Top-Down Cracking Predictions for Airfield Rigid Pavements

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Acknowledgements

Research Grant Number: 95-C-001

Overview

- Introduction and Motivation
- Objectives
- Methodology
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    - factorial analysis
- Results
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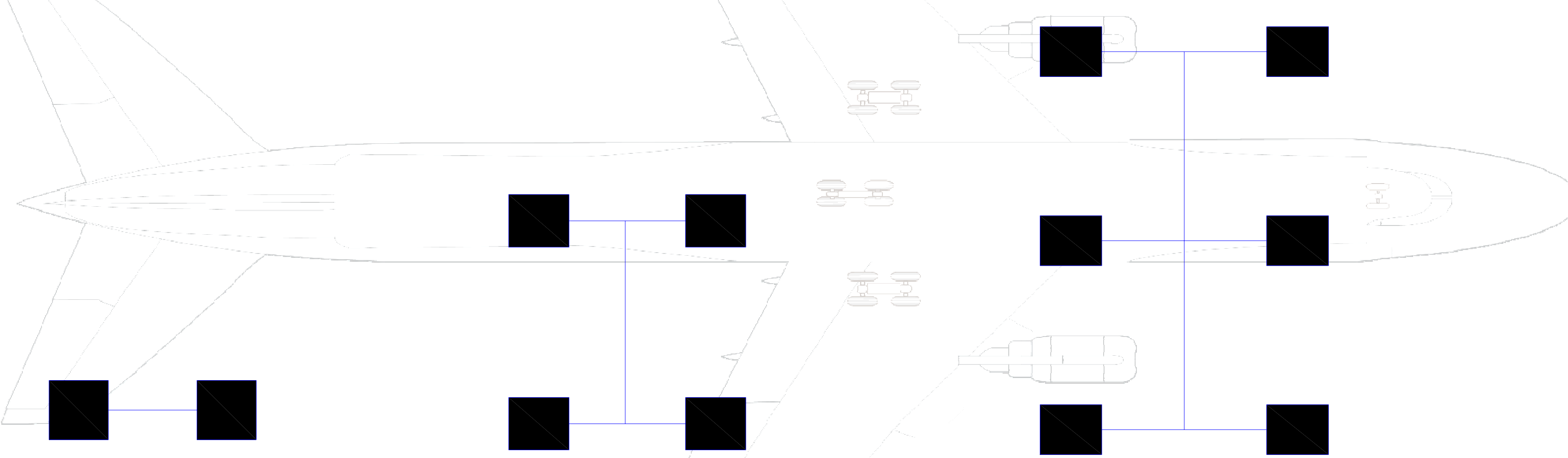
    - load position influence graphs
    - factorial results
- Conclusions
- Cureent Research

Introduction and Motivation

Introduction and Motivation

- Airfield rigid pavement design (FAARFIELD) 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

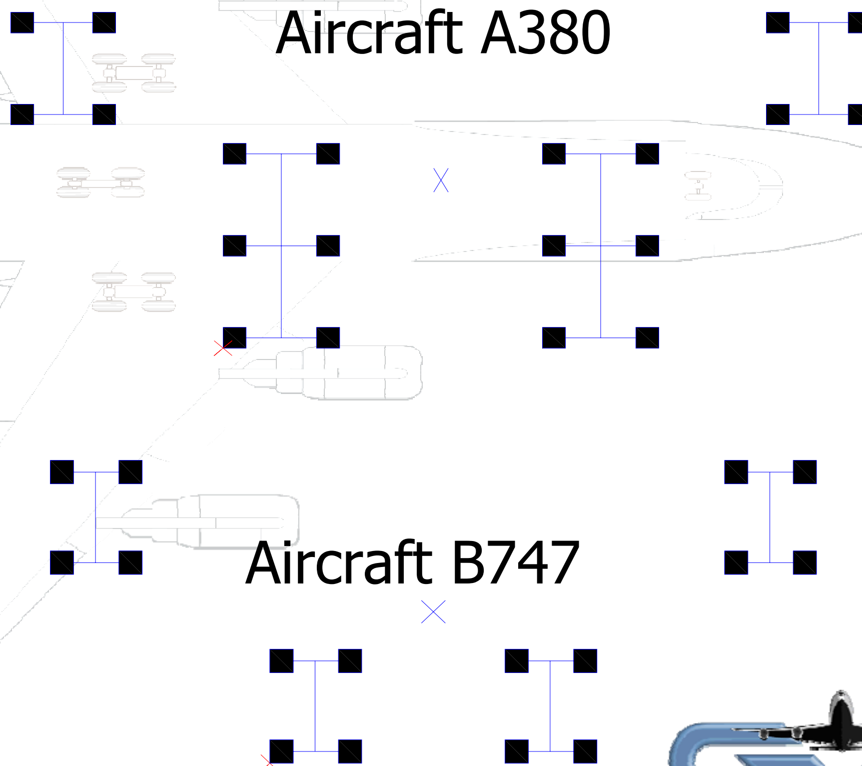
Triple Dual Tandem:
B777, A380

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)

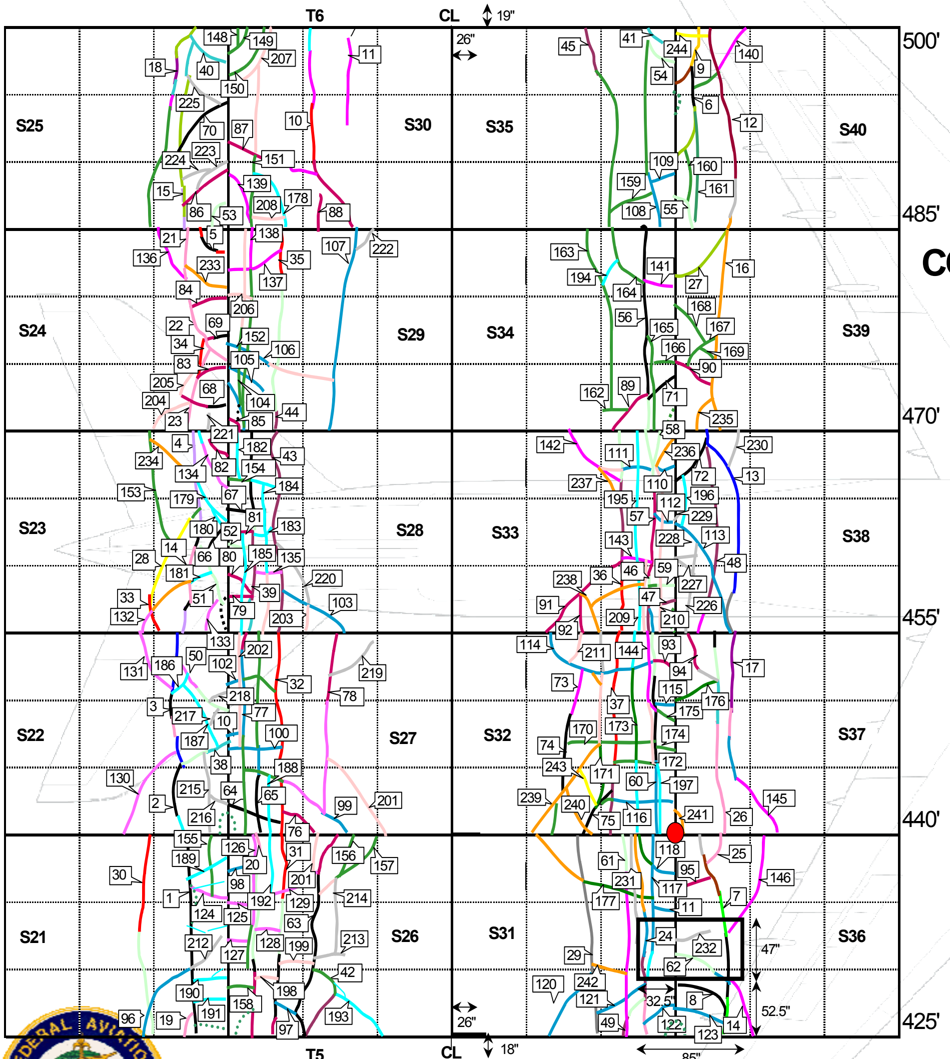
- Certain combined load and slab geometry situations.

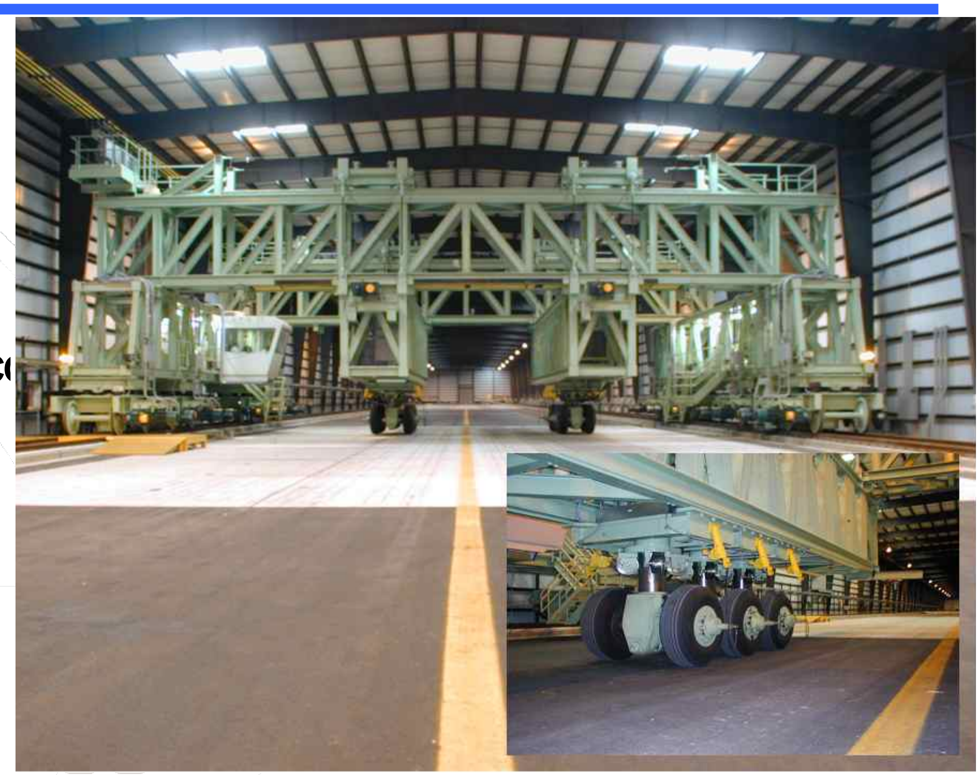
from Dr. Ed Guo (2006)



Introduction and Motivation

- FAA's NAPTF Tests (CC2 - MRG)



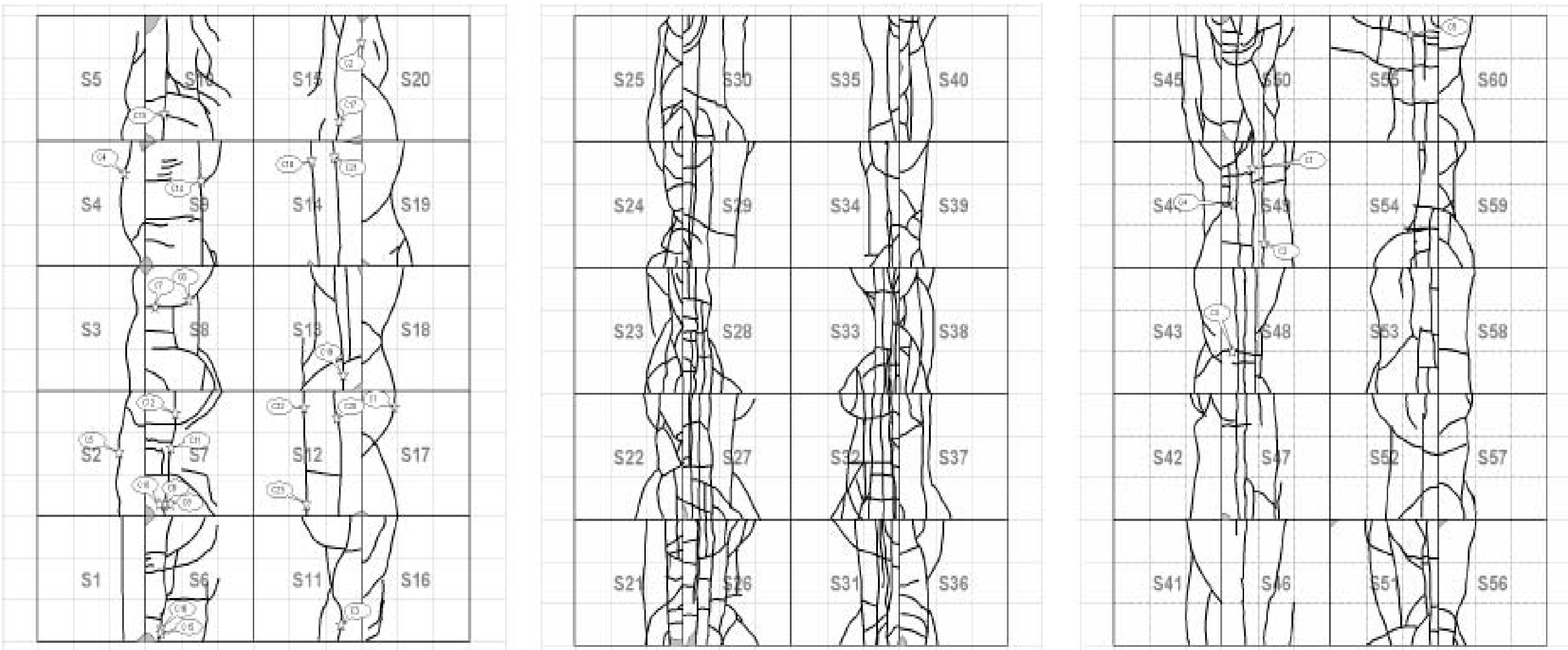


Tests and observed cracks in CC2 tests (Hayhoe and Garg, 2006)

•Tridem and tandem gear loading

Introduction and Motivation

FAA CC2 failure cracks (all sections)

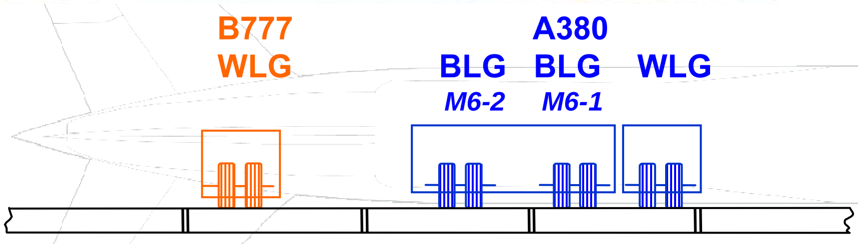


(a) Test Item MRC (b) Test Item MRG (c) Test Item MRS

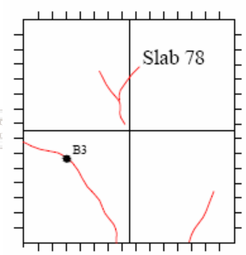
Brill et al. 2006

Introduction and Motivation

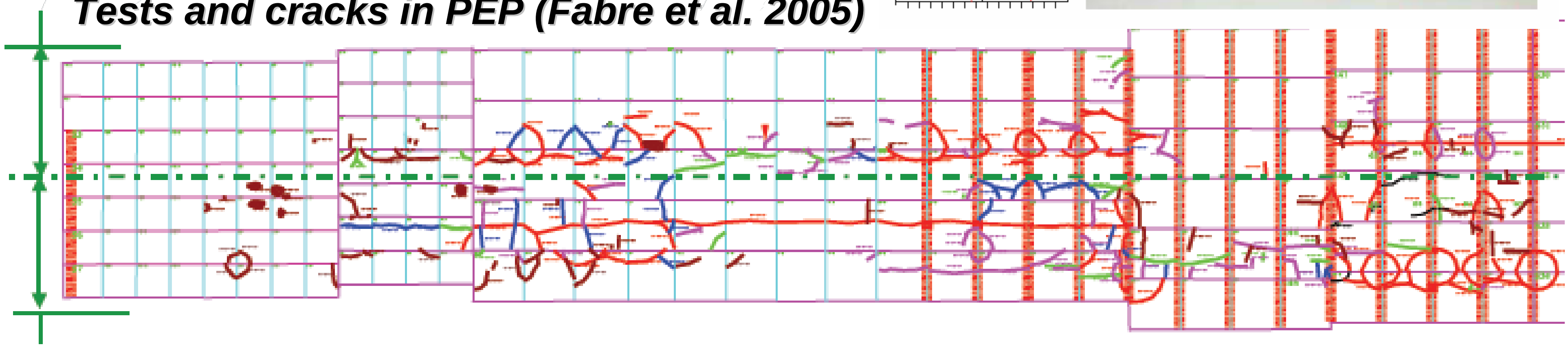
- A-380 Pavement Experimental Programme - Rigid Phase (France)



Slabs 7.5mx7.5m - Cross section A_1



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



Objectives

Objectives

• Identify key aircraft loading locations on rigid pavements which induce high top tensile stresses (ratio between top and bottom);

- *NO CURLING (2-D and 3-D)*
- *CURLING (2-D)*

• 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:

$$LTE = \frac{\delta_{unloaded}}{\delta_{loaded}} x100$$

Methodology

Methodology

Scenario's description

A system of 4x4 slabs were simulated with ILLISLAB under different load conditions:

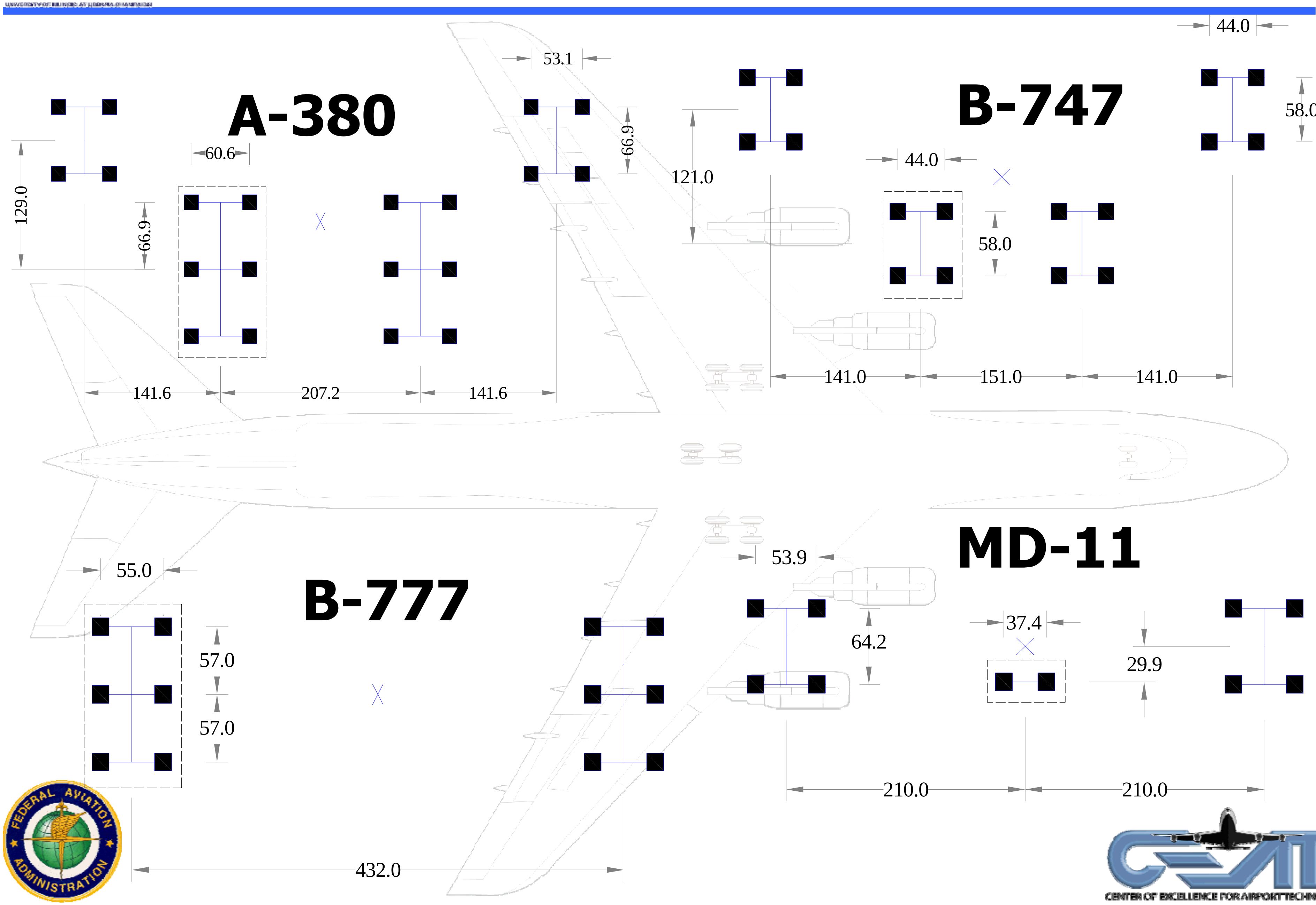
Case I: **Individual (single) gears** for the A-380 (TDT), B-747 (DT), B-777 (TDT), and MD-11 (D) aircraft were traversed over the central slab in both the x- and y- directions.

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

The following properties were constant for all simulations:

- Concrete elastic properties: $E_c = 4.5x10^6$ psi and u = 0.15
- Tire contact pressure: p = 200 psi
- Tire geometry: length = width = 15 in.
- Wheel load per tire: P = 45,000 lbs

Aircraft configurations



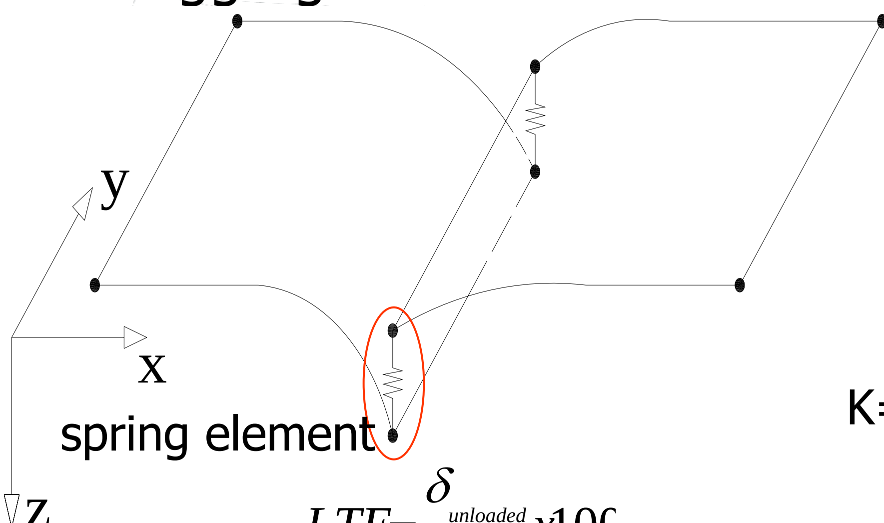
Structural Analysis (Finite Element)

- **<u>2-D</u>** <u>Finite Element Analysis -</u> **<u>ILLISLAB</u>**

- Tabatabaie (1979) and Khazanovich and Ioannides (1994);

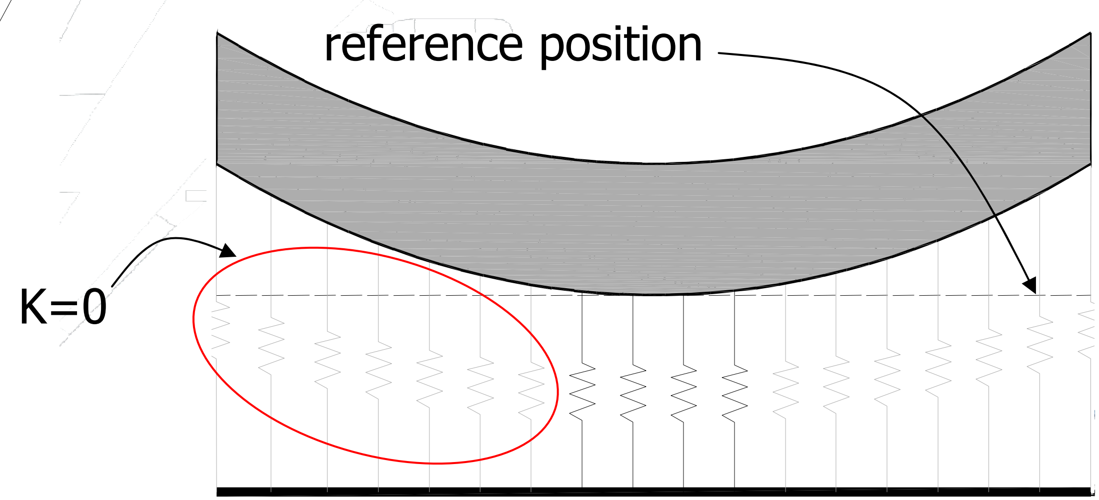
- Medium Thick Plate Theory
  - Kirchoff plate assumptions
  - 4-noded, 12-dof plate bending element.

- Multiple plates (joint simulation):
  - aggregate interlock:

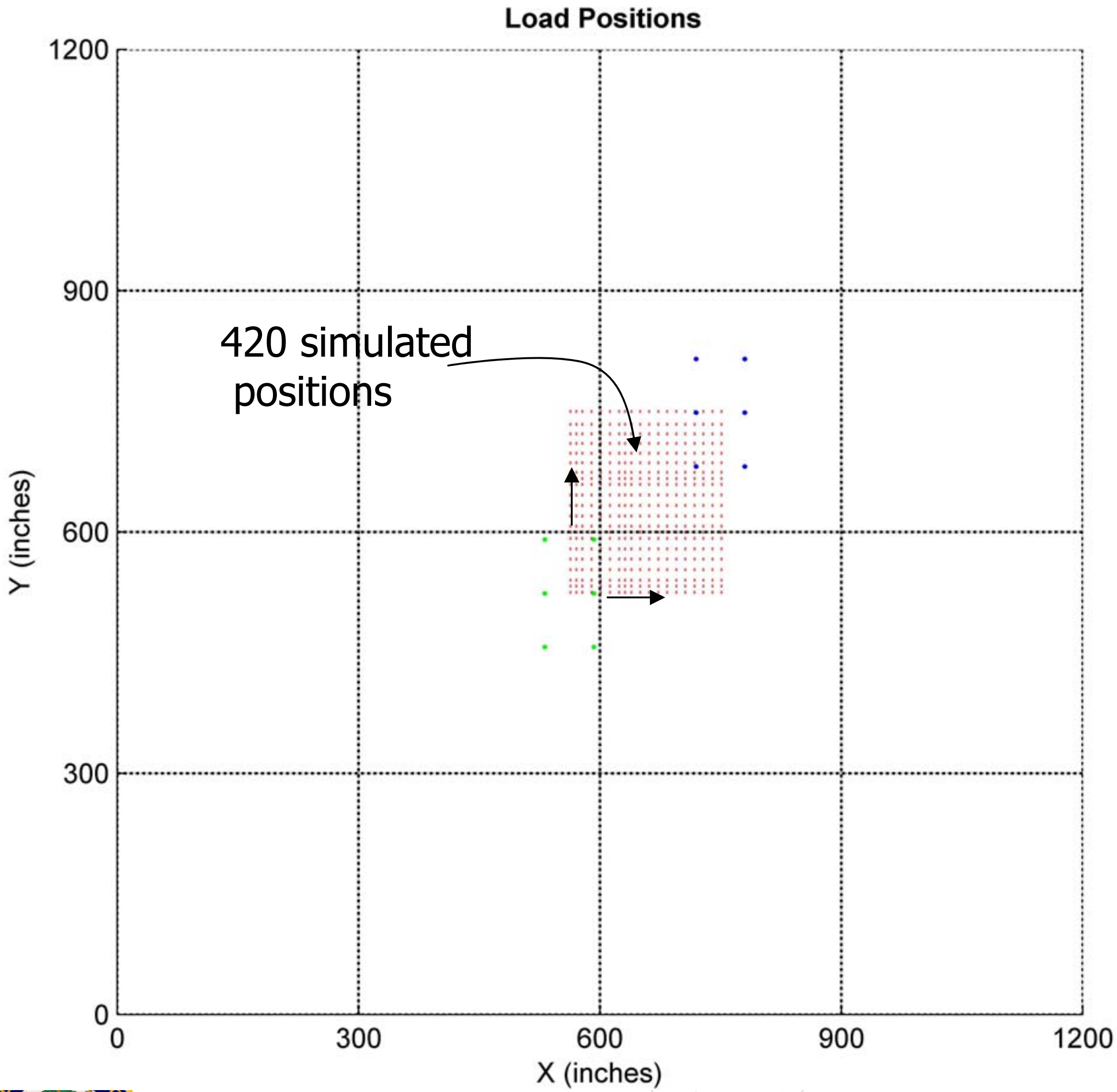


$$LTE = \frac{\delta_{unloaded}}{\delta_{loaded}} x100$$

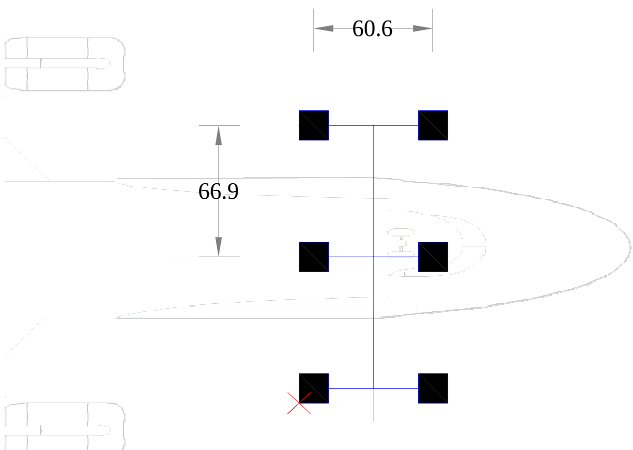
- Curling (loss of contact):
  - mechanical+thermal+body loadings



Load Type: Single Gear (e.g. A-380)

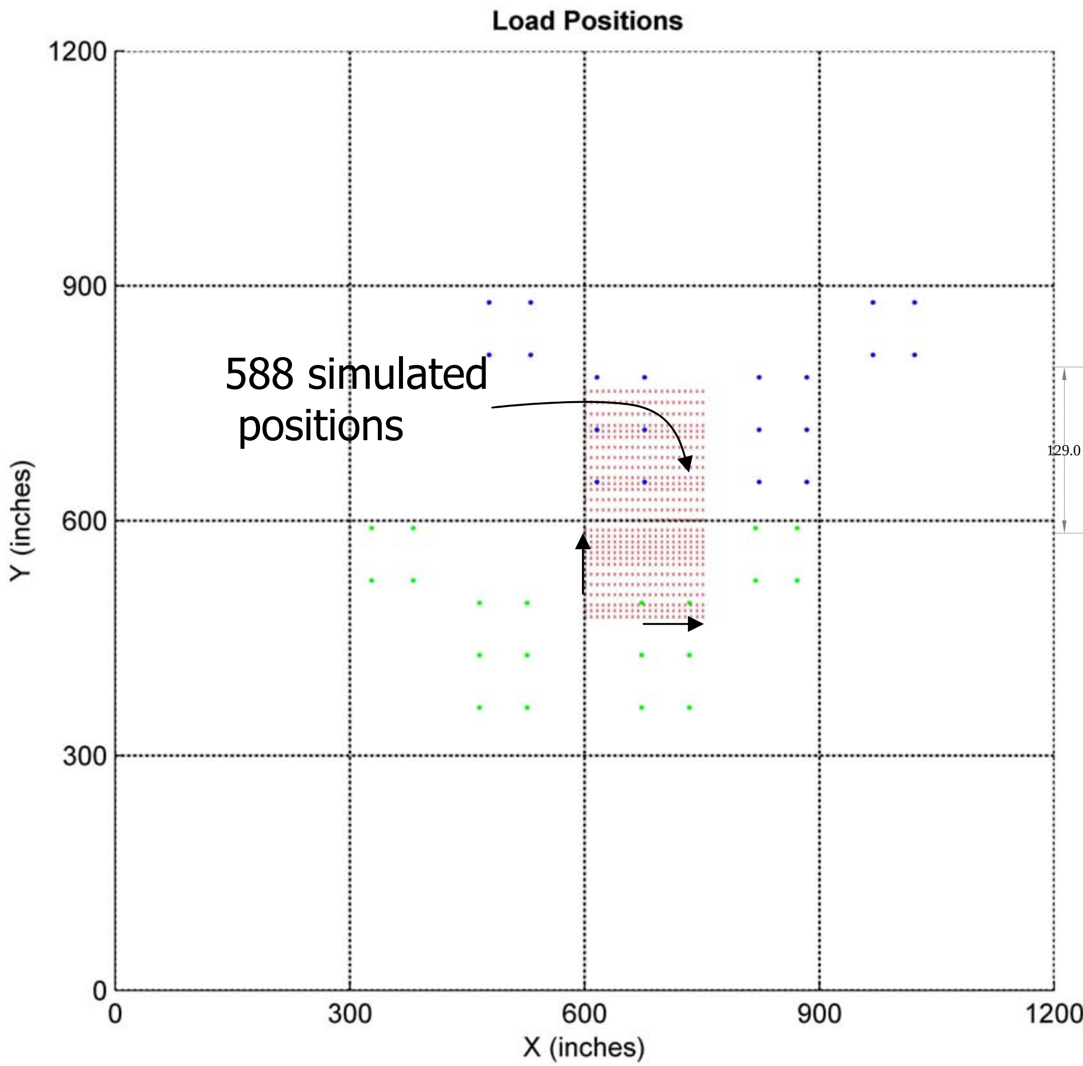


- Single gear traverses an inner slab

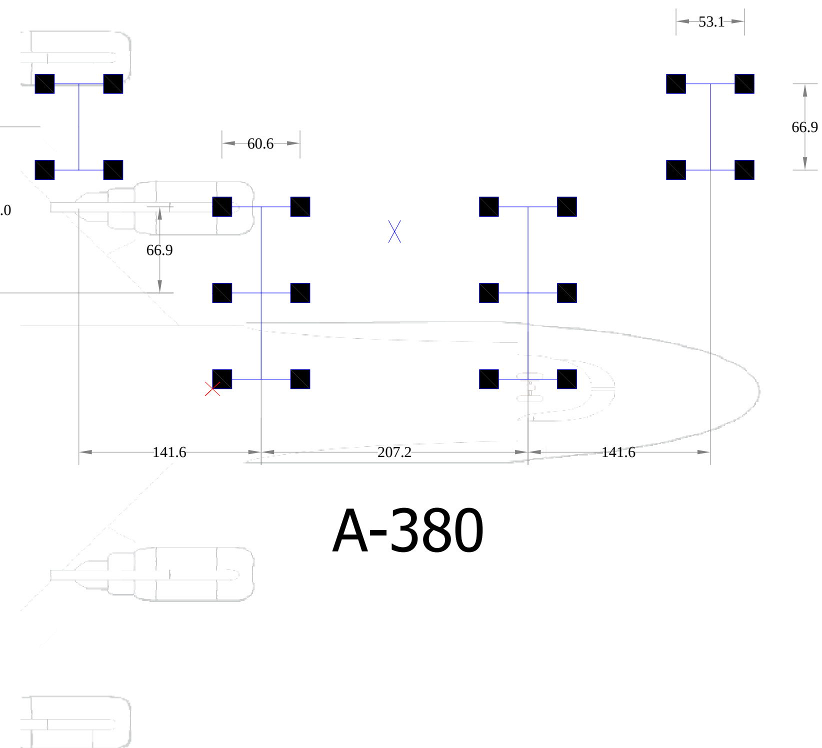


A-380

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



- Full Aircraft traverses an inner slab



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:

Level	Slab length (L)	Radius of relative stiffness (ℓ)[a]	Load Transfer Efficiency (LTE)	Load Configuration (LC)
-	in. (m)	in. (m)	%	-
Low (-)	240 (6.10)	57[b] (1.44)	85	Single gear
High (+)	300 (7.62)	89[c] (2.26)	0	Full aircraft

[a] $\ell = \sqrt{\dfrac{Eh}{12(1-\upsilon^2)k}}$ where E is the Young modulus for the slab, h is the thickness, υ is the Poisson ratio, and k is the modulus of subgrade reaction;

[b] calculated using k = 150 psi/in (40.7 MPa/m), and h = 16 inches (40.6 cm);.

[c] calculated using k = 50 psi/in (13.6 MPa/m), and h = 20 inches (50.8 cm).

response (2^4=16)

average (1)

$$Y = \mu + \sum_{i=1}^{4} \alpha_i x_i + \sum_{i<j}^{4}\sum \alpha_{ij} x_i x_j + \sum_{i<j<k}^{4}\sum\sum \alpha_{ijk} x_i x_j x_k + \sum_{i<j<k<l}^{4}\sum\sum\sum \alpha_{ijkl} x_i x_j x_k x_l$$

1st order (4)

2nd order (6)

3rd order (4)

4th order (1)

α_1: L

α_2: ℓ

α_{12}: L-ℓ

Relative Effect →

$$\overline{E_f} = \frac{\alpha}{\mu} \times 100\%$$

Results
(no curling)

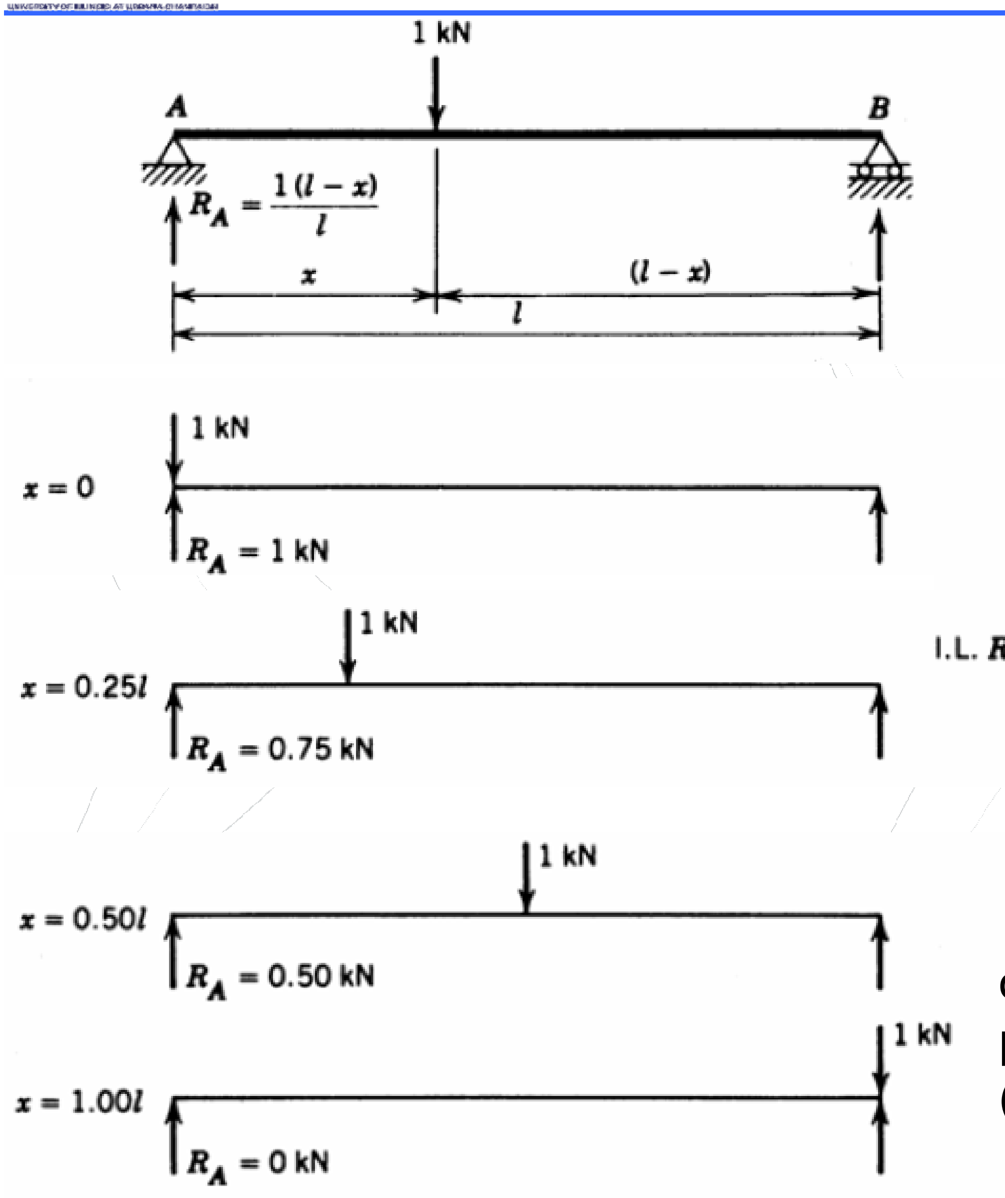
Top to Bottom Stresses (t/b)

- 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%.

- full a/c;
- LTE=0%;
- σ_{xx} critical;
- A-380 or MD-11

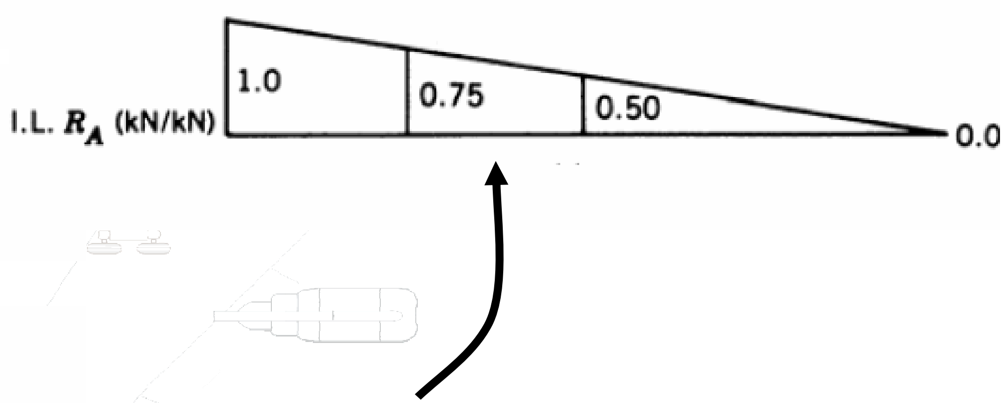
Factors				Aircrafts			
L (in)[a]	ℓ (in)[a]	LTE (%)	LC	A-380	B-747	B-777	MD-11
300	57	85	single	0.49	0.48	0.50	0.35[y]
300	57	0	single	0.68	0.61	0.66	0.61[y]
300	89	85	single	0.45	0.41	0.45	0.31[y]
300	89	0	single	0.62	0.62	0.66	0.58[y]
240	57	85	single	0.47	0.49	0.49	0.37[y]
240	57	0	single	0.66	0.59	0.64	0.64[y]
240	89	85	single	0.47	0.42	0.46	0.32[y]
240	89	0	single	0.65	0.61	0.62	0.63[y]
300	57	85	full a/c	0.66	0.56	0.50	0.59
300	57	0	full a/c	**0.95**	0.71	0.63	**0.84**
300	89	85	full a/c	0.67	0.51[y]	0.48	0.59
300	89	0	full a/c	**1.04**	0.65[y]	0.60	**0.86**
240	57	85	full a/c	0.67	0.58	0.49	0.59
240	57	0	full a/c	**0.98**	**0.82**	0.66	**0.89**
240	89	85	full a/c	0.71	0.55[y]	0.49	0.58
240	89	0	full a/c	**1.00**	0.78	0.63	0.87

Load Position: Influence Lines (1D)



How the **movement** of a unit **load influences** a force effect (reaction, shear, bend moment…) at one point.

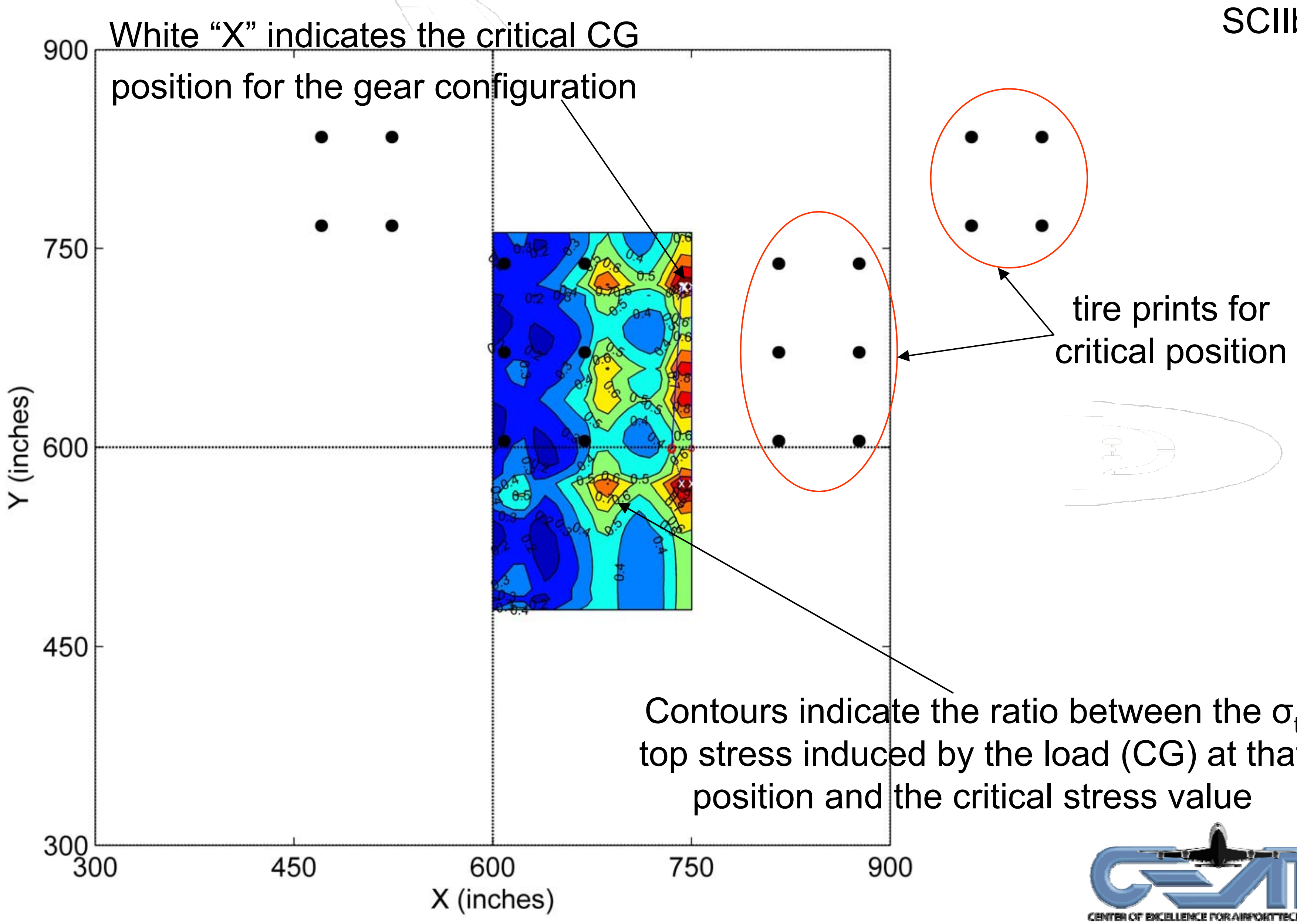
Influence line of reaction A at x=0



one can tell **where** the **load** should be **placed** to induce the **greatest** influence (R_A) at the specified point (x=0).

Load Position Influence Graphs

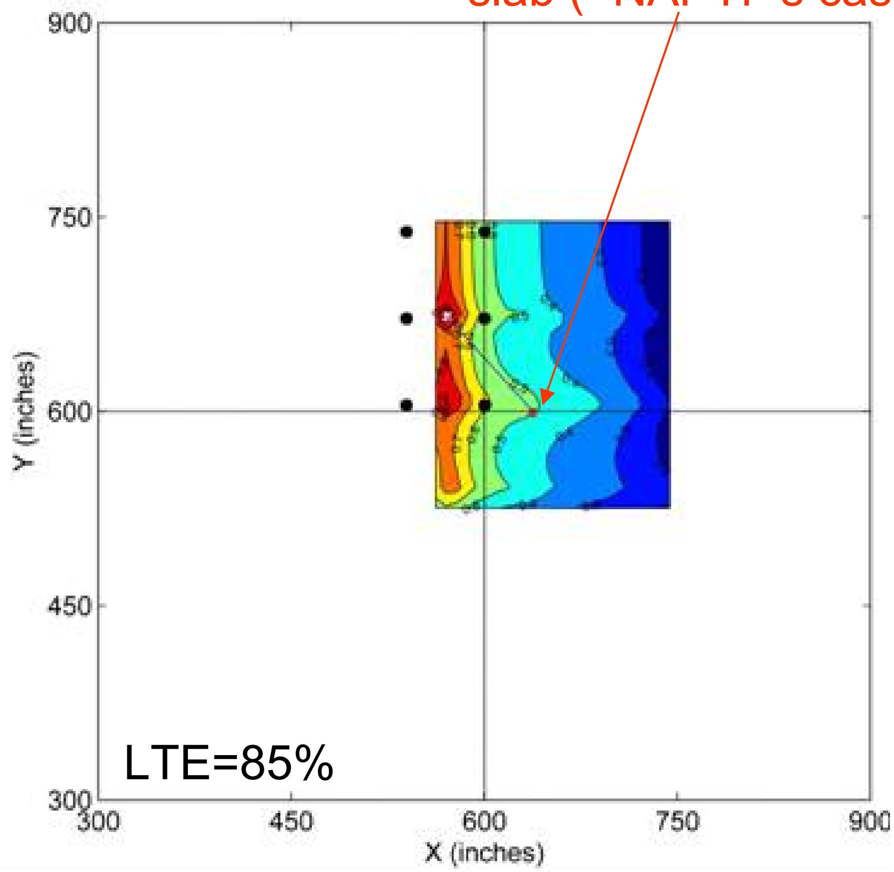
SCIIb

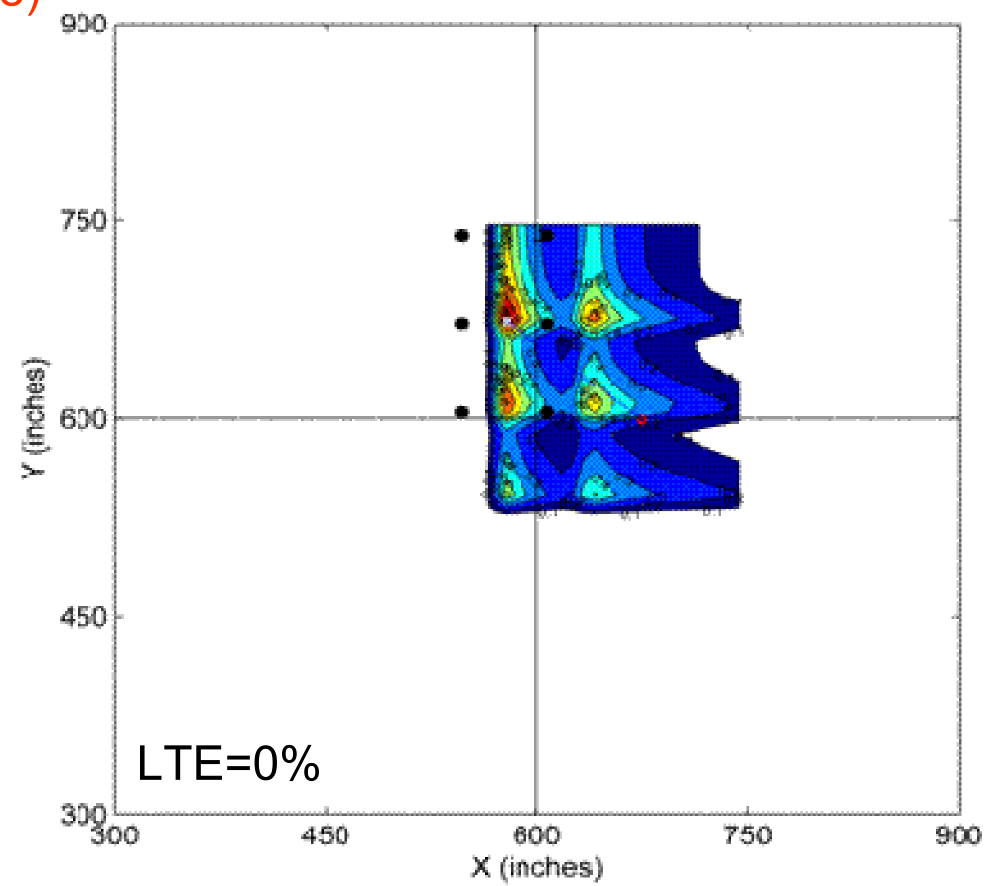


Load Position Influence Graphs – Single gear

A-380 (TDT)

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



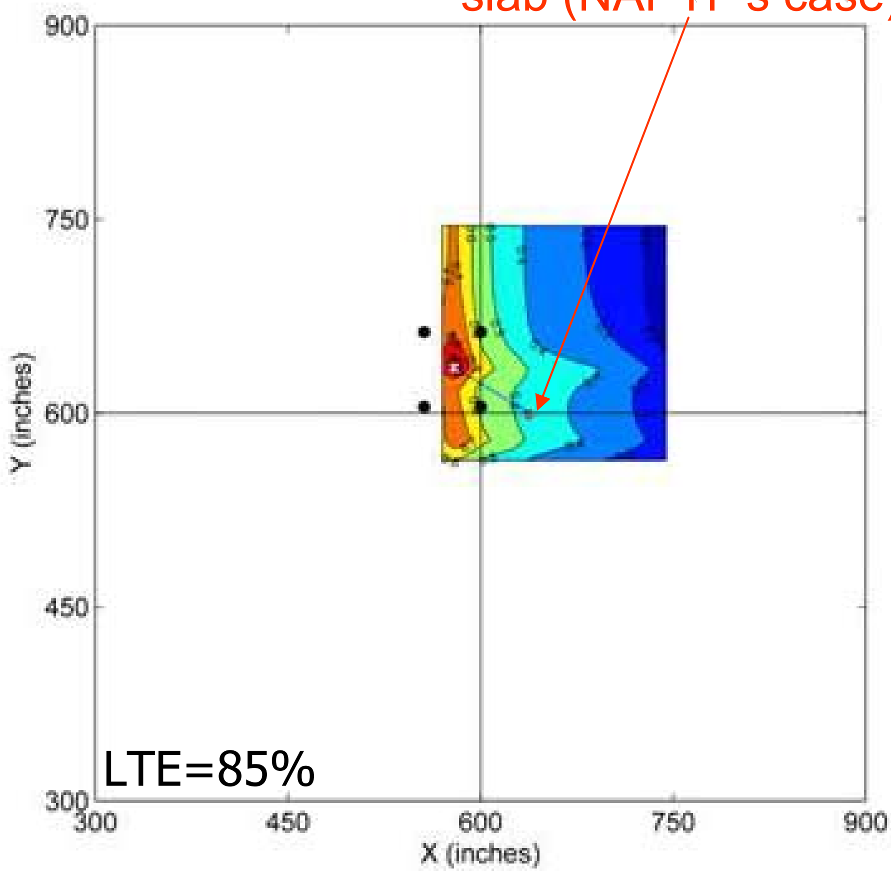


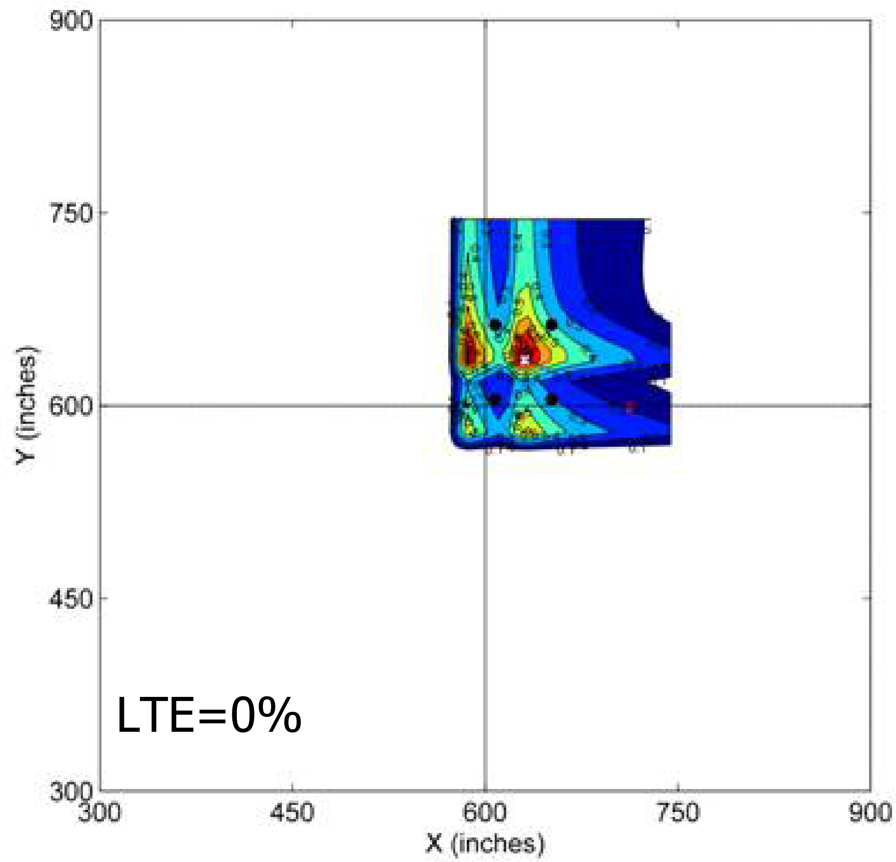
- t/b ratios around 0.48
- t/b ratios around 0.67

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.

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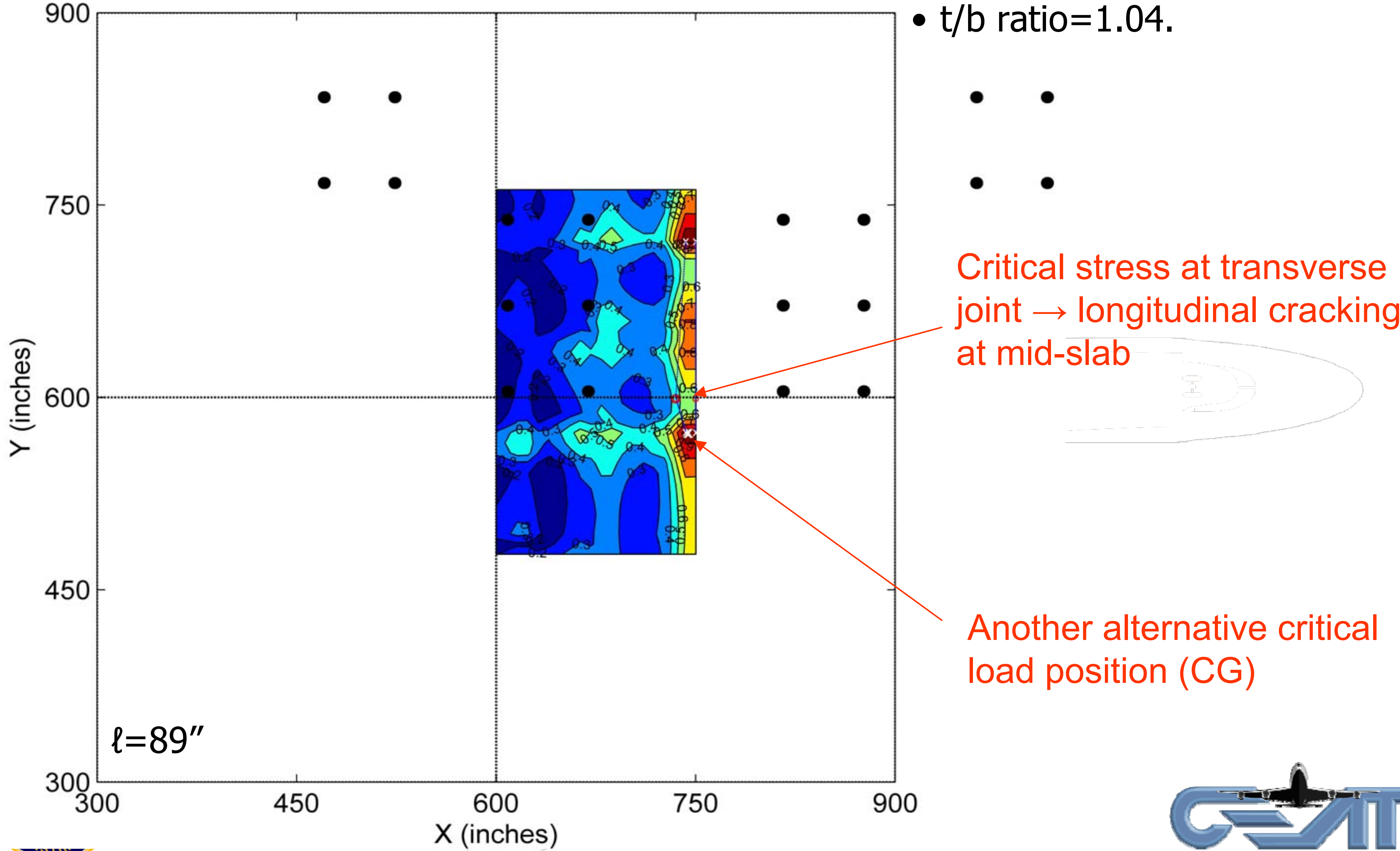
Load Position Influence Graphs – Full A/C

A-380: *L= 300″* and LTE=0%

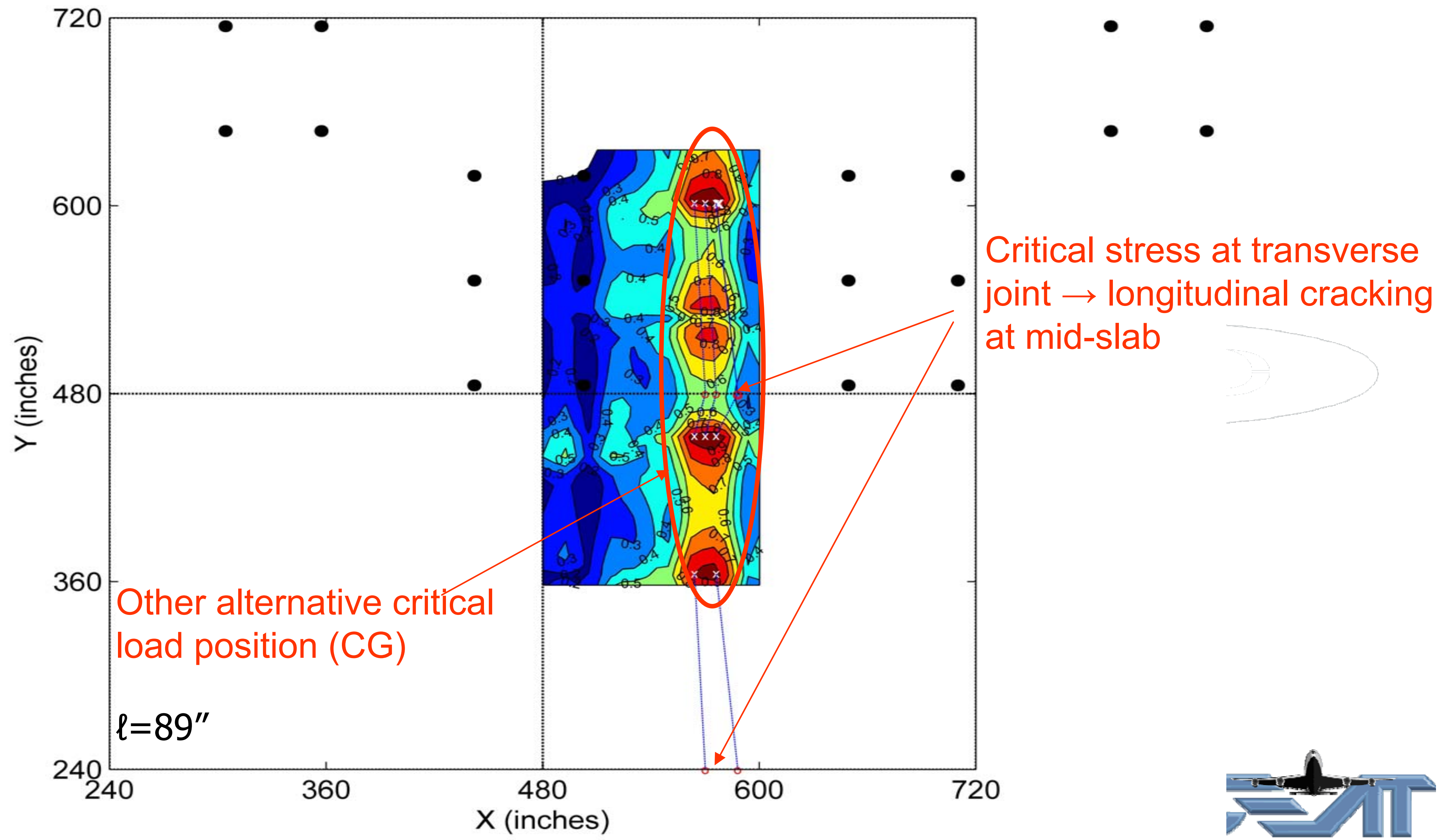


- t/b ratio=1.04.

Load Position Influence Graphs – Full A/C

A-380: *L= 240″* and LTE=0%

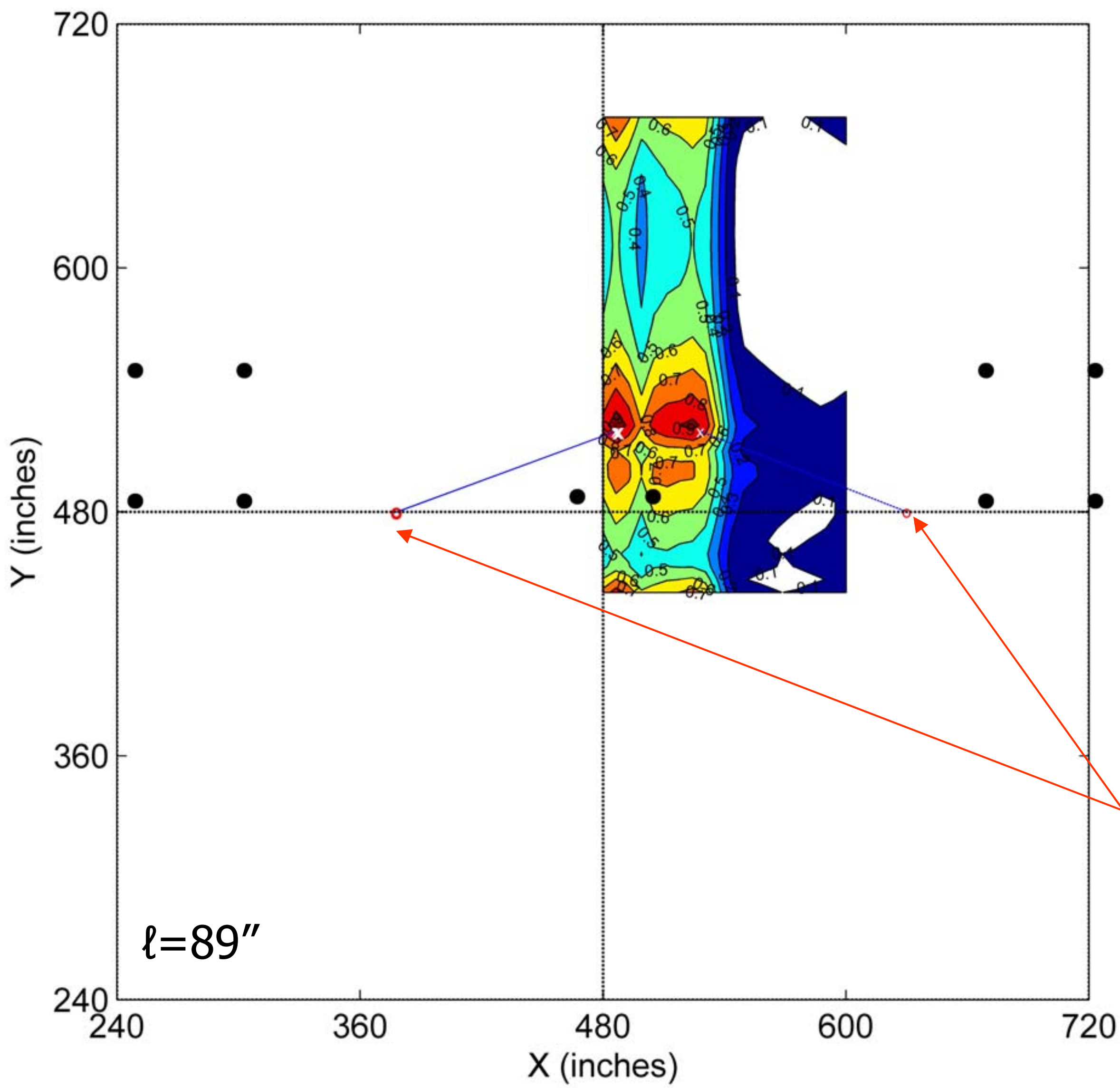
- t/b ratio=1.00



Load Influence Graphs – Full A/C

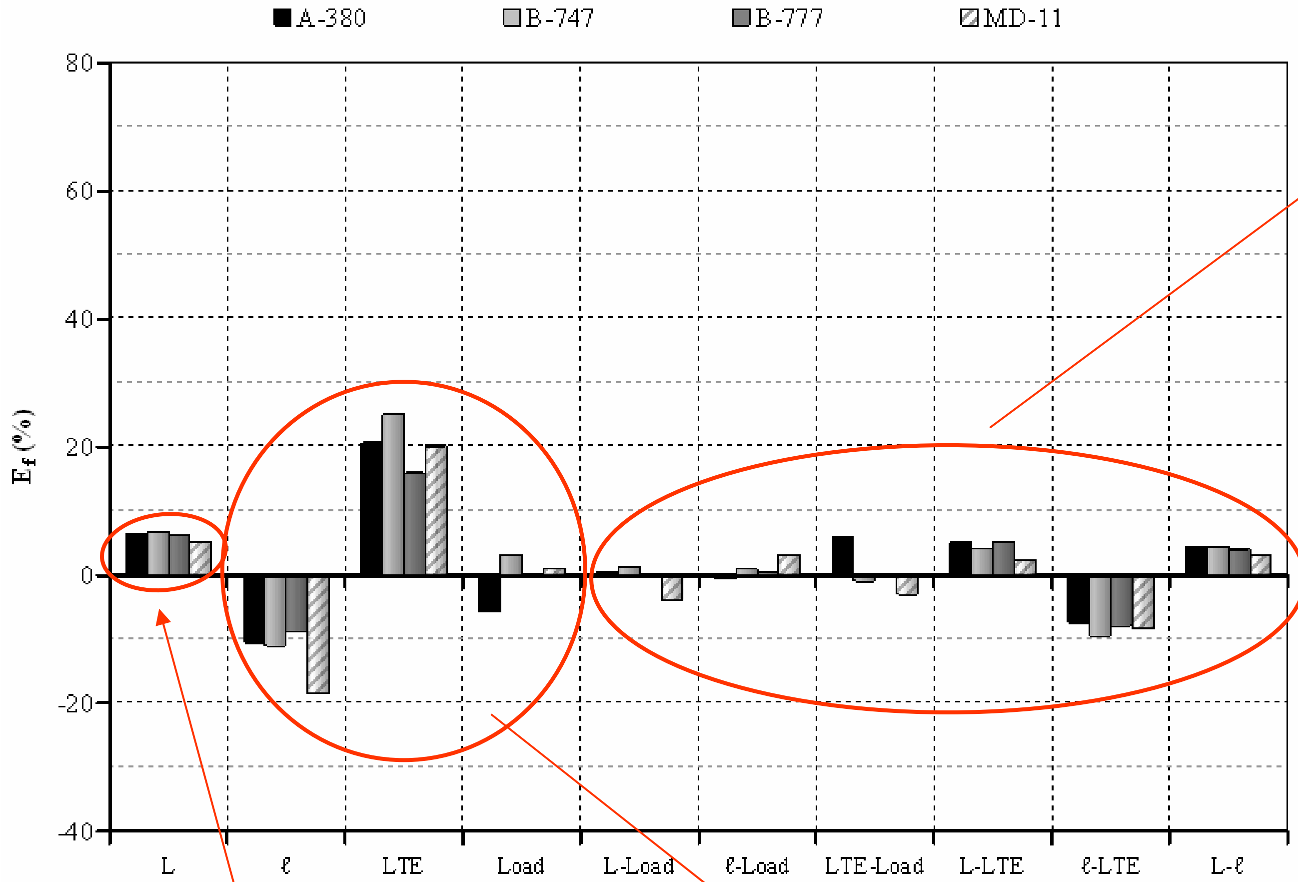
<u>MD-11: *L= 240″* and LTE=0%</u>

- t/b ratio=0.86.



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

Factorial results (bottom tensile stress)



Few significant 2nd order interactions:

- L-LTE: for all A/C;

- ℓ-LTE: for ALL A/C

- little effect of L on bottom tensile stress

- LTE affects bottom tensile stress for all A/C

- Full gear has little effect on bottom stresses

No need to determine critical positions

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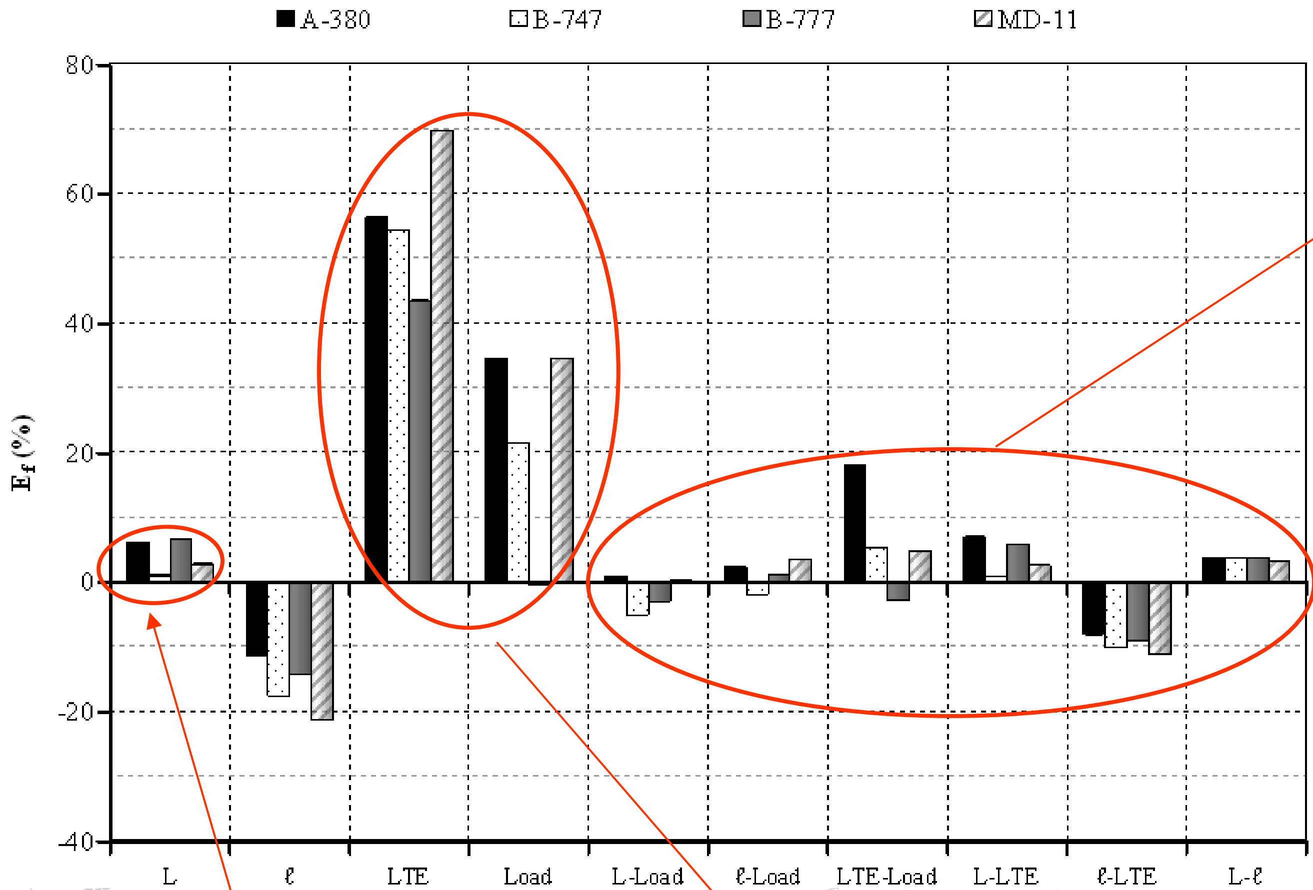
Factorial results (top tensile stresses)



Few significant 2nd order interactions:

- Load-LTE: for A-380

- ℓ-LTE: for ALL A/C

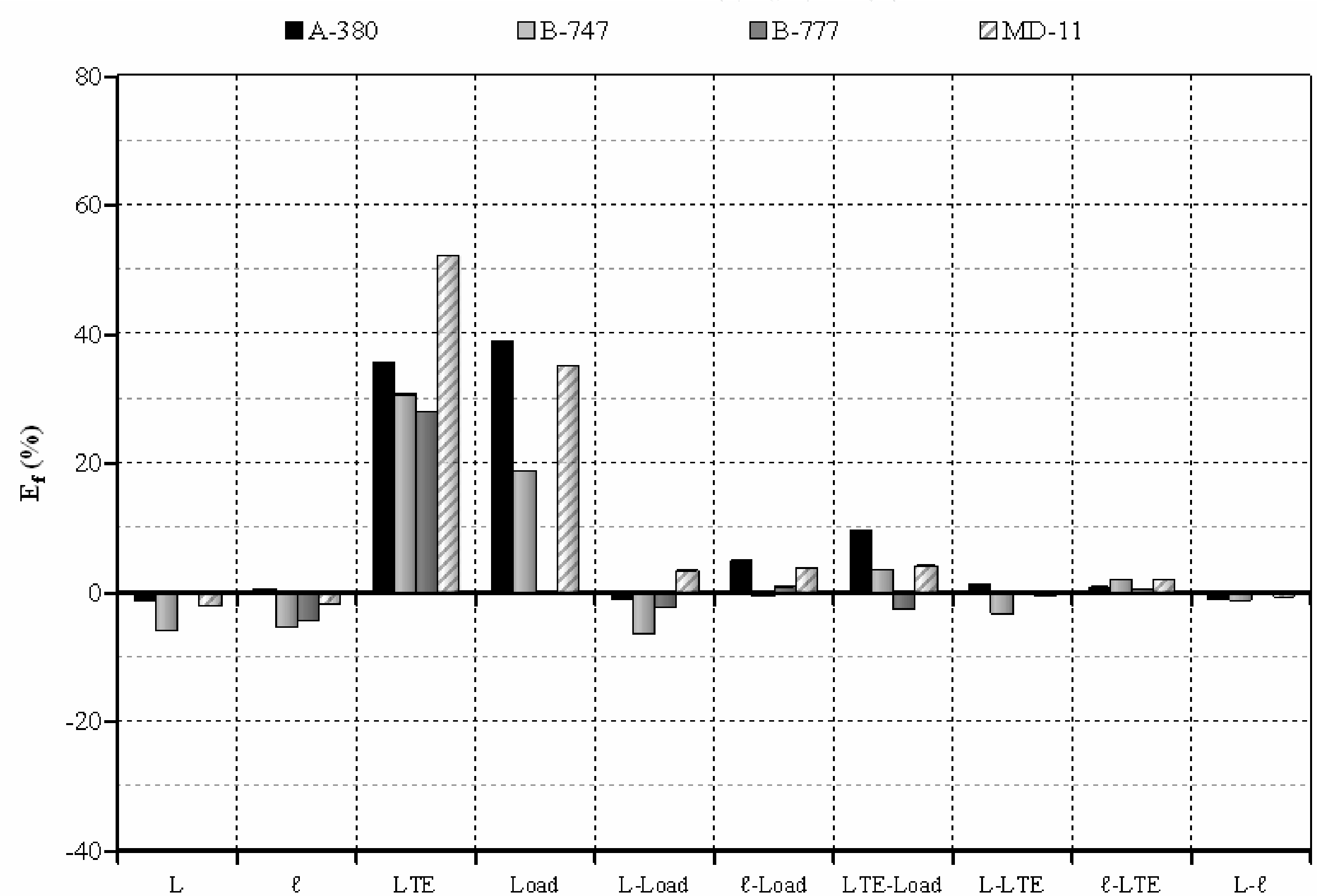
- L is not so important to top tensile stress

- LTE highly affects top tensile stress for all A/C

- Full gears affect A/C results, but B777

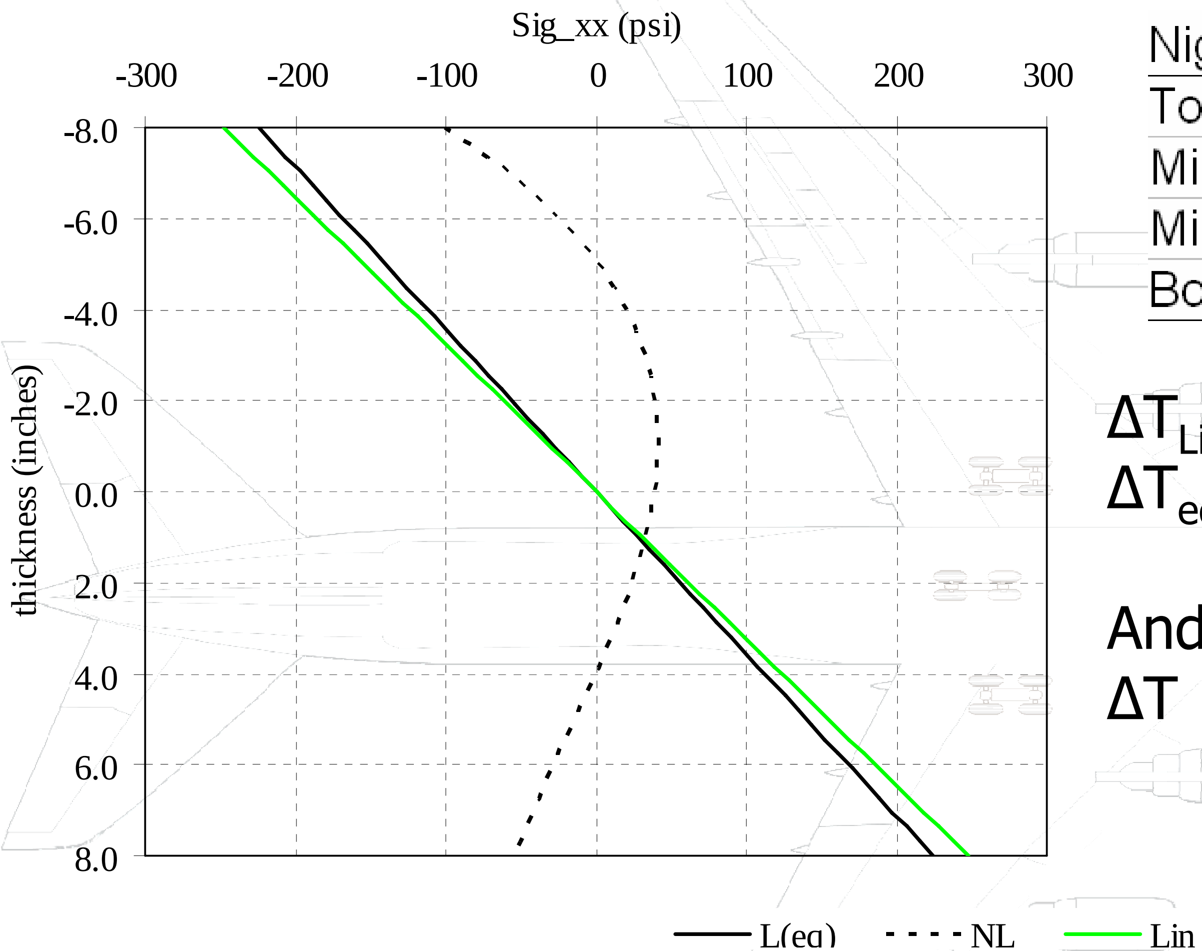
Factorial results (t/b stress ratio)

Same trend as in Top Stresses



Results
(with curling)

Thermal Loads



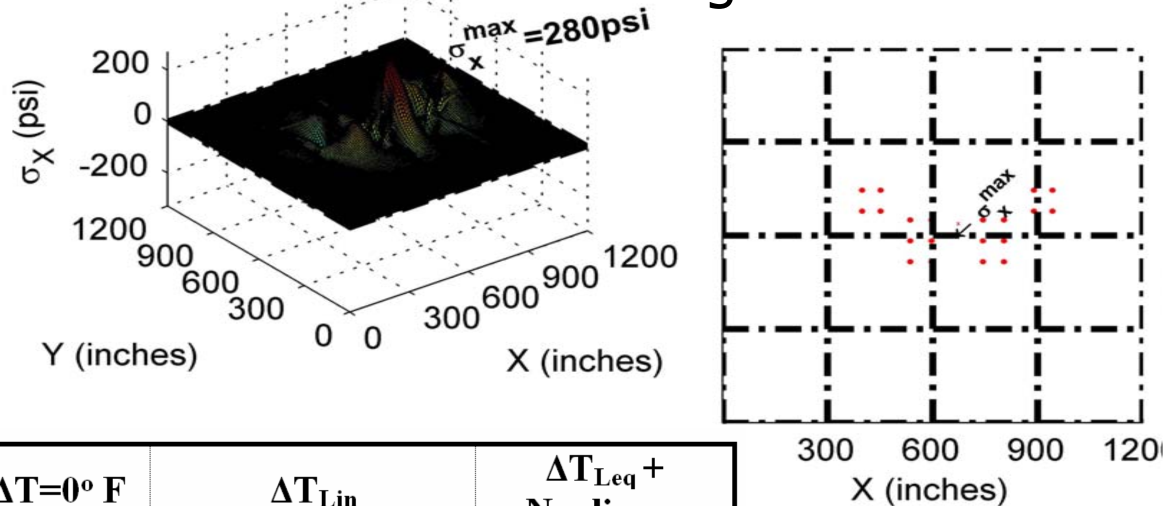
Nighttime profile	T (°F)
Top (Tt)	42
Mid-top (Tmt)	50
Mid-bottom (Tmb)	57
Bottom (Tb)	59

ΔT_{Lin} =-17.0°F
ΔT_{eq}= -15.4°F

And no thermal load applied:
ΔT = 0.0°F

Top σ_{xx} results

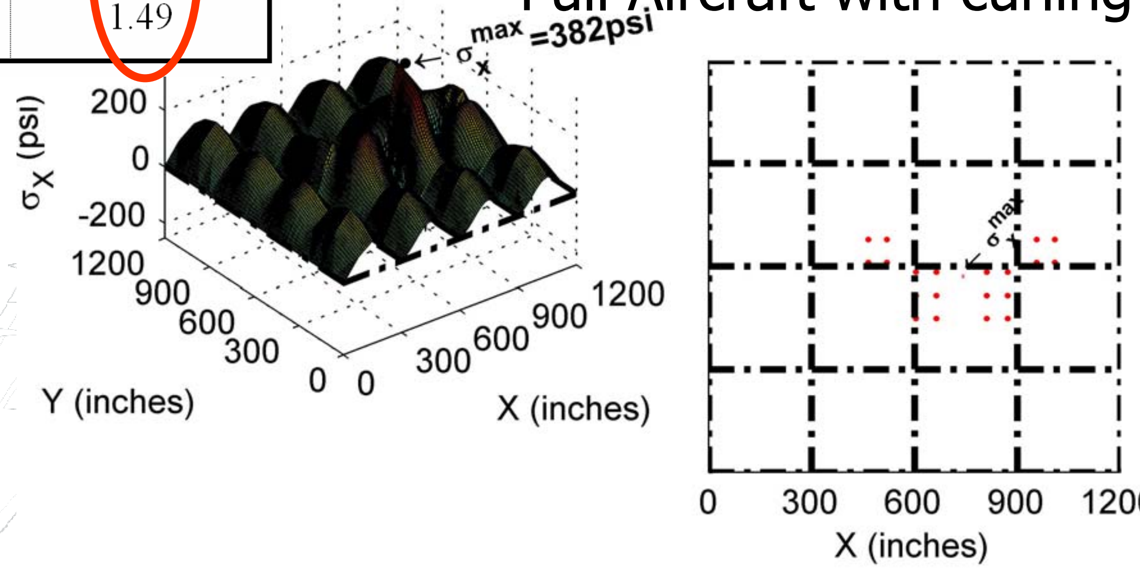
Full Aircraft no curling



t/b ratios

Level	ΔT=0° F	ΔT_{Lin}	ΔT_{Leq} + Nonlinear
Single gear	0.67	1.02	1.07
Full A/C	0.95	1.38	1.49

Full Aircraft with curling

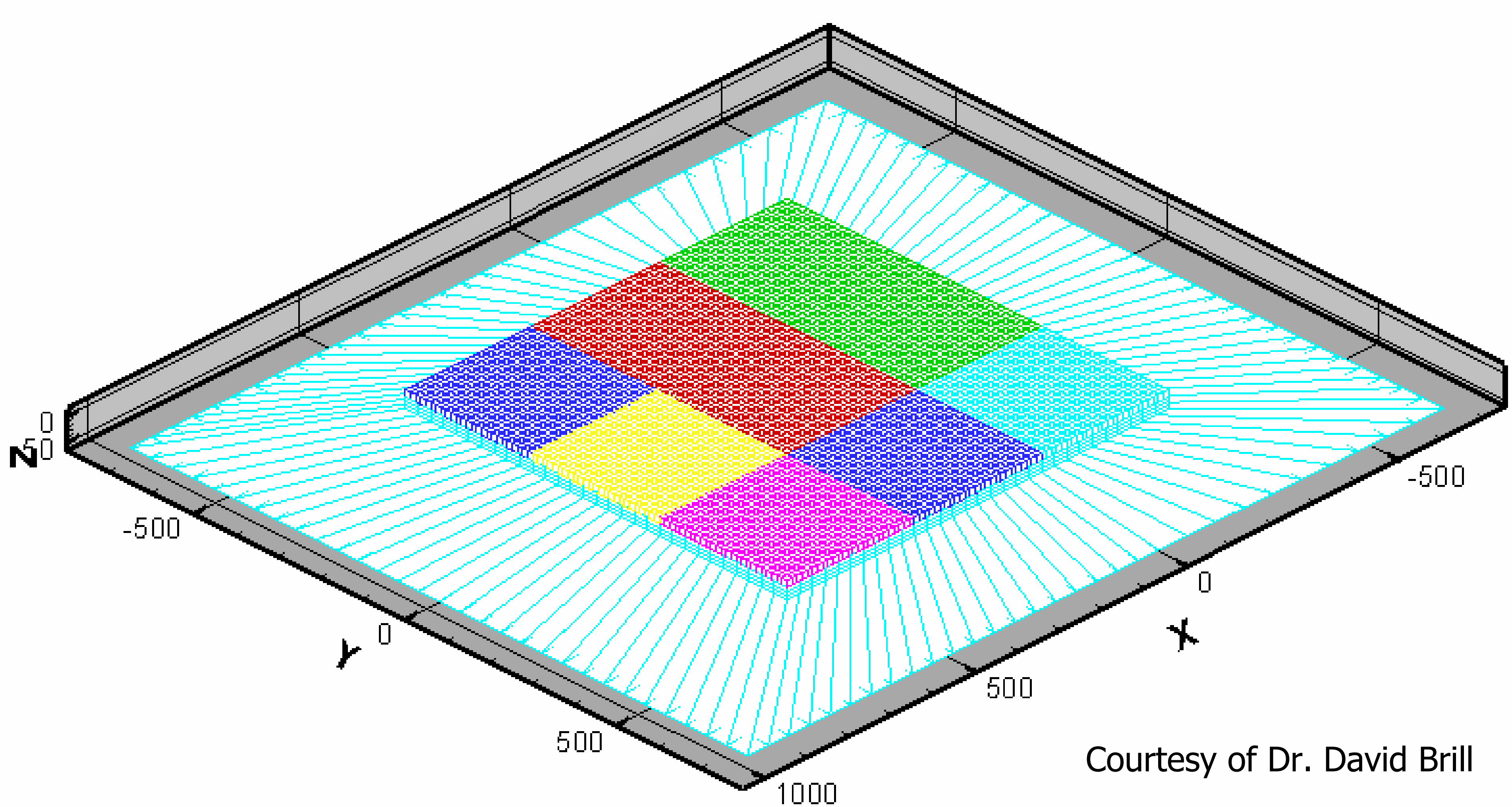


3-D Results for
A-380, B747 and MD11
FULL AIRCRAFT

Methodology - 3D runnings

Scenario's description

A 3x3 slab system was simulated with NIKE 3D:



Courtesy of Dr. David Brill

3D FE Analysis (NIKE3D)

• **3-D** Finite Element Code – Lawrence Livermore Nat. Lab. (**LLNL)**

• Nonlinear, Implicit/explicit 3D
  - 13 solvers;
  - 28 constitutive models

•Open and free;

• Used by FAA design guide

• Incompatible mode element:
  - avoid shear locking
  - use 1 el. through thickness

$$N_1 = u = \sum_{i=1}^{8} N_i a_{1+(i-1)\times 3} + (1-\xi^2)b_1 + (1-\eta^2)b_4 + (1-\zeta^2)b_7$$

$$N_2 = v = \sum_{i=1}^{8} N_i a_{2+(i-1)\times 3} + (1-\xi^2)b_2 + (1-\eta^2)b_5 + (1-\zeta^2)b_8$$

$$N_3 = w = \sum_{i=1}^{8} N_i a_{3+(i-1)\times 3} + (1-\xi^2)b_3 + (1-\eta^2)b_6 + (1-\zeta^2)b_9$$

$$N_4 = \frac{1}{8}\ldots$$

$$N_5 = \frac{1}{8}(1+\xi)(1-\eta)(1+\zeta)$$

$$N_6 = \frac{1}{8}(1+\xi)(1-\eta)(1-\zeta)$$

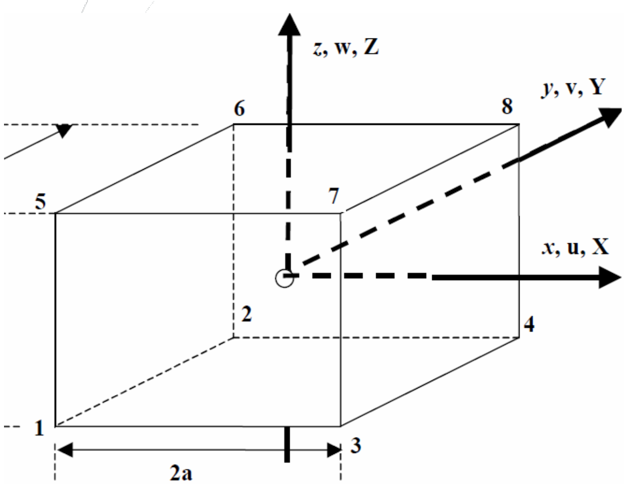
$$N_7 = \frac{1}{8}(1+\xi)(1+\eta)\ldots$$

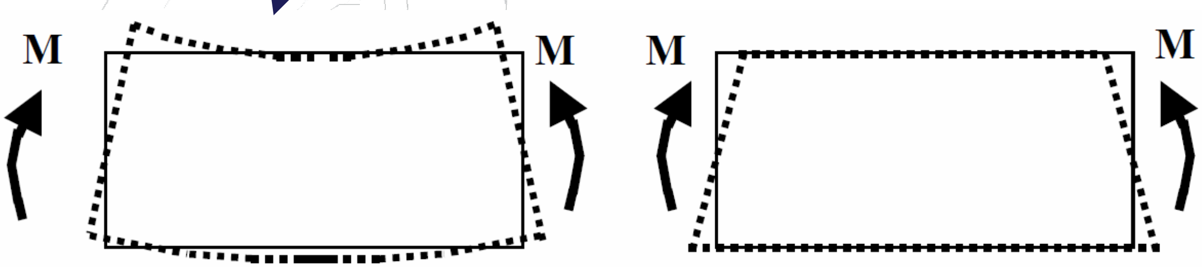
$$N_8 = \frac{1}{8}(1+\xi)(1+\eta)(1+\zeta)$$

$$\{U\} = [N]_{3x24}\{a\}^e_{24x1} + [N_C]_{3x9}\{b\}^e_{9x1}$$

nodal d.o.f

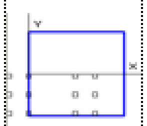
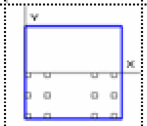
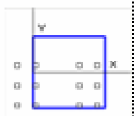
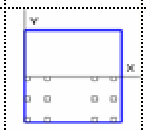
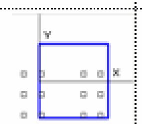
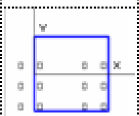
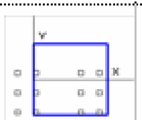
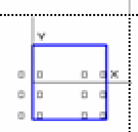
internal d.o.f.





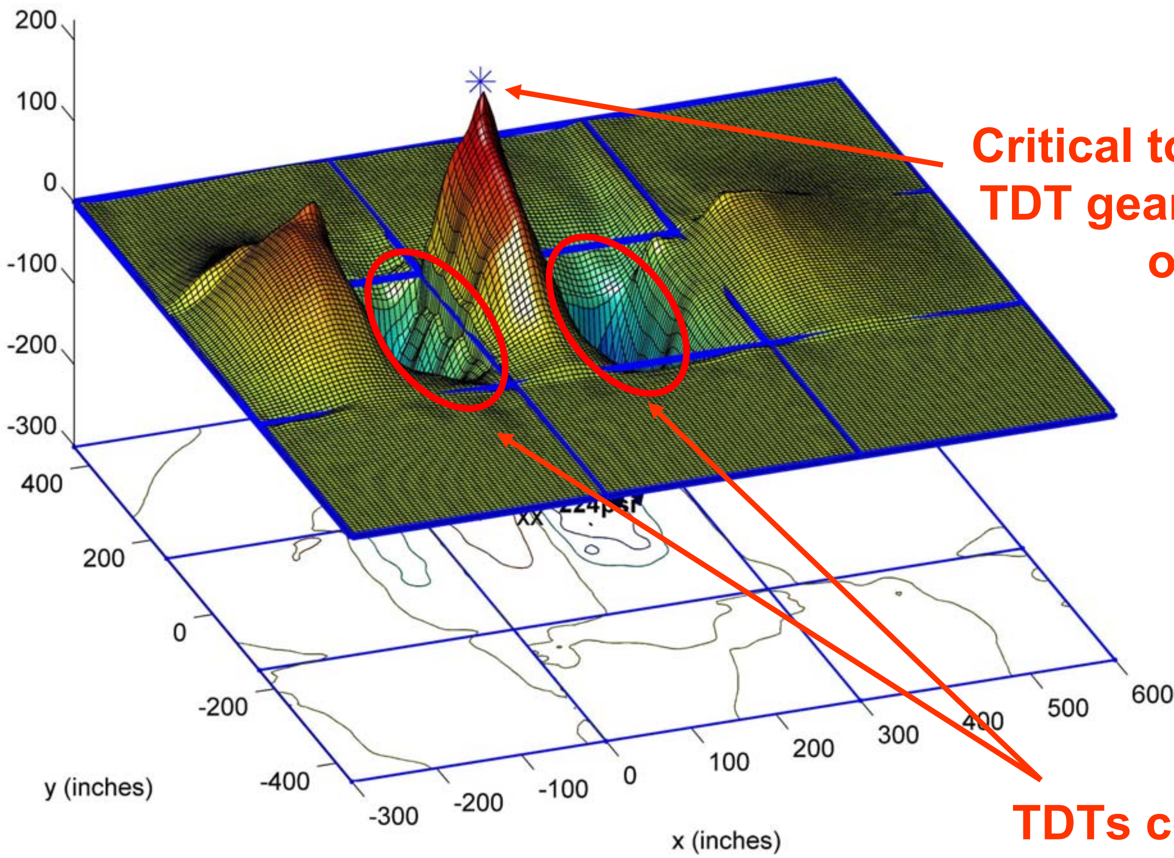
(a) True Deformation (b) Assumed Deformation by

A380-full aircraft (TOP stress)

Case	Loading Position	LTE (E^{spring})	Slab Length, L	ℓ	3-D (NIKE3D)		2-D (ILLISLAB)		3-D critical stress position at the central slab	3-D alternative critical stress position at adjacent slabs
		(psi)	(inch)	(inch)	σ^{TOP} (psi)	Dir.	σ^{TOP}(psi)	Dir.		
SCIIa		1.E+05	300	57	224	XX	277	XX	Inbetween the two TDTs gears at the transverse joint	
SCIIb		1.E+01	300	57	211	XX	560	XX	Inbetween the two TDTs gears at the transverse joint	
SCIIIa		1.E+05	300	89	128	XX	266	XX	Inbetween the two TDTs gears at the transverse joint	- Top stress of 186psi at the longitudinal joint of bottom adjacent slab (90" of the corner).
SCIIIb		1.E+03	300	57	238	XX	558	XX	Inbetween the two TDTs gears at the transverse joint	- Top stress of 257psi at the longitudinal joint of bottom adjacent slab (90" of the corner); - Top stress of
SCIVa		1.E+05	240	57	224	XX	281	XX	Inbetween the two TDTs gears at the transverse joint	
SCIVb		1.E+01	240	57	252	XX	556	XX	Inbetween the two TDTs gears at the transverse joint	
SCVa		1.E+05	240	89	145	XX	276	XX	Inbetween the two TDTs gears at the transverse joint	- Top stress of 174psi at the tranverse joint of right adjacent slab (60" of the corner).
SCVb		1.E+03	240	89	286	XX	449	XX	Inbetween the two TDTs gears at the transverse joint	

A380-full aircraft (TOP stress)

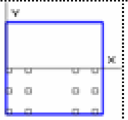
SCIIa		1.E+05	300	57	224	XX	277	XX	Inbetween the two TDTs gears at the transverse joint

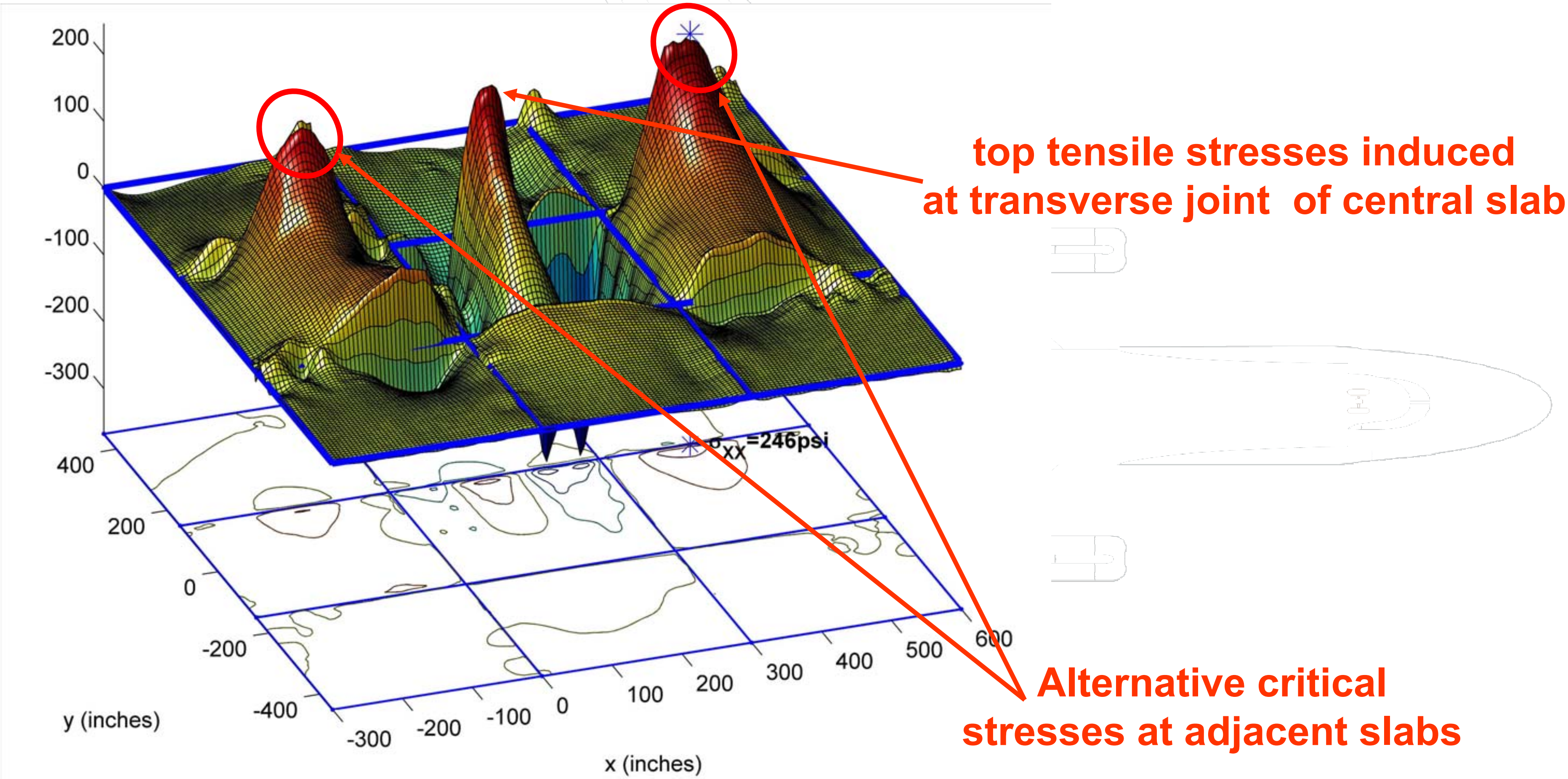


Critical top tensile in between TDT gears at transverse joint of central slab

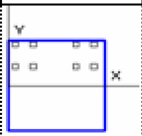
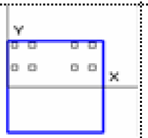
TDTs compression zone

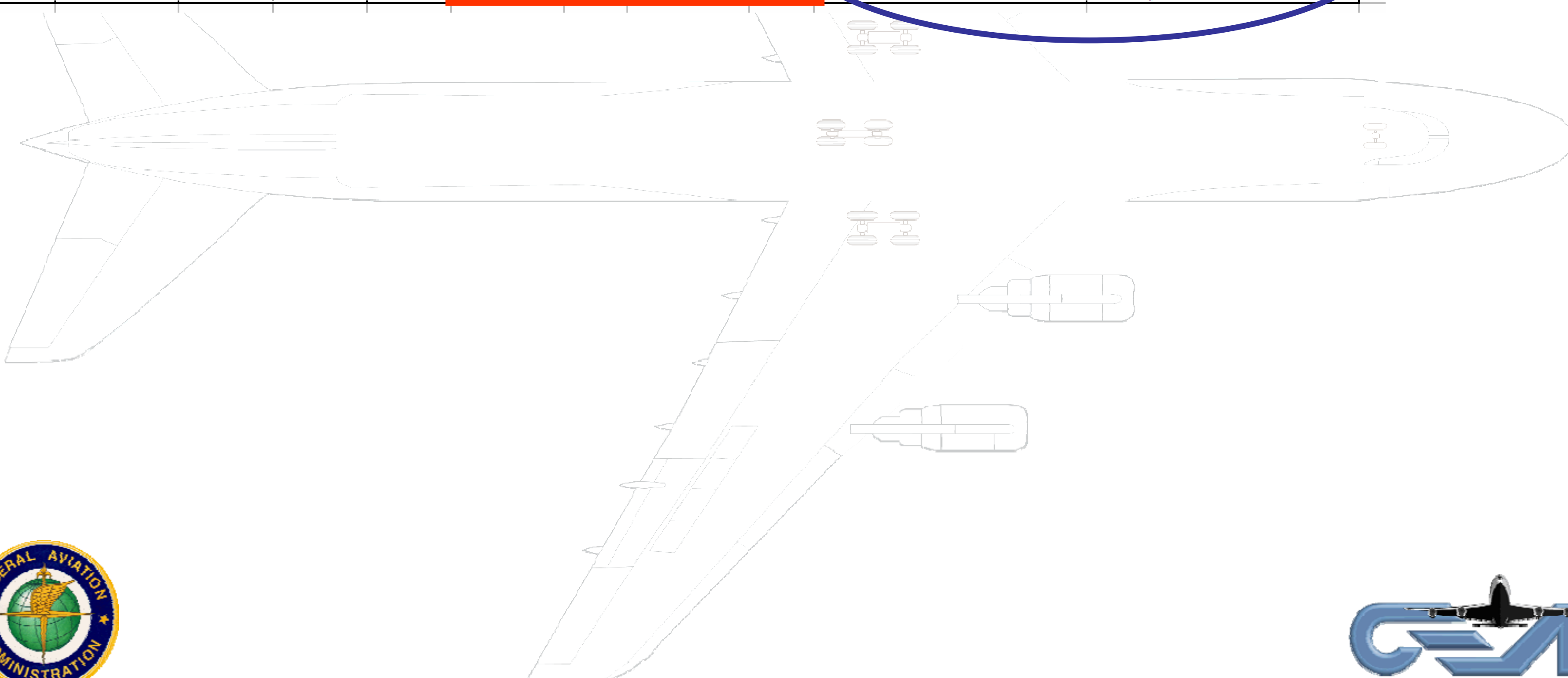
A380-full aircraft (TOP stress)

SCIIIb		1.E+03	300	57	238	XX	558	XX	Inbetween the two TDTs gears at the transverse joint	- Top stress of 257psi at the longitudinal joint of bottom adjacent slab (90" of the corner); - Top stress of



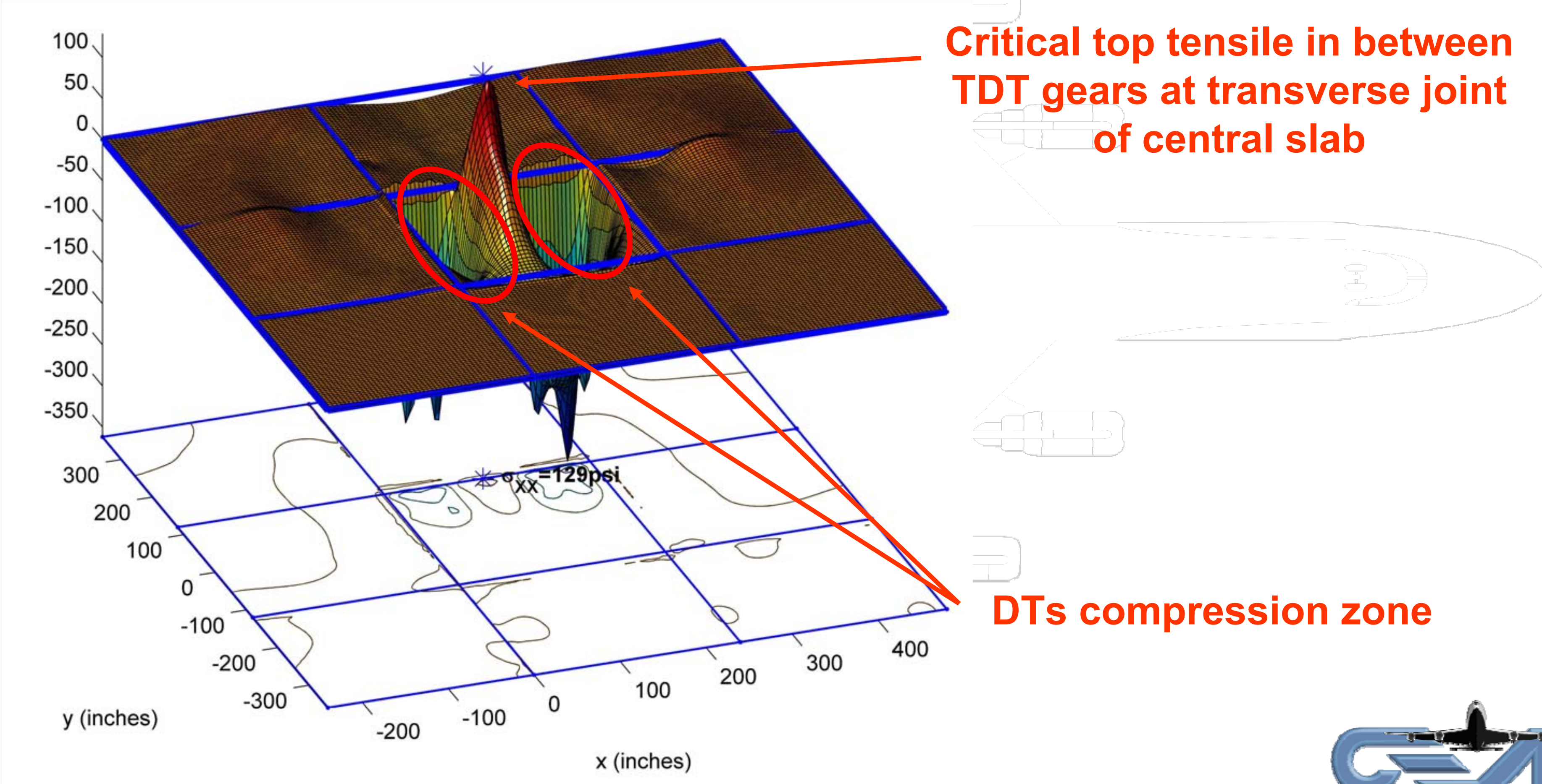
B747-full aircraft (TOP stress)

Case	Loading Position	LTE (E^{spring})	Slab Length, L	ℓ	3-D (NIKE3D)		2-D (ILLISLAB)		3-D critical stress position at the central slab	3-D alternative critical stress position at adjacent slabs
		(psi)	(inch)	(inch)	σ^{TOP} (psi)	Dir.	σ^{TOP} (psi)	Dir.		
SCIVb		1.E+02	240	57	129	XX	523	XX	Inbetween the two DTs gears at the transverse joint	
SCVb		5.E+03	240	89	0	XX/YY	385	XX	Central slab entirely under compression	- Top stress of 168 psi at the longitudinal joint of top adjacent slab (100" of the corner).



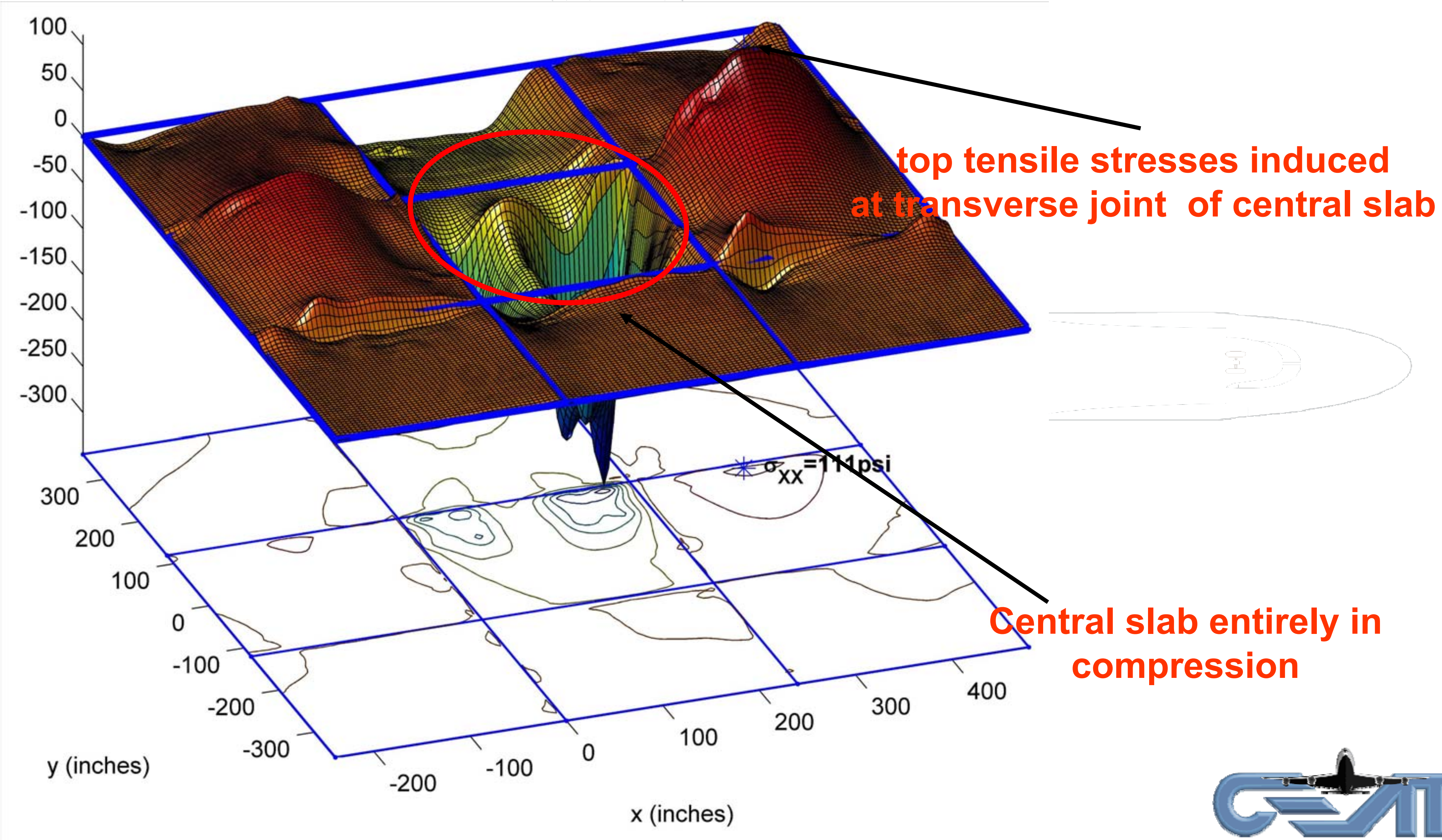
B747-full aircraft (TOP stress)

Case	Loading Position	LTE (E^{spring})	Slab Length, L	ℓ	3-D (NIKE3D)		2-D (ILLISLAB)		3-D critical stress position at the central slab	3-D alternative critical stress position at adjacent slabs
		(psi)	(inch)	(inch)	σ^{TOP} (psi)	Dir.	σ^{TOP} (psi)	Dir.		
SCIVb		1.E+02	240	57	129	XX	523	XX	Inbetween the two DTs gears at the transverse joint	

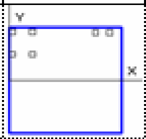
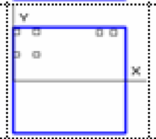
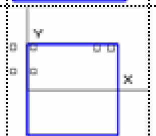
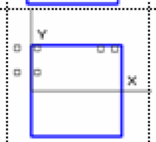


B747-full aircraft (TOP stress)

SCVb		5.E+03	240	89	0	XX/YY	385	XX	- Central slab entirely under compression	- Top stress of 168 psi at the longitudinal joint of top adjacent slab (100" of the corner).

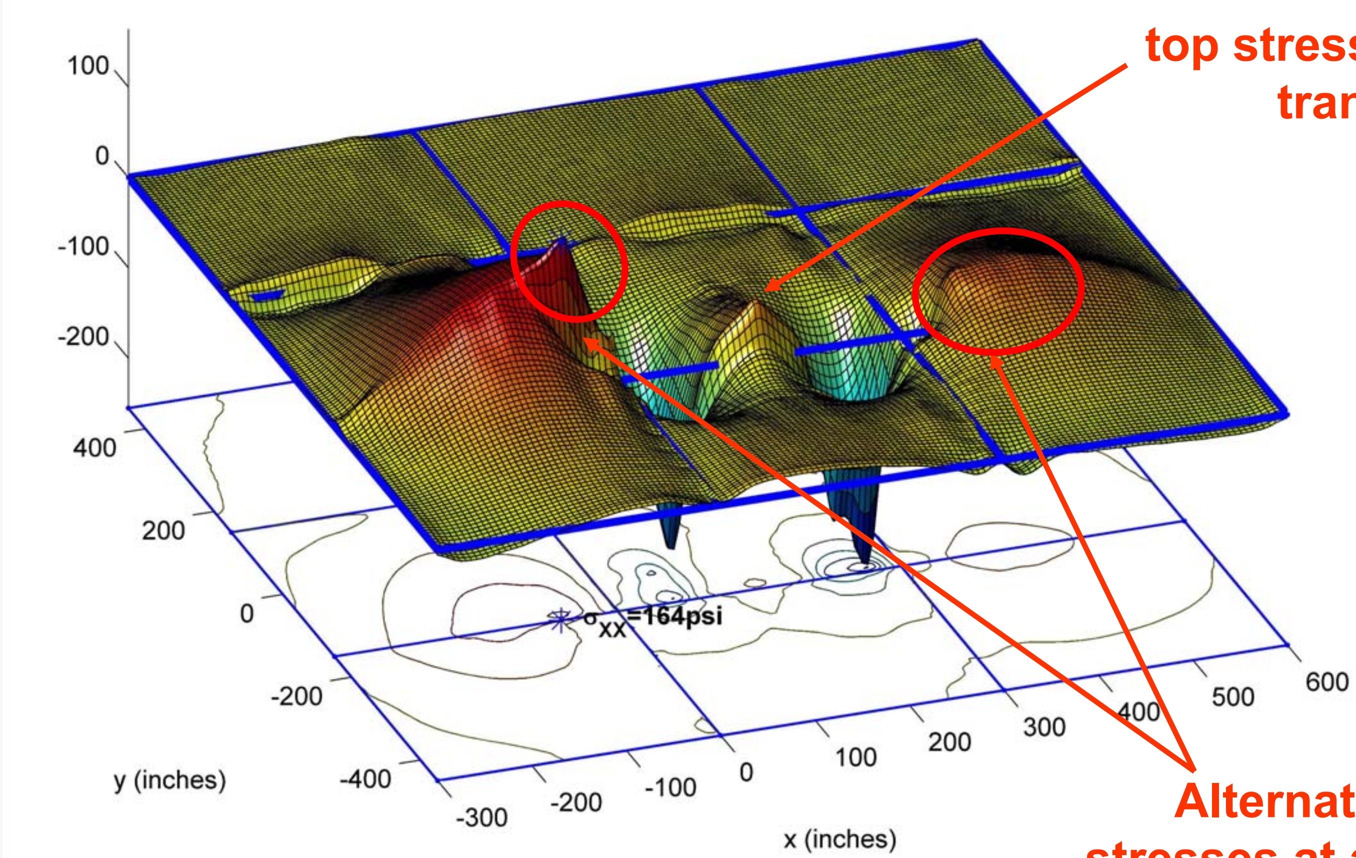


MD11-full aircraft (TOP stress)

Case	Loading Position	LTE (E^{spring})	Slab Length, L	ℓ	3-D (NIKE3D)		2-D (ILLISLAB)		3-D critical stress position at the central slab	3-D alternative critical stress position at adjacent slabs
		(psi)	(inch)	(inch)	σ^{TOP} (psi)	Dir.	σ^{TOP}(psi)	Dir.		
SCIIb		1.E+02	300	57	226	XX	487	XX	Inbetween DT and T gears at the transverse joint	
SCIIIb		1.E+01	300	89	70	XX	437	XX	- Inbetween DT and T gears at the transverse joint	- Top stress of 165 psi at the transverse joint of left adjacent slab (60" of the corner); - Top stress of 167
SCIVb		1.E+02	240	57	275	XX	500	XX	Inbetween DT and T gears at the transverse joint	
SCVb		1.E+03	240	89	260	XX	383	XX	Inbetween DT and T gears at the transverse joint	

MD11-full aircraft (TOP stress)

SCIIIb		1.E+01	300	89	70	XX	437	XX	- Inbetween DT and T gears at the transverse joint	- Top stress of 165 psi at the transverse joint of left adjacent slab (60" of the corner); - Top stress of 167

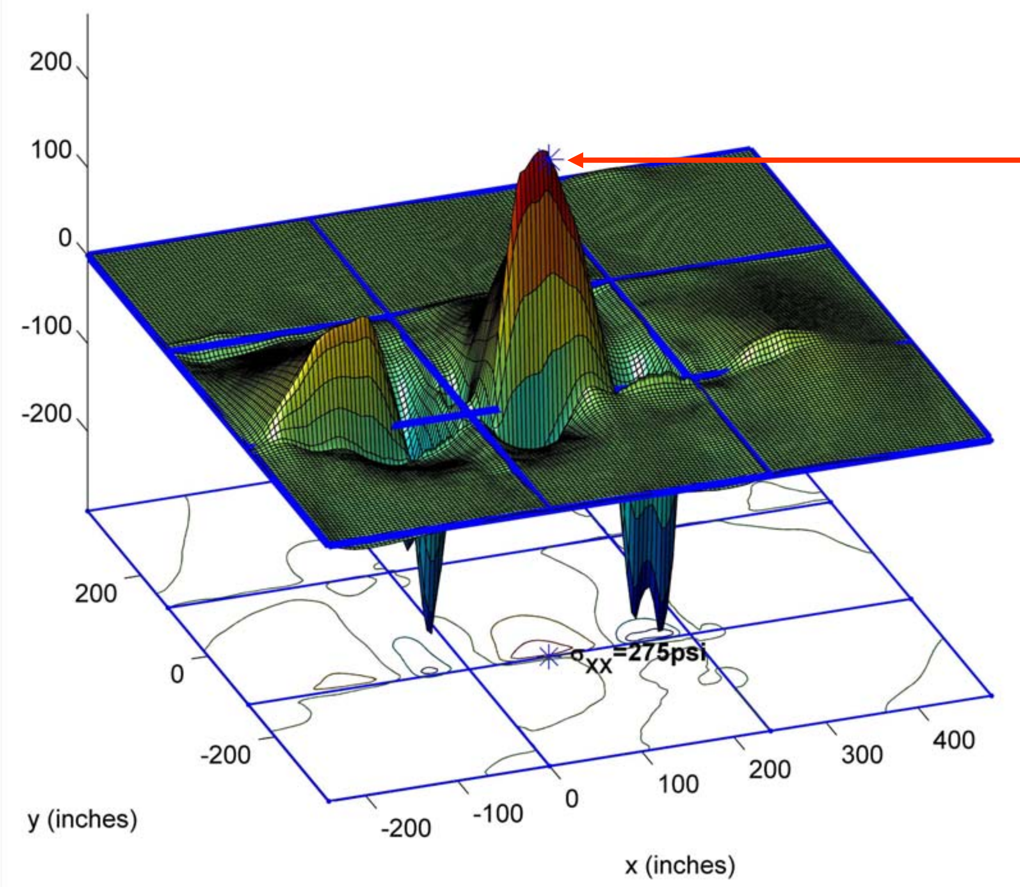


top stress at central slab at transverse joint

Alternative critical stresses at adjacent slabs (longitudinal and transverse joints)

MD11-full aircraft (TOP stress)

SCIVb		1.E+02	240	57	275	XX	500	XX	Inbetween DT and T gears at the transverse joint



top tensile stresses induced at transverse joint of central slab

Conclusions

Conclusions

- Finite element analysis shows consideration of full A/C gear IS NOT necessary for bottom tensile stresses prediction
  - Full A/C gear IS necessary for top tensile stress prediction
- Top to 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 → *longitudinal cracking* (e.g., NAPTF and Airbus tests)
  - *Slab size affect critical response position more than its magnitude for this analysis.*
- 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

- *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!*

- Critical tensile stresses are can be greater at the top *with curling.*

- Full Aircraft and curling induce critical positions at the center of transverse joint (strong interaction with LTE).

- Almost all 3-D stress results were lower than 2-D ones:
  - especially lower LTE (crucial for top-down cracking);
  - Work still needed to validate top stresses in NIKE 3D

- **Top Tensile stresses are an interaction of the of slab configuration, moisture/temperature profile, full gear geometry and load levels.**

THANK YOU

???Questions???

!!!Comments!!!

...Suggestions...