

Is Top-Down Cracking Critical On Airfield Rigid Pavements?

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Abstract

This paper identifies the key slab loading locations for inducing critical bottom and top tensile stresses on airfield rigid pavements servicing the A-380 aircraft. Finite element simulations were conducted for the A-380's individual triple dual tandem (TDT) gear and all its main landing gears for a given slab geometry and pavement material properties. The numerical results show that the ratio between the top and bottom tensile stresses of the slab were significantly higher for the main landing gear analysis relative to the individual gear analysis and could be 1.0 for some cases. Furthermore, this initial finite element analysis has shown consideration of the entire main landing gear of the aircraft is necessary if the top tensile stresses are going to be accurately predicted.

Introduction

For many years, airfield rigid pavement thickness design has been based on the maximum tensile bending stress at the bottom of the slab. The Westergaard edge stress has been used as the critical tensile stress in the Federal Aviation Administration (FAA) design guide for concrete pavements without aircraft in the mix that have a triple dual tandem (TDT) gear. The LEDFAA design procedure (1995) was partially developed to accommodate this new commercial gear type. LEDFAA employed a layered elastic analysis which used the greater of the interior stress or 75 percent of the free edge stress. The proposed 2008 FAA pavement design procedure will cease using Westergaard or layered elastic analysis for rigid pavement design and only use 3-D finite element analysis (NIKE-3D) for the critical tensile stress calculations. Observations from full-scale rigid pavement tests at the FAA's National Airport Pavement Test Facility (NAPTF) and Airbus Pavement Experimental Program (PEP) have recently shown top-down cracking can occur under certain combined loading and pavement geometry configurations (Brill et al. 2005; Fabre et al. 2005, Roesler et al. 2007; Evangelista and Roesler 2008). Top-down cracking modes have also been identified in recent years under certain highway loading and slab

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configurations (Mahoney et al. 1991; Harvey et al., 2000; Heath and Roesler, 2000; Beckemeyer et al. 2002). Finite element analysis has shown these alternative cracking modes, especially top-down cracking, primarily occur on highway slabs in the presence of large built-in curling (Hiller and Roesler, 2005; Rao and Roesler, 2005).

Researchers at the FAA pointed out the occurrence of top-down cracking in previous full-scale rigid pavement tests at the NAPTF (Brill et al. 2005; Brill 2006; Guo 2006). Brill et al. (2005) reported top-down cracks in both the outside and inside lanes of the Construction Cycle 2 (CC2) test section even though the slabs were reported to have minimal permanent curl (corner lift-off $\leq 0.38\text{mm}$). Both top-down and bottom-up crack patterns were observed on interior traffic lanes (trafficked with 4- and 6-wheel gears). On most of the test sections, the outside lanes received trafficking from only the outer wheels of the gear and cracked in a top-down pattern, earlier than the inside lane. In one section (MRC-north), no tandem gear loading occurred on the outer slabs but top-down cracking (longitudinal) still occurred on these slabs (Figure 1: slabs S1 to S5). Brill et al. (2005) suggested that this kind of cracks in the outside lanes were induced by the transfer of load through the dowelled joints.

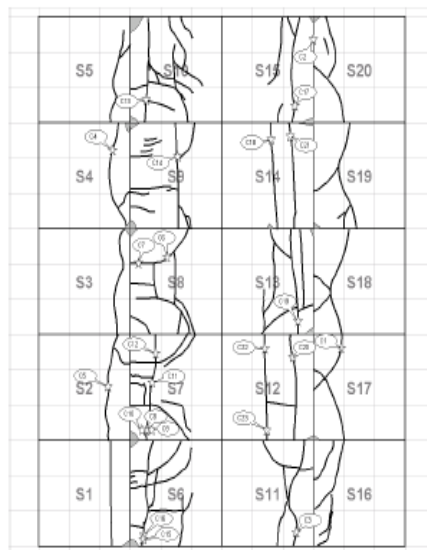


Figure 1 – Crack map for section MRC-North at CC2 for the loadings of a

Triple Dual Tandem (TDT) and a Tandem (from Brill et al, 2005).

Guo (2006) analyzed the results of several NAPTF tests (CC1 and CC2) and proposed consideration of both the environmental and traffic loading, since some level of initial or residual curling existed in the slab. This assumption was proposed to try to explain top-down cracking especially at the corners which had been reported by other authors to explain corner cracking developed during accelerated load testing of highway rigid pavements (Rao and Roesler 2005). Guo also observed that top-down cracks occurred, even for thick slabs, in the longitudinal direction between two consecutive transverse joints when both loaded gears moved near these joints. Guo (2006) cited results from the CC1 testing in 2000 to show that the top-down patterns occurred when measured load (rebound) strains at the top of the slab were lower than the strains at the slab bottom. It was reported that some longitudinal cracks formed between consecutive transverse joints after only 28 gear passes before corner cracks were noticed. Guo reported that the tensile stresses developed on the slab bottom were related primarily to the wheel load, while the tensile stresses on the slab top were related primarily to the gear load at both the longitudinal and transverse joint locations.

Research Objectives and Significance

With the introduction of heavier, wide body aircraft, it is important to quantify their affects on the critical bottom stresses and determine if they may induce excessive top tensile stresses that previously have not been considered. In this paper, the proposed A-380 aircraft will be analyzed for its critical top and bottom tensile stresses. The same analysis for other aircraft e.g., B-777, B-747, and MD-11, and the A-380 can found in a report by Evangelista and Roesler (2008).

The main objective of this paper is to determine if simulation of all the main landing gears of the A-380 on airfield rigid pavements is necessary to capture the critical top and bottom tensile stresses relative to only using its individual TDT body gear. This study also documents key slab loading locations

for the A-380 which induce the highest tensile stresses at the top and bottom of the slab given a flat slab condition (no curling). The 2-D finite element analysis program ILLISLAB (Khazanovich 1994) was used for the initial stress analyses.

Numerical Program

A 4x4 slab system supported by a dense liquid foundation was chosen to determine the critical tensile locations under an A-380 loading. Table 1 lists the input parameters used in the finite element code ILLISLAB. Temperature and moisture curling in the slab was ignored for this preliminary analysis.

Table 1- Input parameters used in the analysis.

	values	unit
Concrete Young's Modulus (E_c)	4.5×10^6	psi
Concrete Poisson's ratio (ν)	0.15	n/a
Modulus of subgrade reaction (k)	150	psi/inch
Slab length (L)	240	inch
Slab thickness (h)	16	inch
Tire contact pressure (p)	200	psi
Tire geometry (length=width)	15	inch
Wheel load per tire (P)	45,000	lb.
Radius of relative stiffness (ℓ)	89	inch

In one set of analyses, the load transfer efficiency (LTE) across the transverse and longitudinal joints was assumed to represent a stress load transfer of 75 percent for both directions (deflection load transfer of $LTE_x = LTE_y = 85\%$). The load transfer between adjacent slabs was simulated by aggregate interlock or shear transfer only. Another set of analyses assumes no load transfer between adjacent slabs ($LTE_x = LTE_y = 0\%$) in order to determine how the magnitude and position of the critical tensile stress was affected. Note, a LTE equal to zero is

consistent with how the 2008 proposed FAA rigid pavement stress analysis is conducted with NIKE-3D.

FIGURE 2 shows all main landing gears (full aircraft) for the A-380 reported in Fabre et al. (2005). The A-380 has a set of Triple Dual Tandems (TDT) body gears and a set of Dual Tandem (DT) wing landing gears. The TDT gear encircled by the hatched lines in FIGURE 2 represents the individual gear that would be used for the 2008 proposed FAA rigid pavement design procedure. The spacing between the TDT of the A-380's body gear (207.2 inches) is much smaller than the TDT spacing of the B-777 (432 inches) suggesting a potential interaction of the TDT stresses on the top or bottom of the slab. In this way, the analysis considered not only the simulation of the individual TDT of the A-380 but also the full aircraft configuration, as depicted in FIGURE 2.

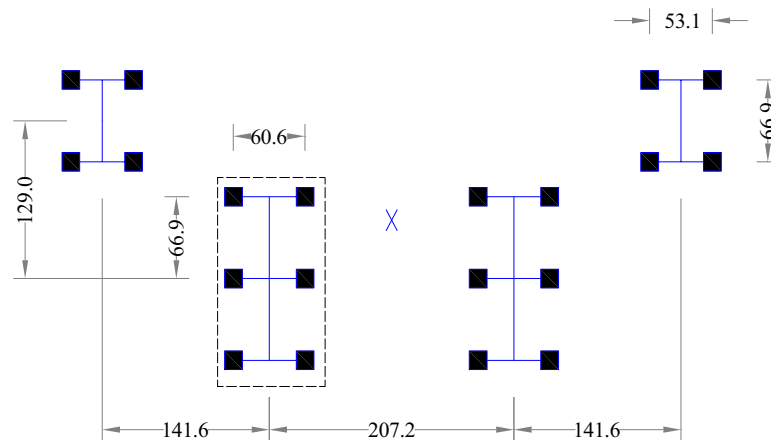
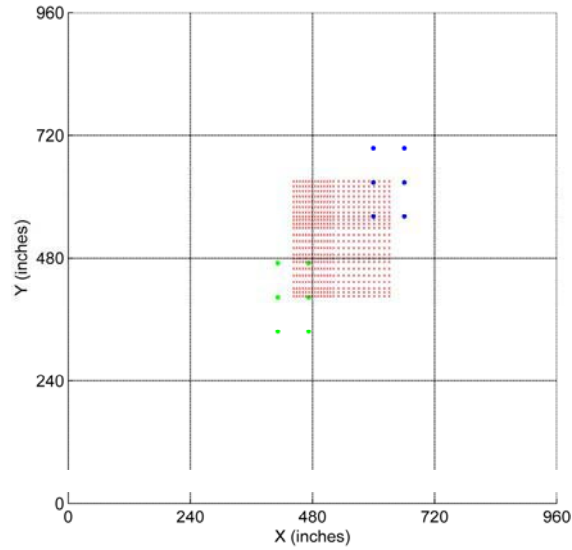


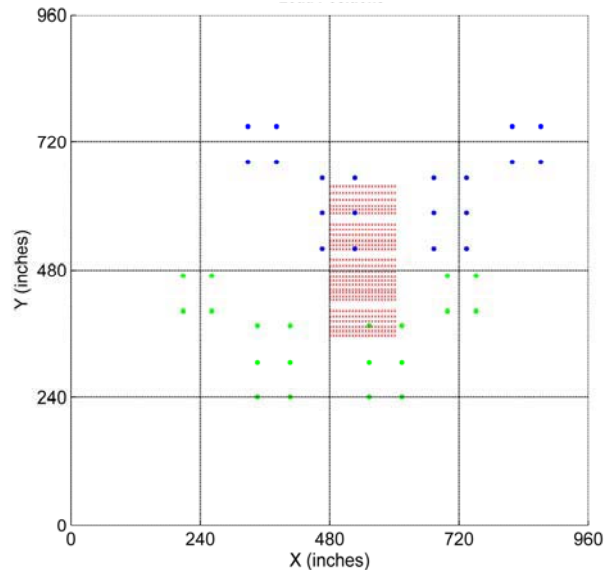
Figure 2 - A-380 gear configuration (dimensions in inches).

In order to predict the critical tensile stress magnitude, its position, and the position of the gear/aircraft to cause this stress, the load configurations (either individual gear or all aircraft gears) were stepped across the transverse and longitudinal joints. Figure 3 shows the load positions over the slab system using the individual gear (Figure 3a) and the full aircraft configuration (Figure 3b). The smaller dots in Figure 3 represent the center of gravity (CG) positions that were

analyzed. The tire prints for gear or full aircraft were also plotted for the first and last CG analysis position.



(a)



(b)

Figure 3 - Load positions for the A-380, (a) individual gear, and (b) full aircraft.

Results and Discussion

The following sections present the results from the numerical analysis for the critical bottom and top tensile stresses.

Critical stress results and top-down ratios

Table 2 and Table 3 summarize the results for the critical top and bottom tensile stress induced by the A-380 for LTE=85% and LTE=0%, respectively.

Table 2- Maximum tensile stress values for the A-380 simulations with LTE=85%.

		Individual gear	Full aircraft
Top	σ_x	224	281
	σ_y	194	208
Bottom	σ_x	475	418
	σ_y	355	404
$\sigma_x^{\text{top}} / \sigma_x^{\text{bot}}$		0.47	0.67

Table 3- Maximum tensile stress values for the A-380 simulations with LTE=0%.

		Individual gear	Full aircraft
Top	σ_x	374	556
	σ_y	348	377
Bottom	σ_x	568	568
	σ_y	451	526
$\sigma_x^{\text{top}} / \sigma_x^{\text{bot}}$		0.66	0.98

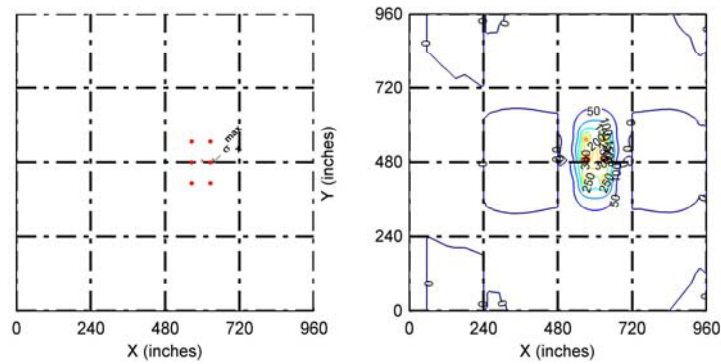
For LTE=85%, both the individual gear and full aircraft analysis found the tensile stresses at the bottom of the slab were the most critical and in the x-direction (Table 2). The top tensile stresses increased for the full aircraft analysis which is confirmed by the increase in the top to bottom tensile stress ratios calculated for the critical direction (x). The analysis also demonstrated that the

consideration of the full aircraft gear configuration did not exceed the maximum bottom tensile stress calculated with the individual gear for the critical direction (x). Therefore, the current FAA analysis procedure for determining the maximum bottom tensile stress in a slab using an individual gear still gives a conservative estimate.

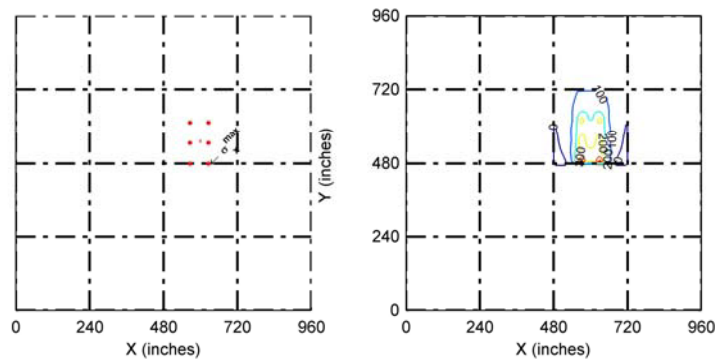
When no LTE is considered (Table 3), the A-380 induces higher top tensile stresses relative to the 85% LTE case as expected. The ratio between the top and bottom tensile stresses was significantly higher for the full gear analysis relative to the single gear analysis (See Table 3). For this case, the A-380 had top to bottom tensile stresses that were approximately the same. Although the slab configuration in this paper led to a ratio equal to 0.98 between top and bottom stresses, other configurations (slab geometry, material properties) could lead to slightly greater ratios than one ($\sigma^{\text{top}} > \sigma^{\text{bot}}$) or less than one. Evangelista and Roesler (2008) performed a sensitivity study using a factorial analysis to demonstrate that some input parameter combinations (slab length, ℓ , and LTE) may induce high top to bottom tensile ratios for full aircrafts simulations even without curling. Based on the preliminary stress analysis without curling, there may be cases where the top tensile stresses exceed the bottom tensile stresses for the A-380.

Critical loading and bottom tensile stress positions

Figure 4 shows the critical individual gear positions, the tensile stress (σ_x) contours on the bottom of the slab for the critical case, and the exact location of the critical tensile stress (left hand side). Considering LTE=85%, the critical position of the individual gear analysis is when the TDT straddle two slabs with the middle TDT axle centered on the transverse joint. For the no LTE simulation, the TDT is entirely positioned on the main slab with the critical bottom tensile stress. For both levels of LTE, the critical bottom tensile stress was induced in the x-direction near the middle of the transverse joint.



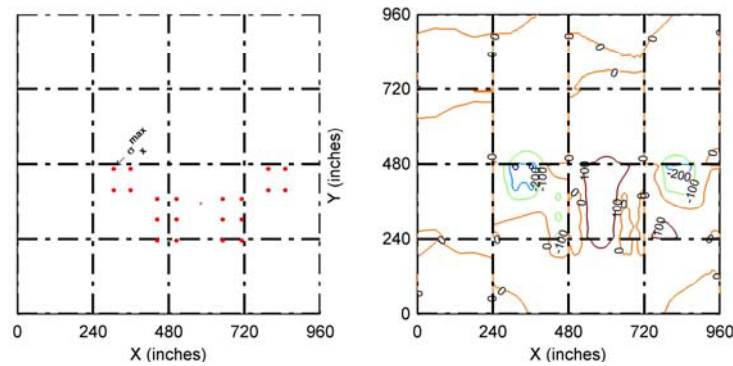
(a) LTE=85%



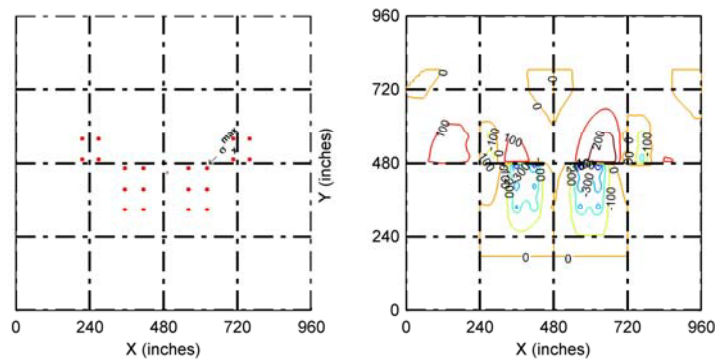
(b) LTE=0%

Figure 4 – Critical gear positions and stress contour curves for bottom tensile σ_x for the individual TDT gear.

Figure 5 shows the results for the critical bottom tensile stress magnitude, stress position, and the critical position of all the main landing gears of the A-380 for this case. For LTE=85%, the DT wing landing gear was responsible for generating the critical bottom tensile stress. Due to the slab size (240 in.) and properties, the set of TDT do not interact at the bottom of the slab. When there is no LTE between the adjacent slabs (Figure 5b), the TDT gear induces the critical bottom tensile stress value.



(a) LTE=85%



(b) LTE=0%

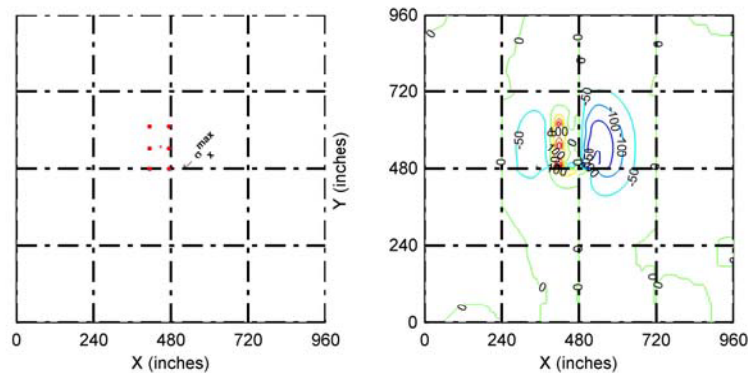
Figure 5 – Critical positions and stress contour curves for bottom tensile σ_x with the full aircraft analysis.

Critical loading and top tensile stress positions

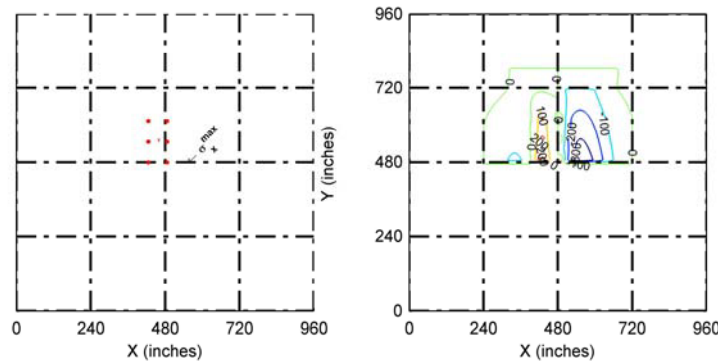
Figure 6 shows the top tensile stress contours (σ_x) for the individual TDT gear loading. The plots confirm that the maximum stress values were induced in the transverse direction (σ_x) and at the transverse joint. The stress position along the transverse joint varies depending on the load transfer efficiency across the joint. For the slabs with LTE = 85%, the critical stress was located approximately less than $\frac{1}{4}$ of slab length from the corner. When the LTE across the joints was set to zero, the critical stress position was closer to the center of the slab.

The position of the individual TDT gear that causes the critical top tensile stress for LTE=85% is at the corner of the adjacent slab with a line of wheels

straddling the longitudinal joint of the main slab. For the case of no LTE, the line of wheels is slightly more displaced to the interior of the main slab (see Figure 6). The critical top tensile stress positions indicated in Figure 6a partially confirm the observations of the top-down cracking (Figure 1) during the NAPTF's CC2 tests. When the TDT wheels are placed on or straddling the longitudinal joint at the slab corner, the critical top tensile stress is induced in the adjacent slab between the corner and mid-slab. However, without any level of negative slab curling or reduced concrete strength at the slab's surface, an individual gear should not be able to propagate a top-down crack over a bottom-up crack as indicated by the top-down ratios significantly less than one in Table 2 and Table 3. Actually, a reduced top strength was previously reported at the literature both for highways (McCullough and Dossey, 1999), and airfield slab pavements (Fabre and Balay, 2005). The latter researchers performed indirect tension tests on cores extracted from top and bottom of the slabs at the PEP tests. The results indicated that the strength at the top was a maximum of 35 and an average of 22 percent less than the bottom concrete strength.



(a) LTE=85%



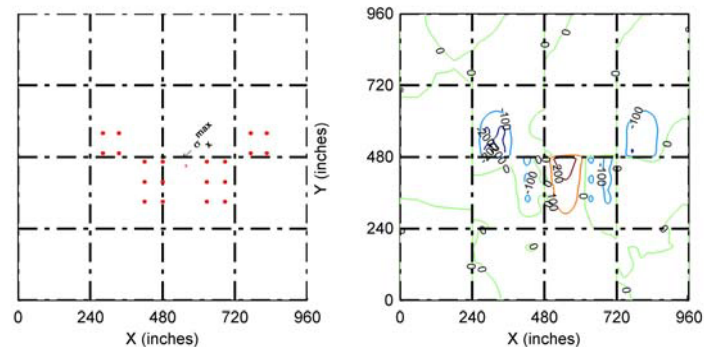
(b) LTE=0%

Figure 6 – Critical gear positions and stress contours for top tensile σ_x for the individual TDT gear.

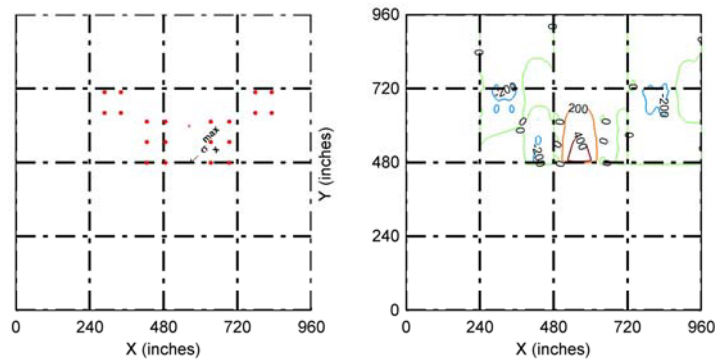
The top tensile stress contour curves (σ_x), critical stress positions, and critical location for the full aircraft simulation is presented in Figure 7. It is observed that when the slabs have LTE=85%, the maximum top tensile stresses were reached when the A-380 TDT gears straddled two of the central slabs. The critical loading position has one TDT near the corner of the slab which contains the location of the critical stress and the other TDT placed at the adjacent slab but with a line of wheels straddling the longitudinal joint of the slab. It is important to note that there is only interaction between the two body landing gears (TDTs). There is a zero stress contour between the DT of the wing landing gears and the TDT indicating no interaction between these gears. For the case of no LTE, the critical stress position and gear positions are similar to the LTE=85% case except that the line of wheels straddling the longitudinal joint is more displaced to the interior of the main slab.

The plots for the full gear analysis confirm that, again, the maximum tensile stress values were induced in the transverse direction (σ_x) at the transverse joint for the A-380. The magnitude of the top stress is similar to the bottom stress for the no LTE case and will likely result in a longitudinal crack propagating from the transverse joint. For LTE=85%, it is unlikely a top-down crack will form

before a bottom-up crack based on the top to bottom tensile stress ratios being less than 0.70 as seen in Table 2 and Table 3.



(a) LTE=85%



(b) LTE=0%

Figure 7 – Critical positions and stress contour curves for top tensile σ_x with the full aircraft analysis.

Conclusions

For the A-380 aircraft, the numerical simulations showed that the individual TDT gear analysis resulted in the largest tensile stresses at the bottom of the slab without any curling. The analysis also showed that the consideration of the full gear configuration does not significantly affect the maximum bottom tensile stress in the slab. This suggests that the current FAA analysis procedure for determining the maximum bottom tensile stress in a slab using an individual gear for a given aircraft type conservatively estimates the critical tensile stress. The analysis of the top tensile stresses showed that the ratio between the top and

bottom of the slab tensile stresses were significantly higher for the full gear analysis relative to the individual gear analysis. For the no joint load transfer case, the A-380 had top to bottom tensile stresses that were approximately the same when all the A-380 main landing gears were considered. The top to bottom tensile stress ratios were significantly decreased when the load transfer efficiency was 85 percent. The critical top tensile stresses occurred at the transverse joint for all the cases analyzed which would promote propagation of longitudinal or corner cracks. The common critical aircraft position for top-down cracking was when one gear straddled the adjacent slab at the corner and the other gear was located on the main slab producing the critical top tensile stress.

This initial 2-D finite element analysis has shown consideration of the full aircraft gear is necessary if the top tensile stresses are going to be accurately predicted. If only the individual gear types are analyzed, it is unlikely that top-down cracking will occur unless strength reduction of 30 percent exist at the top of the slab relative to bottom half of the slab or significant magnitude of negative temperature differential exists. For high LTE, top-down cracking would likely occur only if there were even more significant strength reduction at the top of the concrete slab and greater negative temperature differentials present. Factors such as the concrete mixture constituents and proportions, homogeneity of vibration, paving temperature, and curing could effect the relative tensile strength of concrete at the top of the slab versus the bottom of the slab.

Acknowledgments

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