Alternative Fatigue Cracking Modes for Airfield Rigid Pavement Design

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Introduction and Motivation
Introduction and Motivation

- Airfield rigid pavement design is based on:
  - FE analysis of individual gear loads;
  - Critical tensile stress at the bottom;
  - No thermal loads (flat slab condition);

- Dual: B727, B737
- Dual Tandem: B747, B757, B767
- Triple Dual Tandem: B777, A380
Introduction and Motivation

• Top-Down cracking observations from full-scale tests:
  • FAA’s NAPTF at Atlantic City (USA)
  • A-380 PEP tests at Toulouse (France)

• Certain combined load and slab geometry situations.
Introduction and Motivation

• FAA’s NAPTF Tests (CC2 - MRG)

Tests and observed cracks in CC2 tests (Hayhoe and Garg, 2006)

• Tridem and tandem gear loading
FAA CC2 Failure Cracks

All Sections

(a) Test Item MRC
(b) Test Item MRG
(c) Test Item MRS

Brill et al. 2006
Introduction and Motivation

- A-380 Pavement Experimental Programme - Rigid Phase (France)

Tests and cracks in PEP (Fabre et al. 2005)
Introduction and Motivation

- California Highway Cracking

Hiller and Roesler (2005)
Objectives
Objectives

- Identify key aircraft loading locations on rigid pavements which induce high top tensile stresses (ratio between top and bottom);
  - *NO CURLING*

- Investigate the quantitative effect of several parameters and their interaction on predicted critical tensile stresses and positions:
  - Slab Length: L
  - Load type: individual gear versus full aircraft;
  - Radius of Relative Stiffness, \( ℓ - (h,k) \)
  - Load Transfer Efficiency (LTE) between slabs:

\[
LTE = \frac{\delta_{\text{unloaded}}}{\delta_{\text{loaded}}} \times 100
\]
Methodology
Methodology

Scenario’s description

A system of 4x4 slabs were simulated with ILLISLAB (Khazanovich, 1994) under different load conditions:

Case I: Individual (single) gears for the A-380 (TDT), B-747 (DT), B-777 (TDT), and MD-11 (D) aircraft were positioned over the central slab so that all gears traversed a slab in both the x- and y- directions.

• Case II: All main landing gears (full aircraft) for the A-380, B-747, B-777, and MD-11 aircraft were also positioned over the central slab so that all gears traversed the slab in both the x- and y- directions.

The following properties were constant for all simulations:
- Concrete elastic properties: $E_c = 4.5 \times 10^6$ psi and $\nu = 0.15$
- Tire contact pressure: $p = 200$ psi
- Tire geometry: length = width = 15 in.
- Wheel load per tire: $P = 45,000$ lbs
Load Type: Single Gear (e.g. A-380)

- Single gear traverses an inner plate

420 simulated positions

A-380
Load Type: Full Aircraft (e.g. A-380)

- Full Aircraft traverses an inner plate

588 simulated positions

A-380
Factorial Analysis

A 2^4 factorial design (4 factors at 2 levels each one) were used to investigate the effect of the below factors as well their interaction for the critical stress value and location:

<table>
<thead>
<tr>
<th>Level</th>
<th>L (inches)</th>
<th>t (inches)</th>
<th>LTE (%)</th>
<th>Load configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (-)</td>
<td>240</td>
<td>57</td>
<td>85</td>
<td>Single gear</td>
</tr>
<tr>
<td>High (+)</td>
<td>300</td>
<td>89</td>
<td>0</td>
<td>Full aircraft</td>
</tr>
</tbody>
</table>

• Factorial design (geometric analogy):

Definition of Main and Interaction Effects:

\[ E_f(A) : \Delta \text{ of averages at 2 levels (- and +) of A;} \]
\[ E_f(AB) : \Delta \text{ of averages of A at 2 levels (- and +) of B;} \]
\[ E_f(ABC) : \Delta \text{ of averages of AB interaction at 2 levels (- and +) of C} \]

Montgomery (1997)
Analysis procedures

I – Pre-process and run all load positions in ILLISLAB for a given configuration

II – Run load cases from step I and for all configurations with ILLISLAB

III – Post-processing the results in MatLab for each load case at each configuration

IV – Create data structure and construct the load influence graphs with MatLab

- create mesh
- vary the load position

- factorial design
- vary L, ℓ, and LTE

- read the output files;
- create contour plots.

- Maximum stress result from all cases @ each configuration to factorial analysis
Results
Top to Bottom Stresses (t/b)

- Maximum tensile stresses were on the slab bottom for all single gear simulations;
- Single gear results: TDT of the B-777 and A-380 gear produced the highest ratios;
- Higher t/b stress ratios for no LTE;
- Full aircraft results: t/b ratios increased significantly for almost all aircrafts, but the B-777;
- A-380 induced similar tensile stresses at the top and bottom when LTE=0%.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>A-380</th>
<th>B-747</th>
<th>B-777</th>
<th>MD-11</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>SCI-IIa</td>
<td>0.49</td>
<td>0.52</td>
<td>0.48</td>
<td>0.47</td>
</tr>
<tr>
<td>SCI-IIb</td>
<td>0.68</td>
<td>0.73</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>SCI-IIIa</td>
<td>0.45</td>
<td>0.47</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td>SCI-IIIb</td>
<td>0.62</td>
<td>0.61</td>
<td>0.62</td>
<td>0.60</td>
</tr>
<tr>
<td>SCI-IVa</td>
<td>0.47</td>
<td>0.55</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>SCI-IVb</td>
<td>0.66</td>
<td>0.77</td>
<td>0.59</td>
<td>0.66</td>
</tr>
<tr>
<td>SCI-Va</td>
<td>0.47</td>
<td>0.51</td>
<td>0.42</td>
<td>0.43</td>
</tr>
<tr>
<td>SCI-Vb</td>
<td>0.65</td>
<td>0.74</td>
<td>0.61</td>
<td>0.62</td>
</tr>
<tr>
<td>SCIa</td>
<td>0.66</td>
<td>0.50</td>
<td>0.56</td>
<td>0.53</td>
</tr>
<tr>
<td>SCIb</td>
<td>0.95</td>
<td>0.74</td>
<td>0.71</td>
<td>0.70</td>
</tr>
<tr>
<td>SCI-IIIa</td>
<td>0.67</td>
<td>0.56</td>
<td>0.47</td>
<td>0.51</td>
</tr>
<tr>
<td>SCI-IIIb</td>
<td>1.04</td>
<td>0.71</td>
<td>0.61</td>
<td>0.65</td>
</tr>
<tr>
<td>SCI-IVa</td>
<td>0.67</td>
<td>0.51</td>
<td>0.58</td>
<td>0.51</td>
</tr>
<tr>
<td>SCI-IVb</td>
<td>0.98</td>
<td>0.72</td>
<td>0.82</td>
<td>0.78</td>
</tr>
<tr>
<td>SCI-Va</td>
<td>0.71</td>
<td>0.57</td>
<td>0.49</td>
<td>0.55</td>
</tr>
<tr>
<td>SCI-Vb</td>
<td>1.00</td>
<td>0.75</td>
<td>0.78</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Top $\sigma_{xx}$ contour plot results

$LTE_x = LTE_y = 85\%$

**Single Gear**

**A380: Critical Top Tensile ($\sigma_x$) -- Critical Bottom Compressive ($\sigma_x$)**

- $\sigma_x^\text{max} = 280$ psi
- $X = 660; Y = 600$

- LTEx = LTEy = 85%

- SCIIa
  - $h = 16$ inches
  - $p = 200$ psi
  - $Ec = 4.5 \times 10^6$ psi
  - $k = 150$ psi/ inches
  - LTE = 85%
Load Position Influence Graphs

White "X" indicates the critical CG position for the gear configuration.

Contours indicate the ratio between the $\sigma_t$ top stress induced by the load (CG) at that position and the critical stress value.
Load Position Influence Graphs – Single gear

A-380 (TDT)

Critical top stress at the adjacent slab (~NAPTF’s case)

- LTE=85%
- t/b ratios around 0.48

- LTE=0%
- t/b ratios around 0.67
Load Position Influence Graphs – Single gear

**B-747 (DT)**

Critical top stress at the adjacent slab (NAPTF’s case)

- t/b ratios around 0.45.
- t/b ratios around 0.60.

LTE=85%

LTE=0%
B-747: $L = 300''$ and LTE=0\% (top stress)

- t/b ratio=0.70.

Critical stress at longitudinal joint $\rightarrow$ transverse or corner cracking

Another alternative critical load position (CG)
Load Position Influence Graphs – Full A/C

A-380: \( L = 300'' \) and LTE = 0%

- \( t/b \) ratio = 1.04.

Critical stress at transverse joint → longitudinal cracking at mid-slab

Another alternative critical load position (CG)
Load Position Influence Graphs – Full A/C

A-380: \( L = 240'' \) and LTE=0%  
\( \ell = 89'' \)  
\( t/b \) ratio=1.00

Critical stress at transverse joint → longitudinal cracking at mid-slab

Other alternative critical load position (CG)
Load Influence Graphs – Full A/C

MD-11: $L = 300''$ and $LTE=0\%$

- $t/b$ ratio=0.84.

Critical stress at transverse joint $\rightarrow$ longitudinal cracking at mid-slab

$\ell=89''$
Load Influence Graphs – Full A/C

MD-11: \( L = 240'' \) and LTE=0%

- t/b ratio=0.86.

Critical stress at transverse joint → longitudinal cracking at mid-slab
Factorial results (bottom tensile stress)

Few significant 2\textsuperscript{nd} order interactions:
- LTE-Load: for all A/C;
- L-\ell: for A-380 only

- LTE affects the Bottom tensile stress for all A/C;
- Full gear has little effect on bottom stresses

No need to determine critical positions
Factorial results (top tensile stresses)

Few significant 2nd order interactions:
- LTE-Load: for all A/C;
- L-Ł: for A-380 only

- LTE highly affects the Top tensile stress for all A/C;
- Full gears didn’t affect the B-777 results;
- L is not so important to Top Tensile
Factorial results (t/b stress ratio)

Same trends as in Top Tensile Stress

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>t/b ratio</th>
<th>E(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD-11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-777</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-747</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-380</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusions
Conclusions

- This initial finite element analysis using ILLISLAB has shown the consideration of the full aircraft gear is necessary if the top tensile stresses are going to be accurately predicted;

- Top and bottom tensile stress ratio higher for **full Aircraft analysis**
  - In most cases, critical top tensile stresses created when gears straddle multiple slabs
  - ↑ LTE then top to bottom tensile stress ratio decreases
  - The critical top tensile stress mostly occurred at transverse joint \(\rightarrow\) **longitudinal cracking** (e.g., NAPTF and Airbus tests)

- The analysis showed that the A-380 and the MD-11 induced higher **top tensile stress** values relative to B-777 and B-747; but B-747 and B-777 had much greater **bottom tensile stresses**.
Conclusions

- The top/bottom ratios are significantly increased when the Load Transfer Efficiency (LTE) between adjacent slabs approaches zero.

- The factorial analysis also showed that
  - LTE highly affected the critical top tensile stress
  - Full aircraft assumptions do not affect bottom tensile stress
  - Slab size affect more the critical response position than its magnitude for this analysis.

- A-380 only a/c with t/b stress > 1.0 without curling but does not necessarily produce most critical stress of the 4 a/c analyzed!

*Top Tensile stresses are an interaction of the of slab configuration, full gear geometry, and load levels.*
• Three dimensional analysis of the critical cases;

• Completion of the B-737 case

• FAA suggestions or comments -
  • Analyze only other aircraft with potential for t/b ratios ~1.0
Stress/Deformations  
(critical responses)

Environmental and built-in effects:
- creep (t),
- $\varepsilon_{sh}(t)$,
- $\Delta T(t, T)$

Determine effective curling:
moisture + temperature effects:
- $T_{eq}(z) = A +Bz +Cz^2 +Dz^3$

ICON (Prof. Lange)

Load + Curl Cases (Prof. Roesler)

Apply gear types for different positions to identify critical responses

Curling + Loading  - 2008 Proposed
Fatigue Crack Growth Prediction for Concrete Slabs

Principal Investigators:
Jeffery Roesler, Ph.D., P.E.
Surendra Shah, Ph.D.

Graduate Research Assistants:
Cristian Gaedicke
Notched Beam/Slab Tests
Flexural Capacity of Airfield Rigid Pavements

**October 2007 Project**

- **Concrete properties**
- **Cohesive law**
- **Cohesive Elements are located in Slab FEM model**
- **Cohesive Finite Element**

**Concrete properties**

- Cohesive Elements

**Cohesive law**

- Cohesive Elements are located in Slab FEM model

**Cohesive Finite Element**
Acknowledgements

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