equivalent annual departures by design aircraft,
- \(I\) = growth factor of aircraft movement, B-777-300ER Pass To Load Repetition = 4.05.

### 2.2 Modulus of rupture of concrete

FAA (1995) explains that flexural strength of concrete can be estimated by compressive strength using this formula:

\[
R = 9\sqrt{f_{c'}} \quad (6)
\]

where:
- \(R\) = modulus of rupture of concrete (psi),
- \(f_{c'}\) = compressive strength of concrete (psi).

### 2.3 Thermal stress

Based on Delatte (2008), the thermal stress due to curling and warping is determined by the ratio between slab length \((L)\) and relative stiffness radius \((\ell)\). The formula to determine the relative stiffness radius \((\ell)\) is:

\[
\ell = \left(\frac{E D^3}{12 (1 - \nu^2) k}\right)^{1/4} \quad (7)
\]

where:
- \(\ell\) = relative stiffness radius (mm),
- \(E\) = modulus elasticity of concrete (MPa),
- \(D\) = pavement thickness (mm),
- \(k\) = modulus of subgrade reaction (MPa/m),
- \(\nu\) = Poisson’s ratio.

The next step is to calculate the stress due to temperature difference using formula:

\[
\sigma_{es} = \frac{C E \alpha_t \Delta t}{2(1 - \nu^2)} \quad (8)
\]

where:
- \(C\) = correction factor
- \(\alpha_t\) = thermal expansion of concrete (°C),
- \(\Delta t\) = temperature difference between top and bottom surface on slab (°C),
- \(\nu\) = Poisson’s ratio.

\[
W_2 = \% \text{ load on main gear} \times MTW \times \frac{1}{N} \quad (9)
\]

### 3 Idealization of finite element modelling for pavement structure

Before the computation is performed on the model, the idealization of modeling is firstly carried out to define some modeling conditions in order to represent the actual pavement conditions. In general, the idealization of modeling includes:

#### 3.1 Global modelling

The global model is made using solid elements modeled into 12 slabs, with as many as 4 slabs are connected transversely (x-axis-wise) and 3 slabs are connected longitudinally (y-axis-wise). Due to the limited resources available, the connection between slabs in the global model is not made using dowel. In addition, footprints in the global model are footprints on both sides of main landing gear. The footprint is located on the edge of the slab (edge loading). While the other side's footprint is located on the interior of the slab (interior loading). The dimensions of other parts that have been adjusted can be seen in Table 1 and Figure 1.

#### Table 1. Global modelling part dimension

| No | Part                  | Dimension                          |
|----|-----------------------|------------------------------------|
| 1  | Slab                  | 5,000mm x 5,000mm                  |
|    | Thickness             | 550 mm                             |
| 2  | Elliptical Foot Print |                                    |
|    | Major Axis            | 598.7 mm                           |
|    | Minor Axis            | 374.2 mm                           |
| 3  | Cement Treated Base Course | 20,000mm x 15,000mm            |
|    | Thickness             | 150 mm                             |
| 4  | Base Course           | 20,000mm x 15,000mm                |
|    | Thickness             | 150 mm                             |
| 5  | Subbase               | 20,000mm x 15,000mm                |
|    | Thickness             | 600 mm                             |
| 6  | Subgrade              | 20,000mm x 15,000mm                |
|    | Thickness             | 1,500 mm                           |

![Fig. 1. Global modelling of apron rigid pavement](image-url)
3.2 Local modelling

The aim of local models is to perform more specific analysis, because it analyzes the stress and deflection on the slab connection, especially the ability of dowel to function properly in transferring loads. They are made using solid elements which use dowels to hold together 2 connected slabs, and between slabs are given a gap of 10 mm. Footprint made in a local model is a footprint on one side of main landing gear. The footprint is located on the joint between slab (edge loading). The dimensions of other parts that have been adjusted can be seen in Table 2 and Figure 2.

Table 2. Local modelling part dimension

| No | Part                    | Dimension                  |
|----|-------------------------|----------------------------|
| 1  | Slab                    | 5,000mm x 5,000mm          |
|    | Thickness               | 550 mm                     |
|    | Spacing                 | 10 mm                      |
| 2  | Elliptical Foot Print   |                            |
|    | Major Axis              | 598.7 mm                   |
|    | Minor Axis              | 374.2 mm                   |
| 3  | Cement Treated Base     |                            |
|    | Course                  | 10,000mm x 5,000mm         |
|    | Thickness               | 150 mm                     |
| 4  | Base Course             | 10,000mm x 5,000mm         |
|    | Thickness               | 150 mm                     |
| 5  | Subbase                 | 10,000mm x 5,000mm         |
|    | Thickness               | 600 mm                     |
| 6  | Subgrade                | 10,000mm x 5,000mm         |
|    | Thickness               | 1,500 mm                   |
| 7  | Dowel                   |                            |
|    | Diameter                | 50 mm                      |
|    | Length                  | 610 mm                     |
|    | Spacing                 | 460 mm                     |

The boundary conditions that must be defined in this model are the hinge (joint) on the bottom surface subgrade and roll on the outer surface of the pavement (the x and y fields). The purpose of the roll boundary condition is to lock the pavement model so that it does not have displacement in the x-axis and y-axis direction, even if the displacement still occurs, the value will not be too large.

b) Temperature

The second boundary condition that must be defined in this model is temperature on top surface and bottom surface of the concrete. This temperature can have an effect on the structure response that occurs. The temperature value chosen is temperature during the day, because in the daytime, the temperature value are more extreme than at night, as in Table 3 below.

Table 3. Temperature on top and bottom surface of concrete

| Surface | Temperature (°C) |
|---------|------------------|
|         | Day   | Night |
| Top     | 55    | 25    |
| Bottom  | 25    | 30    |

4 Result and analysis

4.1 Growth analysis of aircraft movement

The first step in this study is to perform growth analysis of aircraft movement, to predict the movement of aircraft at Soekarno-Hatta International Airport over the next 20 years (up to 2037). The data used in this analysis is the aircraft movement data at SHIA from 2002 to 2017 obtained from PT. Angkasa Pura 2, which can be seen in Table 4. From the data, then the aircraft movement for the next 20 years is extrapolated (Figure 3).

Table 4. Soekarno-Hatta International airport aircraft movement data (Source: PT. Angkasa Pura 2)

| Year | Aircraft Movement | (annual growth) |
|------|-------------------|-----------------|
| 2002 | 144,765           | -               |
| 2003 | 186,695           | 28.96%          |
| 2004 | 233,501           | 25.07%          |
| 2005 | 241,882           | 3.59%           |
| 2006 | 247,126           | 2.17%           |
| 2007 | 248,482           | 0.55%           |
| 2008 | 250,173           | 0.68%           |
| 2009 | 272,877           | 9.08%           |
| 2010 | 305,464           | 11.94%          |
| 2011 | 345,398           | 13.07%          |
| 2012 | 381,120           | 10.34%          |
| 2013 | 399,430           | 4.80%           |
| 2014 | 390,984           | -2.11%          |
| 2015 | 386,615           | -1.12%          |
| 2016 | 413,781           | 7.03%           |
| 2017 | 442,214           | 6.87%           |
4.2 Analysis of equivalent annual departure and coverage

The first stage in calculation of equivalent annual departures is to determine the design aircraft. In this study, the design aircraft used is B-777-300ER aircraft, with the type of main landing gear dual-tridem. The calculation steps are the following:

1. Determine annual departures expressed in design aircraft landing gear \( R_2 \)
   To obtain the value of \( R_2 \), annual departures of other aircraft in 2017 are converted into annual departures of design aircraft (B-777-300ER).

2. Determine wheel load of design aircraft \( W_1 \) B-777-300ER
   In Boeing 777 Specification document published by Boeing Commercial Airplanes in 2015, the percentage of load for B-777-300ER aircraft on main landing gear is 92.46% and the maximum design taxi weight (MTW) is 352,442 kg, and the number of main landing gear is 12 wheels.
   \[
   W_1 = 92.46\% \times 352,442 \times \frac{1}{12} = 27,156 \text{ kg}
   \]

3. Determine wheel load of the aircraft in question \( W_2 \)
   Based on FAA (1995), the percentage of load for mixed aircraft type on the main landing gear is 95%.
   For example:
   a. Boeing 737-800
      Number of main landing gear : 4
      Landing gear type : dual wheel
      MTW : 7,333 kg
      \( W_2 = 95\% \times 79,333 \times \frac{1}{4} = 18,842 \text{ kg} \)

4. Determine equivalent annual departures of design aircraft \( R_1 \) B-777-300ER (Table 5)

5. The calculation of coverage value is done annually for the next 20 years up to 2037 according to the design life (Table 6)
4.3 Calculation of contact area

Based on the Boeing 777 specification document issued by Boeing Commercial Airplanes in 2015, the contact area for landing gear of B-777-300ER aircraft was elliptical. The next stage of this research to calculate the magnitude of major axis and minor axis for elliptical footprint (Figure 4). Based on US Corps of Engineer S-77-1 Report in Rahman (2014), the equations are used:

\[
\text{minor axis } (b) = 0.894 \times \sqrt{\text{contact area } (A)} \\
\text{major axis } (a) = 1.6 \times \text{minor axis } (b)
\]

The magnitude of major axis and minor axis:

\[
\text{minor axis } (b) = 0.894 \times \sqrt{1,752} = 37.42 \text{ cm} \\
\text{major axis } (a) = 1.6 \times 37.42 = 59.87 \text{ cm}
\]

4.4 Response structure analysis of local and global modelling

The response structure analysis is conducted on loading and joint areas. Previously, the loading area is divided into 3 area. The areas are located on the intersection of critical point for local modelling and global modelling. Area 1 is located on joint between slab of local modelling. Area 2 and area 3 are located on loading area of global modelling. The area can be seen on Figure 5 and Figure 6.

Table 6. Coverage

| n-th Year | Year | Equivalent Annual Departures (R_{eq}) | Coverage |
|-----------|------|--------------------------------------|----------|
| 2017      | 0    | 11,833                               | 2,922    |
| 2018      | 1    | 12,356                               | 3,031    |
| 2019      | 2    | 12,755                               | 3,130    |
| 2020      | 3    | 13,210                               | 3,262    |
| 2021      | 4    | 13,772                               | 3,401    |
| 2022      | 5    | 14,334                               | 3,540    |
| 2023      | 6    | 14,875                               | 3,673    |
| 2024      | 7    | 15,364                               | 3,816    |
| 2025      | 8    | 15,776                               | 3,896    |
| 2026      | 9    | 16,166                               | 3,992    |
| 2027      | 10   | 16,572                               | 4,092    |
| 2028      | 11   | 17,040                               | 4,208    |
| 2029      | 12   | 17,585                               | 4,342    |
| 2030      | 13   | 18,169                               | 4,487    |
| 2031      | 14   | 18,693                               | 4,616    |
| 2032      | 15   | 19,138                               | 4,726    |
| 2033      | 16   | 19,594                               | 4,839    |
| 2034      | 17   | 20,077                               | 4,958    |
| 2035      | 18   | 20,565                               | 5,078    |
| 2036      | 19   | 21,041                               | 5,196    |
| 2037      | 20   | 21,509                               | 5,311    |
| TOTAL     |      | 350,424                              | 86,524   |
Each dowel can be seen on Table 8 and is illustrated in Figure 8.

Table 8. Deflection on dowel.

| Dowel | Maximum Deflection (mm) |
|-------|-------------------------|
|       | U1 (mm) | U2 (mm) | U3 (mm) |
| 1     | 0.000753642 | 0.000837194 | 0.0303111 |
| 2     | 0.000208204 | 0.001108681 | 0.0363918 |
| 3     | 0.00293389 | 0.00108362 | 0.0424083 |
| 4     | 0.00352594 | 0.000681381 | 0.04693318 |
| 5     | 0.003863549 | 0.000261903 | 0.0492085 |
| 6     | 0.00381748 | 2.49702E-05 | 0.0483923 |
| 7     | 0.0033956 | -0.00023759 | 0.0444841 |
| 8     | 0.00277851 | -0.395735E-05 | 0.0393966 |
| 9     | 0.00180742 | -7.05395E-05 | 0.0324991 |
| 10    | 0.000773807 | -5.31546E-05 | 0.0263213 |

Fig. 8. Deflection on dowel.

2. Stress
   a. Stress on loading area
      The maximum stress in the loading area occurs in the slab and the value is still under the MOR of concrete (Table 9). According to FEA, the MOR value is calculated as follows:

\[
R = 9\sqrt{f'_c} = 624.53 \text{ psi} = 4.31 \text{ MPa}
\]

Where \( f'_c \) = compressive strength of concrete (psi) = 4,815.23 psi

b. Stress on slab joint
   The maximum stress of dowel occurs in dowel #5, as in Table 10. The value is still below the tensile stress of steel. tensile stress = 0.83 x yield stress = 0.83 x 345 = 286.5 MPa

Table 10. Stress on dowel.

| Dowel | Maximum Stress (MPa) |
|-------|-----------------------|
|       | S1 | S2 | S3 | S4 | S5 | S6 |
| 1 Max | 6.08366 | 3.14488 | 16.2169 | 2.77481 | 0.897628 | 5.19962 |
| S/Ny | 2.12% | 3.10% | 5.66% | 0.97% | 0.31% | 1.82% |
| Max | 15.355 | 6.6076 | 19.1751 | 3.70483 | 1.72699 | 5.23582 |
| S/Ny | 5.36% | 2.33% | 6.70% | 1.29% | 0.60% | 1.83% |
| 5 Max | 45.6593 | 15.949 | 22.9732 | 5.28836 | 3.96485 | 7.42625 |
| S/Ny | 15.95% | 5.57% | 8.02% | 1.85% | 1.37% | 1.65% |
| Max | 50.9732 | 17.9397 | 24.745 | 5.30461 | 4.60668 | 4.68848 |
| S/Ny | 17.80% | 6.26% | 8.64% | 1.85% | 1.61% | 1.64% |
| 5 Max | 59.2957 | 20.7584 | 28.934 | 5.43787 | 5.07061 | 5.19841 |
| S/Ny | 20.71% | 7.25% | 10.19% | 1.90% | 1.92% | 1.82% |
| 6 Max | 56.0183 | 19.708 | 28.2801 | 4.4413 | 3.04937 | 5.45661 |
| S/Ny | 15.96% | 6.91% | 9.88% | 1.55% | 1.76% | 1.59% |
| 5 Max | 49.8982 | 17.8671 | 25.3665 | 3.60298 | 4.47447 | 3.92913 |
| S/Ny | 17.43% | 6.24% | 8.86% | 1.26% | 1.55% | 1.37% |
| 8 Max | 39.7314 | 8.74337 | 22.5421 | 2.51051 | 2.38952 | 3.72474 |
| S/Ny | 15.88% | 3.05% | 7.87% | 0.88% | 1.15% | 1.30% |
| 5 Max | 26.8028 | 6.01241 | 18.3847 | 1.56676 | 1.97048 | 3.27086 |
| S/Ny | 9.39% | 2.10% | 6.55% | 0.54% | 0.69% | 1.14% |
| 10 Max | 5.73402 | 3.01778 | 14.7682 | 0.708119 | 0.855936 | 3.78972 |
| S/Ny | 2.00% | 1.05% | 5.16% | 0.25% | 0.30% | 1.32% |

4.4 Thermal stress analysis

The calculation of thermal stress using formula in Delatte (2004). Previously, check the temperature difference that occurs after analysis with Abaqus, as can be seen on Table 11. The thermal stress results are shown in Table 12. The maximum cumulative stress of Abaqus running result and thermal stress, occurs in Area 1 and when the temperature difference of 42.82°C still produces value below the MOR of concrete.

Table 11. Temperature difference between top and bottom surface

| Surface | Initial Condition | Global Modelling | Local Modelling |
|---------|-------------------|------------------|----------------|
| Top Surface | 55 | 55 | 42.0036 |
| Bottom Surface | 25 | 0 | -0.811535 |
| ΔT (°C) | 30 | 55 | 42.815135 |

4.5 Fatigue analysis

1. Fatigue on Slab

In this research, the S-N curve used is Cornelissen and Reinhardt curves (1984) in CEB (1998) as in Figure 10, with the following formula:

\[
\log N = 8.94 - 7.68 \frac{\sigma_{max}}{\sigma_{fctm}} - 0.37 \sigma_{min} \frac{\sigma_{fctm}}{\sigma_{max}}
\]

\( \sigma_{max} = \sigma_{es} + S_{max} = 1.547428 \text{ MPa} \)

\( \sigma_{min} = \sigma_{es} + S_{min} = 1.002127 \text{ MPa} \)

Thus, the number of load repetition on the slab is 1,241,484 repetitions.

2. Fatigue on Dowel

The maximum stress on dowel is 59.2957 MPa. If the tensile stress for steel is 286.35 MPa, then the maximum...
stress ratio is 0.2071. The value of 0.2071 is plotted on the S-N curve taken from Juvinall and Marshek (2012) as shown in Figure 9. From the plotting results, it is known that the number of load repetition is infinite repetition.

Fig. 9. S-N Curve of steel
(Source: Juvinall and Marshek, 2012)

5 Conclusions and suggestions

5.1 Conclusions

1. The coverage of apron of Soekarno-Hatta Airport Terminal 3 for 20 years is 86,534.
   a. The maximum stress on the concrete slab is 0.496834 MPa for S11. The value is lower than the concrete MOR 4.31 MPa with a stress ratio of 0.1154.
   b. The maximum deflection in vertical direction (U3) is 0.055 mm. The value is below the allowable vertical deflection threshold for apron pavement of 0.5 mm.
2. Structure response analysis is also analyzed in the connection area between slabs (local modeling).
   a. The maximum stress in the connection between slabs (precisely in slab 1) 0.553916 MPa. The value is lower than the concrete MOR of 4.305967 MPa with a stress ratio of 0.1286.
   b. The maximum stress in the dowel is 59.2957 MPa, or 0.2071 from the tensile stress of steel 286.35 MPa.
   c. The maximum deflection vertical direction (U3) of dowel is 0.0492855 mm.
3. The thermal stress of 1.547428 MPa occurs when the temperature difference reaches 42.82ºC, the value is lower than the concrete MOR of 4.305967 MPa.
4. Fatigue analysis on slab concrete and dowel.
   a. The number of slab concrete load repetitions is 1,494,376 repetitions.
   b. The number of dowel load repetitions is infinite repetitions.

5.2 Suggestions

1. In order to obtain more accurate results, it is necessary to do finite element method modeling to analyze the effect of load repetition.
2. In order to obtain results that are closer to the actual conditions, thermal stress analysis also can be carried out.
3. To obtain the better results and approach the actual condition, more detailed and depth analysis is needed in the future research.
4. More intensive coordination is needed with PT. Angkasa Pura II in terms of the application of apron pavement data, especially the detailed data about the material properties of pavement as one of the input models, so that the data obtained in accordance with the actual conditions.

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