University of Limerick

COMPTEST 2004

Composites Research Centre

Experimental Measurement and Finite Element Analysis of Load Distribution and Strength in Multi-Bolt Composite Joints with Variable Bolt Hole Clearances

M.A. McCarthy, V.P. Lawlor[1], W.F. Stanley, G.S. Padhi, C.T. McCarthy[2]

University of Limerick
Ireland

[1] Now National University of Ireland, Galway
[2] Now University College Dublin

COMPTEST 2004: Composites Testing and Model Identification
University of Bristol, UK, Sept 21st – 23rd, 2004

Content

- Context for work
- Quasi-static loading
- Fatigue loading
- Finite Element Analysis

Context – BOJCAS project

BOLTED JOINTS IN COMPOSITE AIRCRAFT STRUCTURES

EU FRAMEWORK V
COMPETITIVE AND SUSTAINABLE GROWTH
(2000-2003)

Partners:

IRELAND	University of Limerick (Project Co-ordinator)
UNITED KINGDOM	Airbus UK, QinetiQ (formerly DERA)
SWEDEN	SAAB, FOI, Royal Inst of Tech Stockholm
GERMANY	Airbus Germany
ITALY	CIRA
THE NETHERLANDS	NLR
GREECE	ISTRAM
SWITZERLAND	SMR

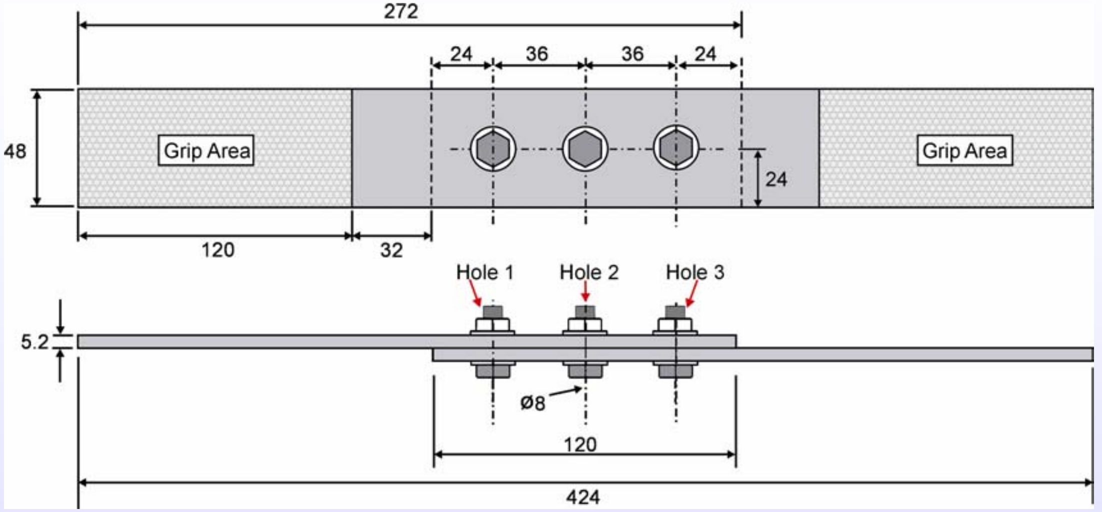
Why Study Clearance?

- Bolt-hole clearance results in 3D variations in stress/strain distributions
  - Good parameter to study for validation of 3D FE
- Clearance is inevitable in any practical manufacturing process – cannot be avoided, so effects should be understood
- Has not been studied experimentally in multi-bolt joints before
- Previous models of effects of clearance have been analytical or 2D FE

Quasi-Static Loading

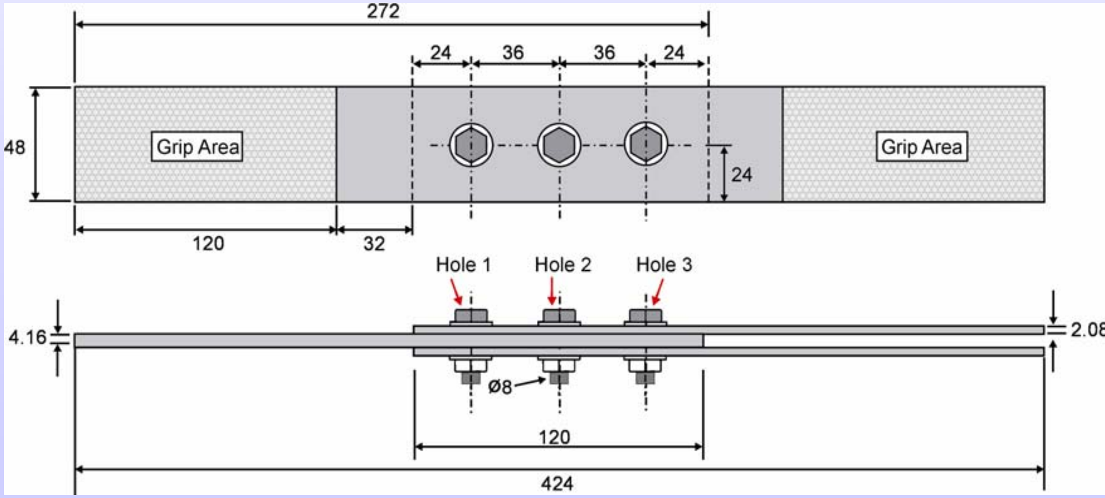
Joint Geometries

- Single-lap joint



- HTA/6376 carbon/epoxy
- Quasi-isotropic lay-ups
- Titanium alloy bolts

- Double-lap joint



Controlling Clearance

Bolts (8 mm) obtained from SAAB (f7 tolerance)

Four different size holes obtained with reamers specially manufactured to a tight (h6) tolerance

each nominal clearance

Four nominal clearances

Drill

Reamer

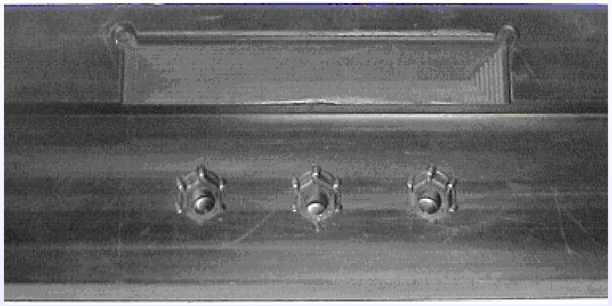
Clearance Code	Nominal Clearance (µm)	Reamer diameter		Bolt Diameter		Possible Clearance	
		Min (mm)	Max (mm)	Min (mm)	Max (mm)	Min (µm)	Max (µm)
C1	0	7.985	7.994	7.972	7.987	-2	22
C2	80	8.065	8.074	"	"	78	102
C3	160	8.145	8.154	"	"	158	182
C4	240	8.225	8.234	"	"	238	262

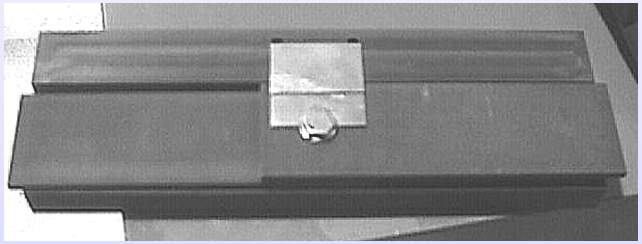
Clearance Cases

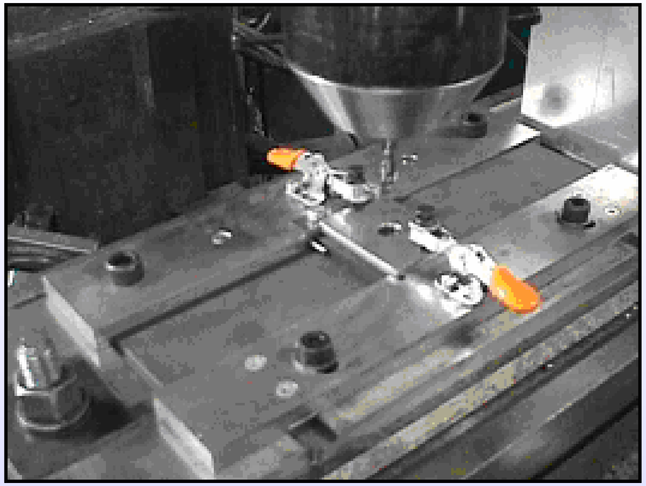
	Nominal Clearance (μm)		
Case Code	Hole 1	Hole 2	Hole 3
C1_C1_C1	0	0	0
C1_C1_C2	0	0	80
C1_C1_C3	0	0	160
C1_C1_C4	0	0	240
C1_C3_C1	0	160	0
C1_C3_C3	0	160	160

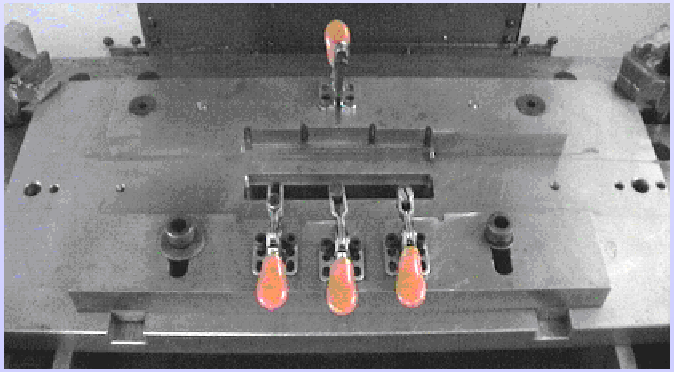
Centring/Aligning/Drilling Jigs

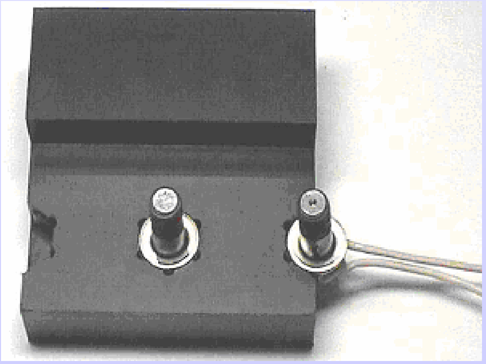
- Manufactured to very high precision









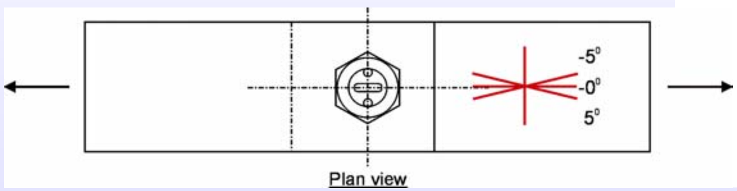


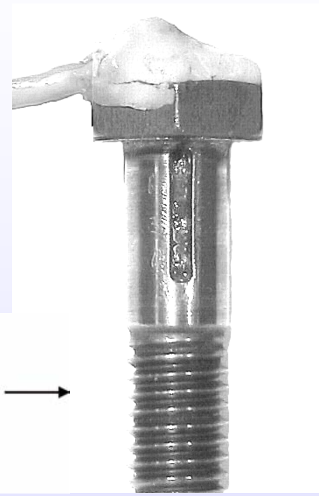
REF for jigs/fixtures: McCarthy, McCarthy, M.A., V.P. Lawlor, W.F. Stanley, 2004, An Experimental Study of Bolt-Hole Clearance Effects in Single-Lap, Multi-Bolt Composite Joints, *Journal of Composite Materials*, in-press.

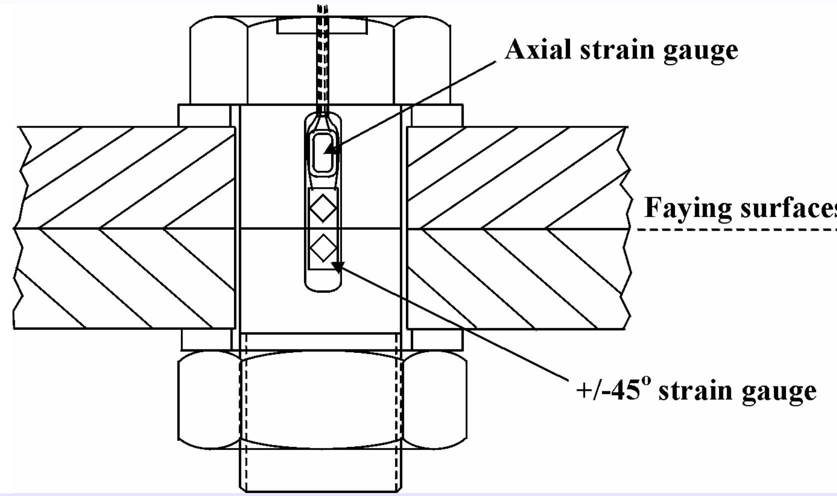
Measuring Load Distribution

Single-lap joints:

→ Instrumented bolts

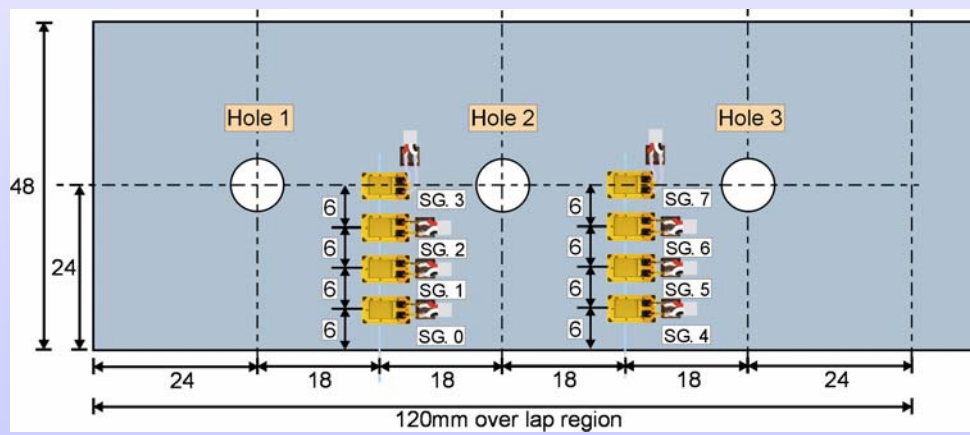




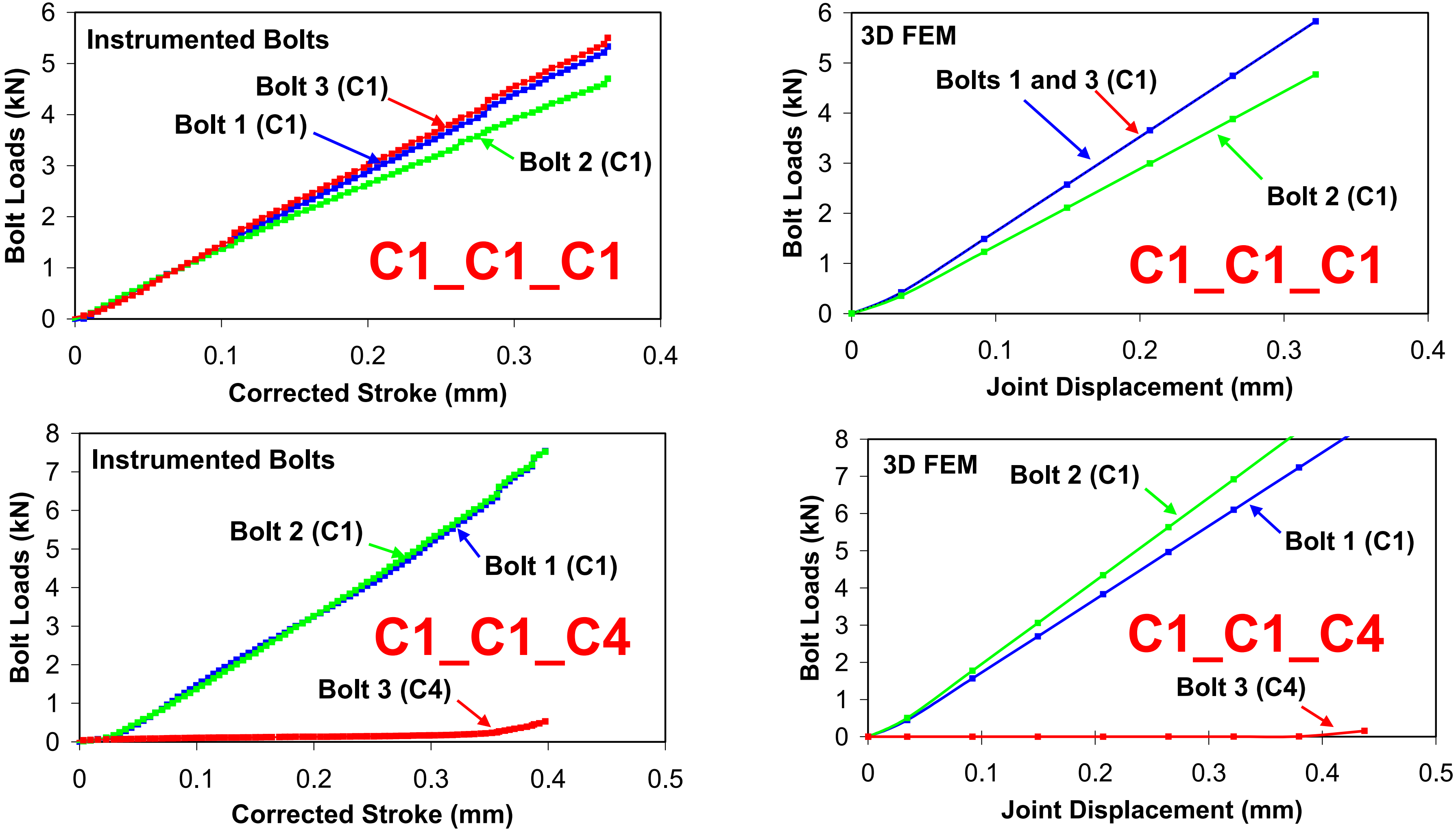


Double-lap joints:

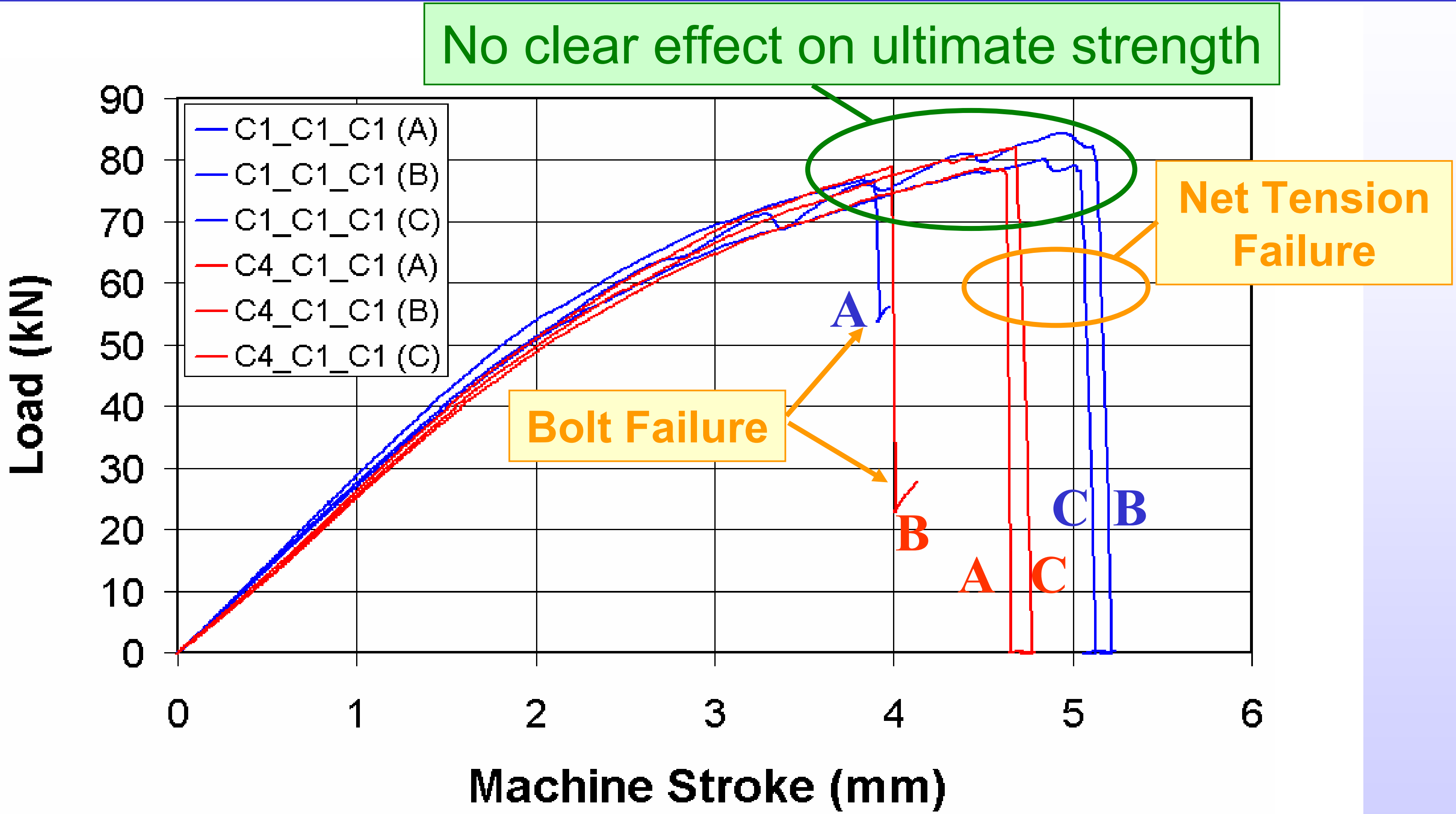
→ Strain gauges



SL Joints – Load Distr.

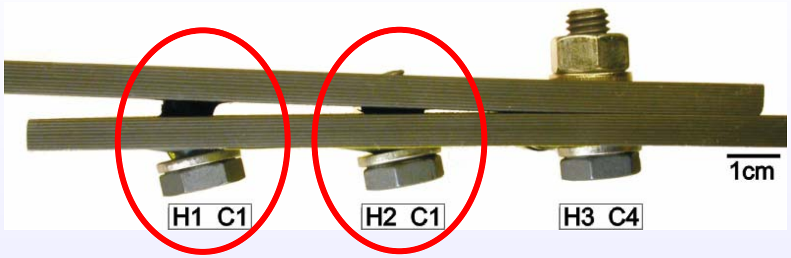


SL Joints - Failure



Most Interesting Failure

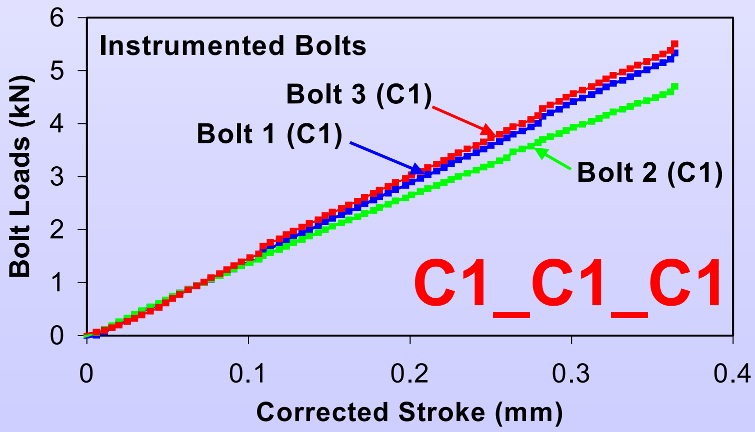
C1_C1_C4 Specimen B

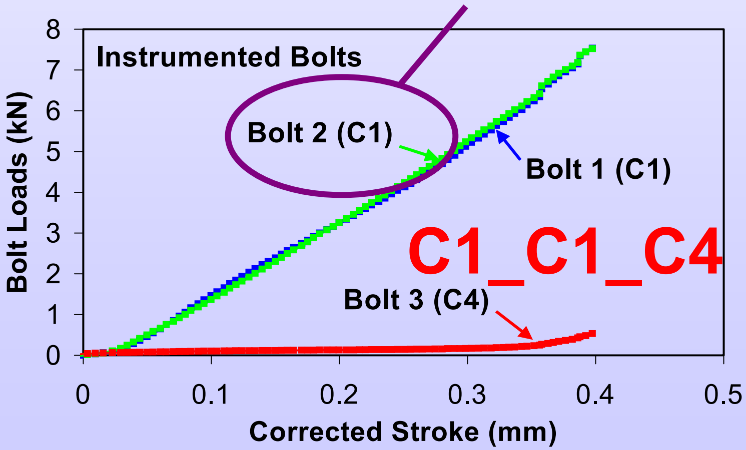


Two bolts failed simultaneously

Usual design rules (ignoring clearance) → middle bolt NOT under any threat of failure

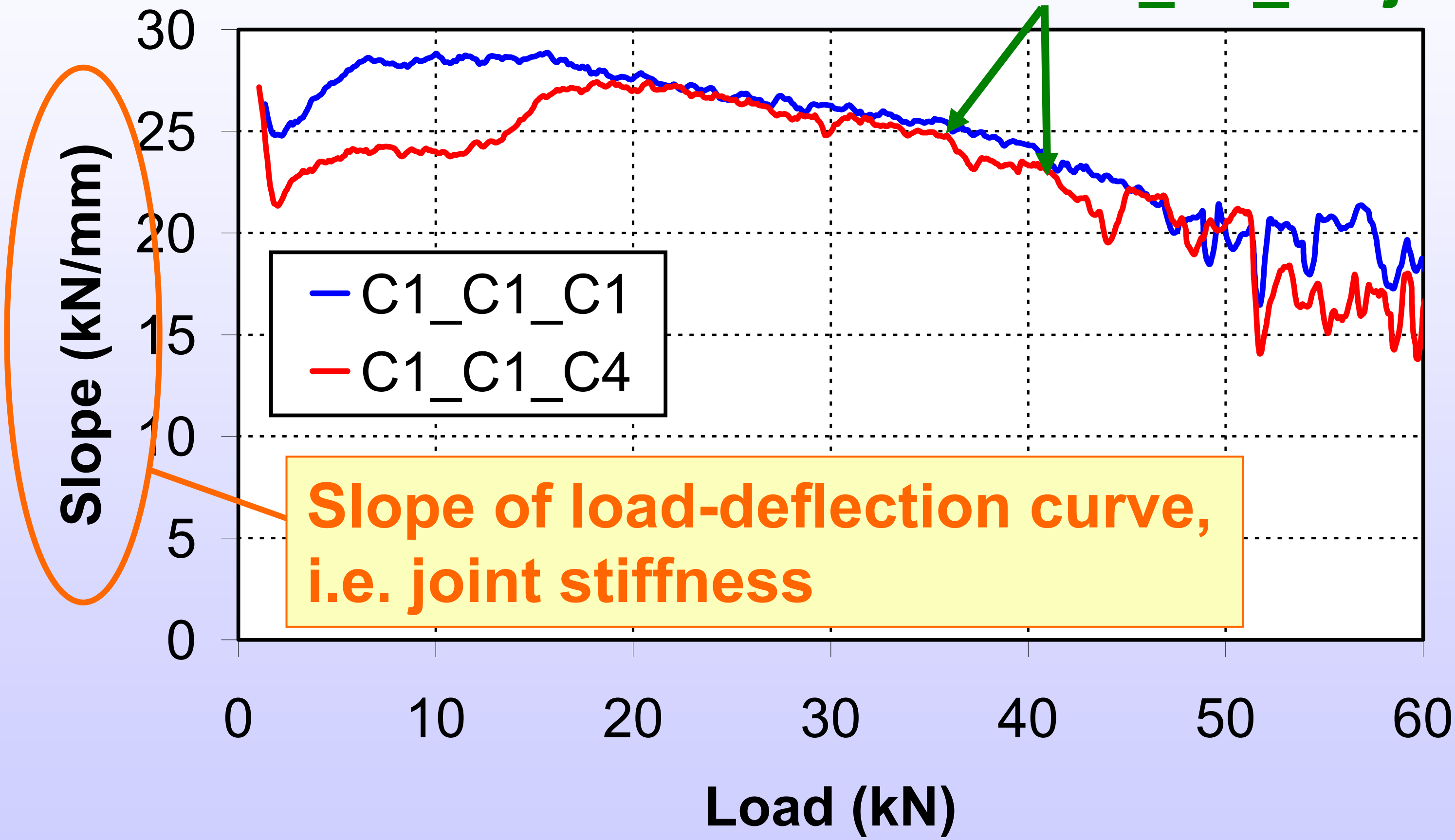
But with clearance in one of the outer holes – failure of middle bolt becomes possible



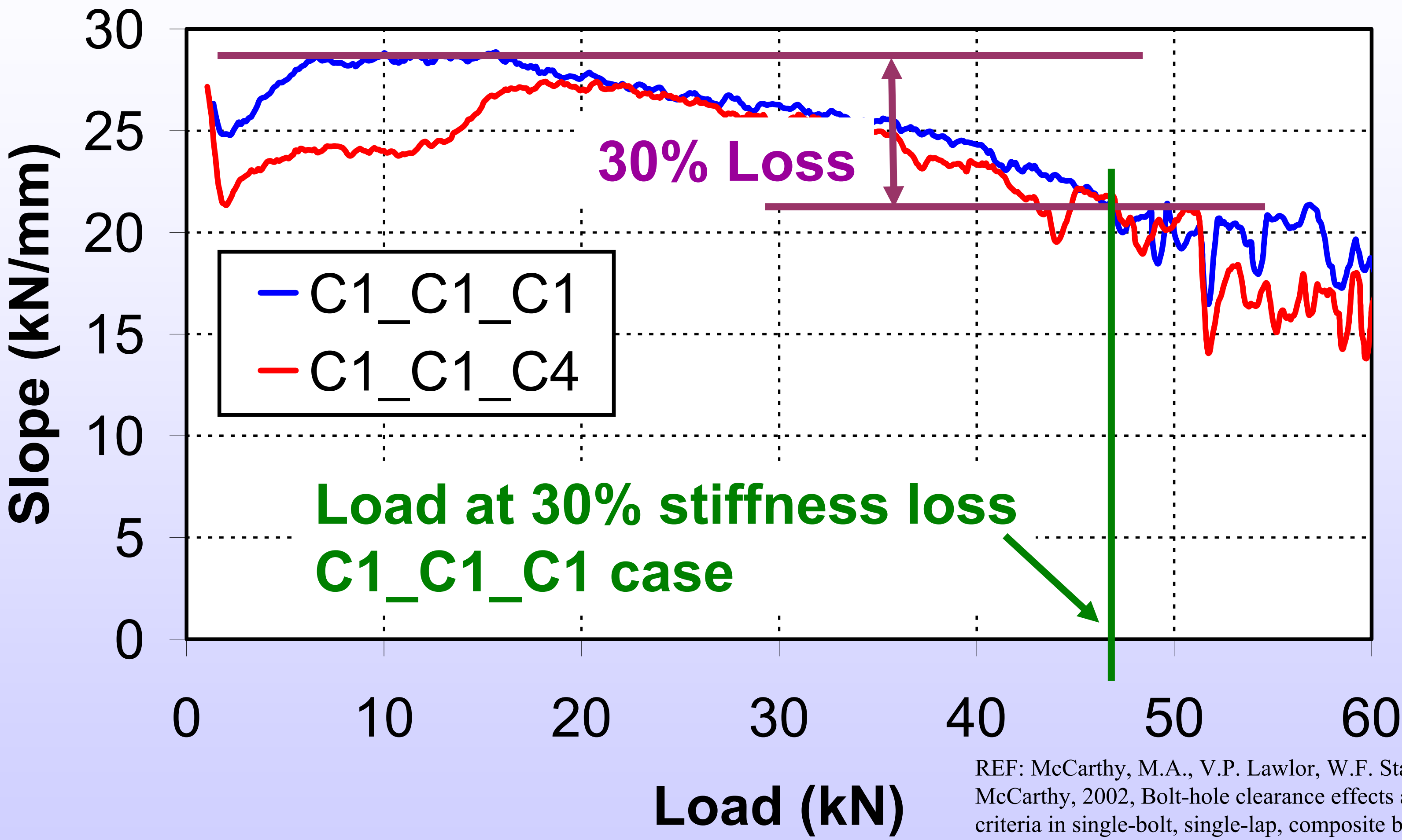


SL Joints – Failure *Initiation*

C1_C1_C4 joint exhibits sharp losses in stiffness earlier than C1_C1_C1 joint



Measure of Failure *Initiation*



REF: McCarthy, M.A., V.P. Lawlor, W.F. Stanley, C.T. McCarthy, 2002, Bolt-hole clearance effects and strength criteria in single-bolt, single-lap, composite bolted joints, *Composites Science and Technology*, Vol. 62, pp. 1415-1431.

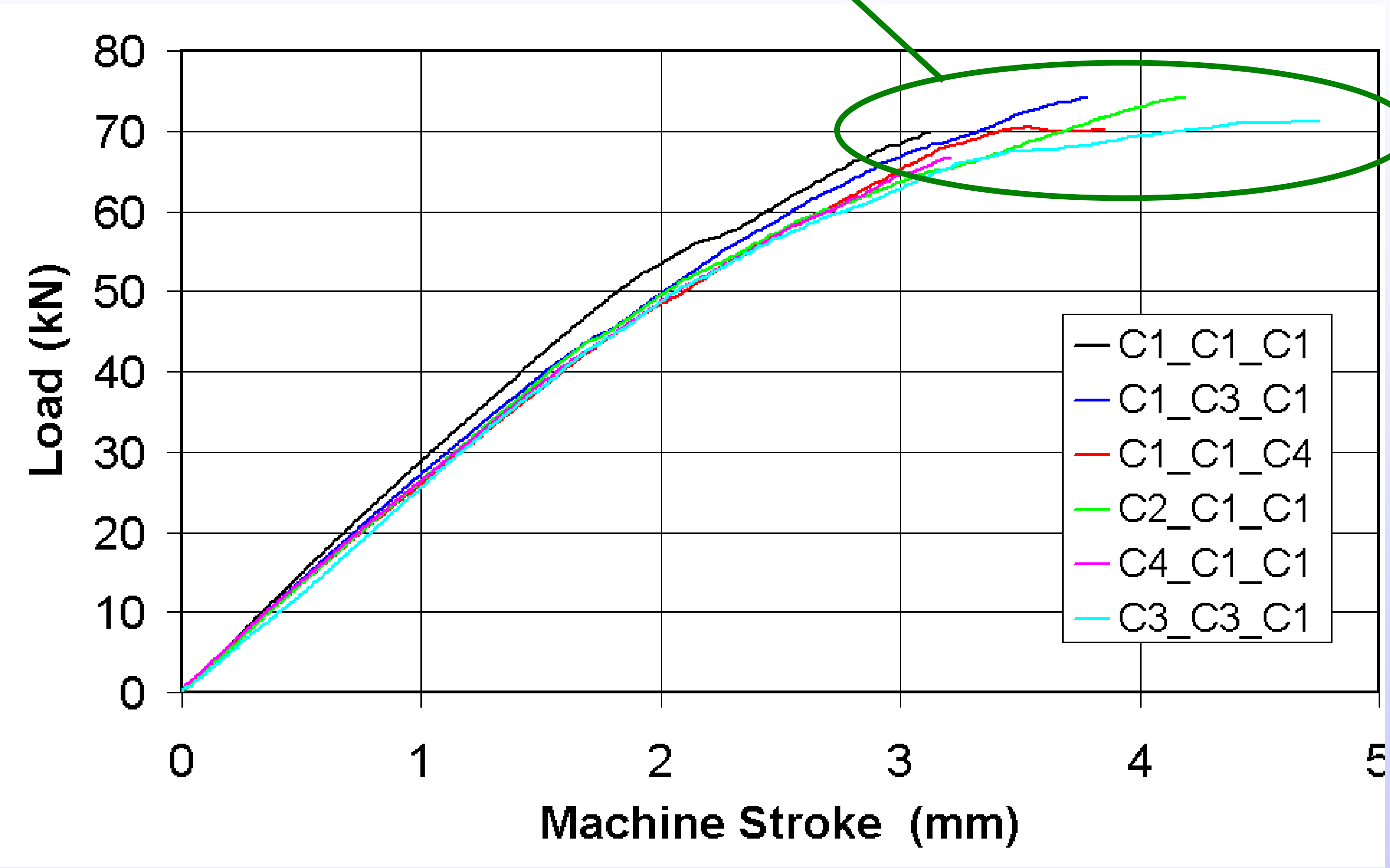
Failure “Initiation” Loads

Specimen	Load at 30% stiffness drop (kN)
C1_C1_C1 (A)	51.06
C1_C1_C1 (B)	47.26
C1_C1_C1 (C)	51.00
Average	**49.77**
C1_C1_C4 (A)	48.25
C1_C1_C4 (B)	47.64
C1_C1_C4 (C)	46.20
Average	**47.36**

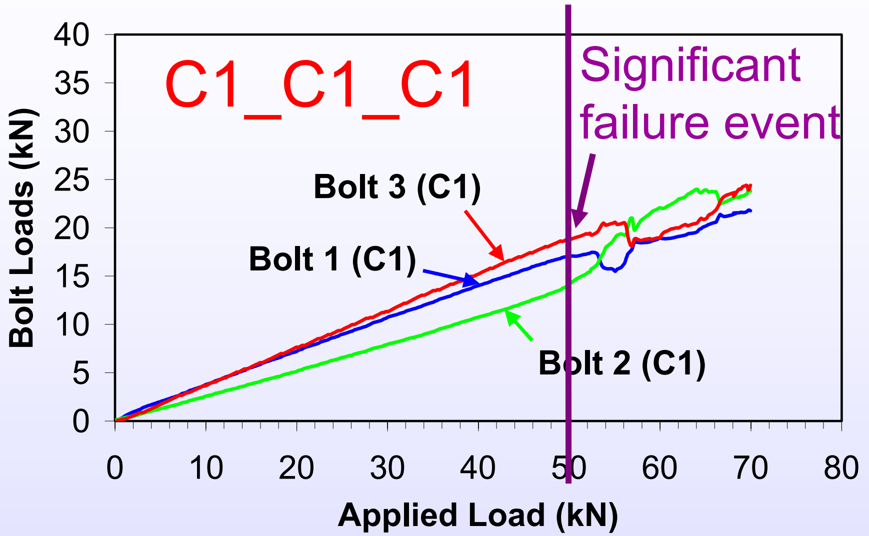
Failure initiated earlier in C1_C1_C4 joints

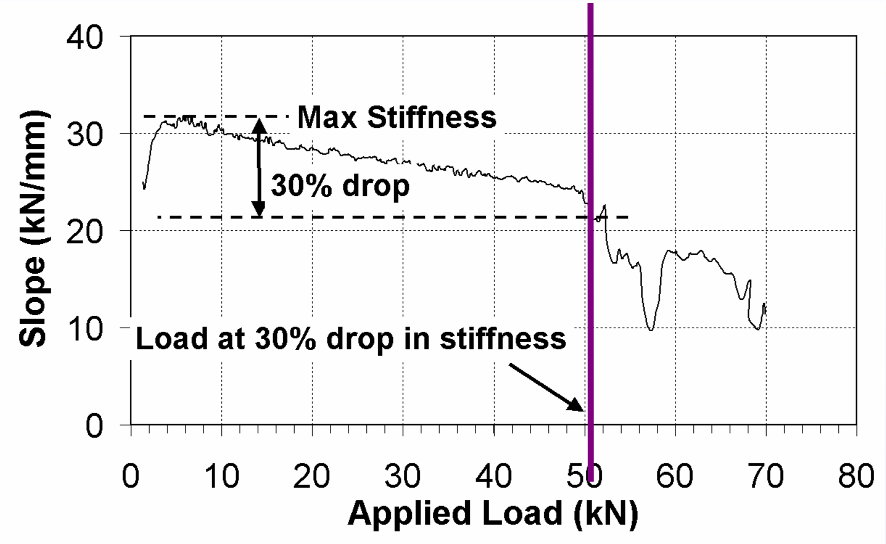
Double-Lap Joints

Again, no clear effect on ultimate strength



DL Joints – Failure Initiation



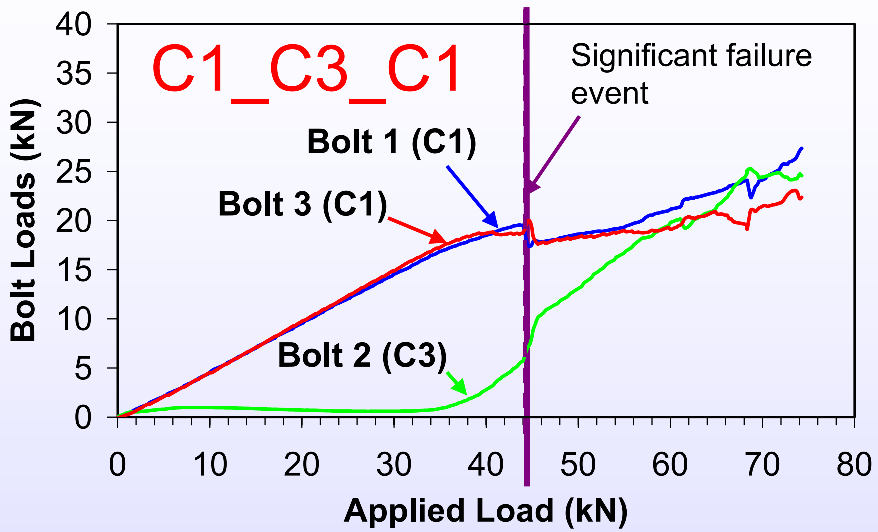


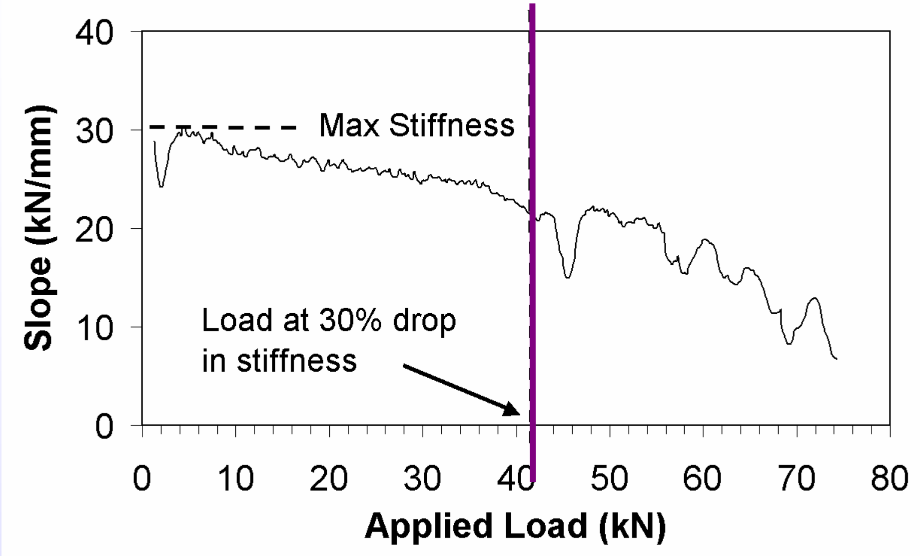
• Strain gauge method of load distribution measurement much cheaper → can test to failure

• strain gauge readings interrupted at a “significant” failure event

Load at 30% loss of stiffness matches load at interruption of strain gauge pattern very well

DL Joint - C1_C3_C1





- Again load at 30% loss of stiffness matches load at interruption of strain gauge pattern very well (true for all six clearance cases)
- Load is significant lower in C1_C3_C1 case than C1_C1_C1
- From consideration of bearing yield allowable, the "first significant failure" was found to be **bearing failure at one of the holes**

Effect of Clearance on first bearing failure

Code	Load at first bearing failure (kN)	Percentage Difference from C1_C1_C1
C1_C1_C1	50	0%
C1_C3_C1	44	12%
C1_C1_C4	44.3	11.4%
C2_C1_C1	43.2	13.6%
C4_C1_C1	40	20%
C3_C3_C1	37.2	25.6%

Conclusions – QS Loading

- Clearance:
  - No significant effect on *ultimate* tensile load
  - DID affect ultimate tensile *mode*
  - Small effect on failure initiation load in SL joints
  - LARGE effect on failure initiation load in DL joints (load at first bearing failure affected by 25%)
- Strain gauge load distribution method cheaper than instrumented bolts – can be used up to failure (cannot easily be used for SL joints though)
- Load at 30% loss in stiffness appears to be a good measure of first "substantial" failure

Fatigue Loading

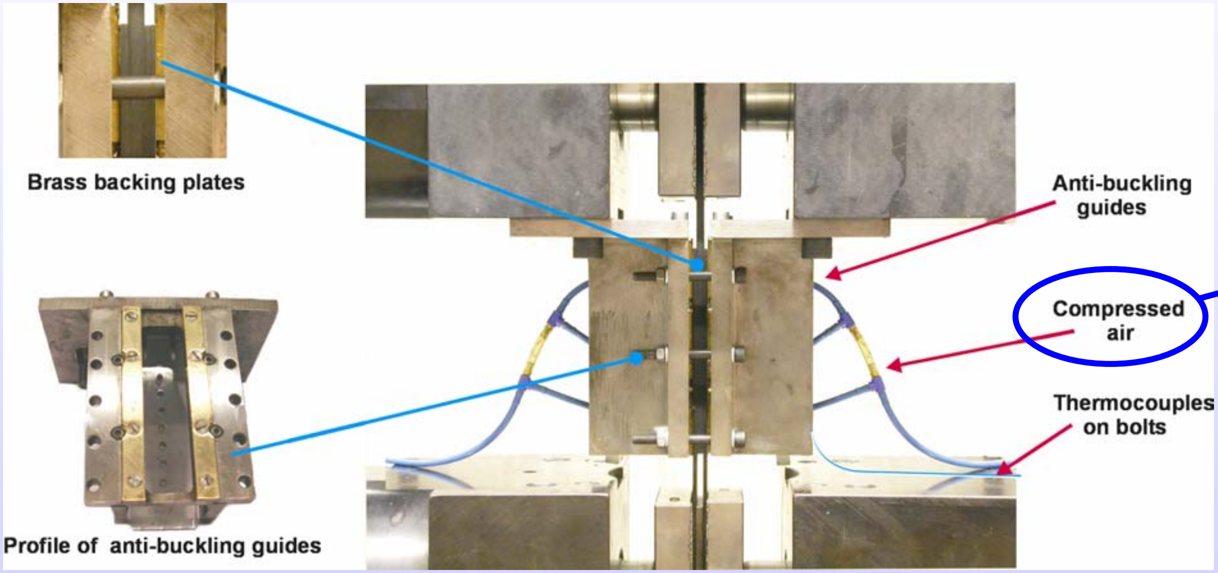
Fatigue Cases

Case Code	Nominal Clearance (μm)		
	Hole 1	Hole 2	Hole 3
C1_C1_C1	0	0	0
C1_C1_C4	0	0	240

- Both Single-Lap and Double-lap joint

Test Set-up

- Constant amplitude fatigue loading, R = -1 ($\sigma_{min}/\sigma_{max}$ = -1)
- Anti-buckling guides

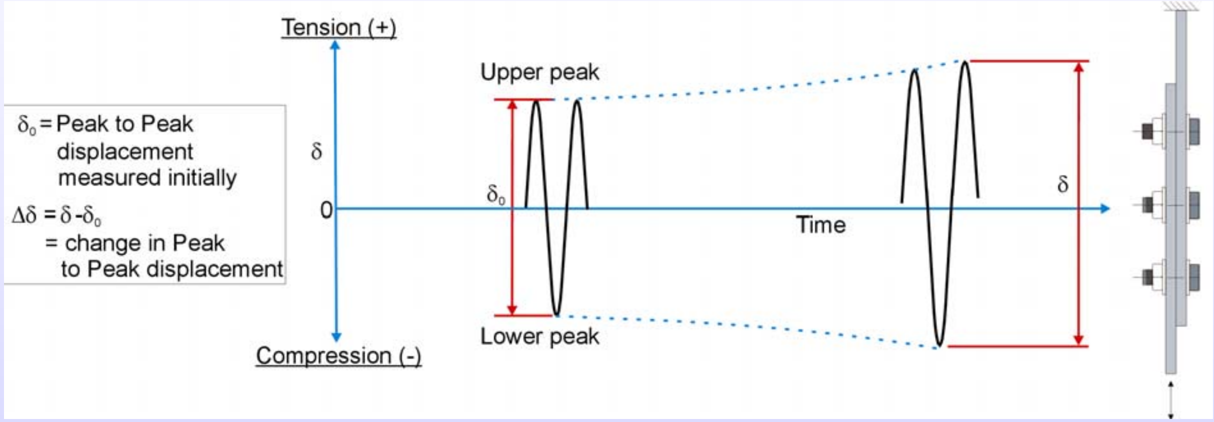


Cooling system (compressed air)

- To avoid temperature rise, frequencies between 0.66 and 5 Hz
- Temperature of each bolt monitored – maintained < 25°C

Failure Criterion

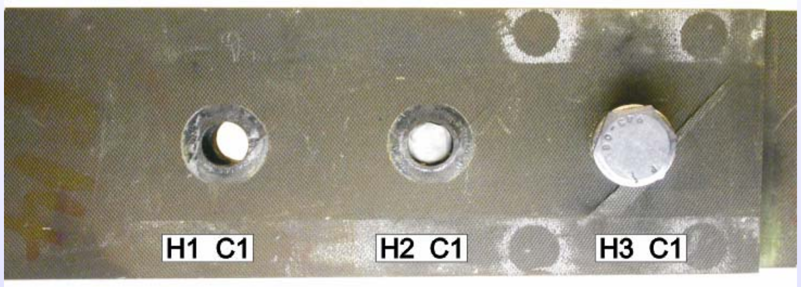
- Hole elongation criterion for failure (Starikov and Schon, 2002)
- Increase in peak-to-peak displacement $\Delta\delta$ of 0.8 mm



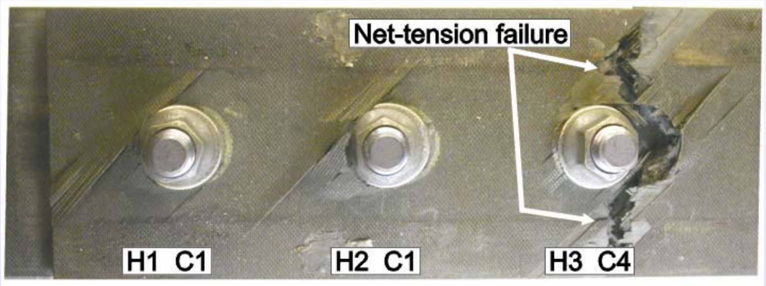
Ultimate Failure Modes

- However, in single-lap joints, other failure modes occurred on continuation of tests beyond the hole elongation failure point

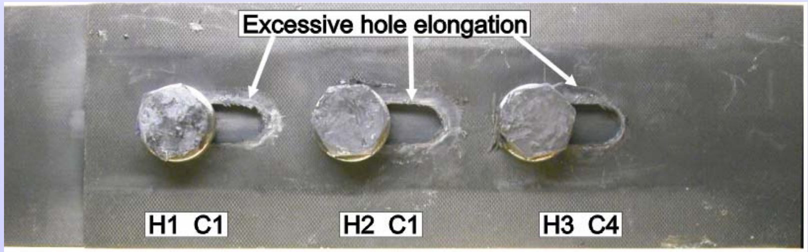
Bolt failure



Net tension failure



Extreme hole elongation

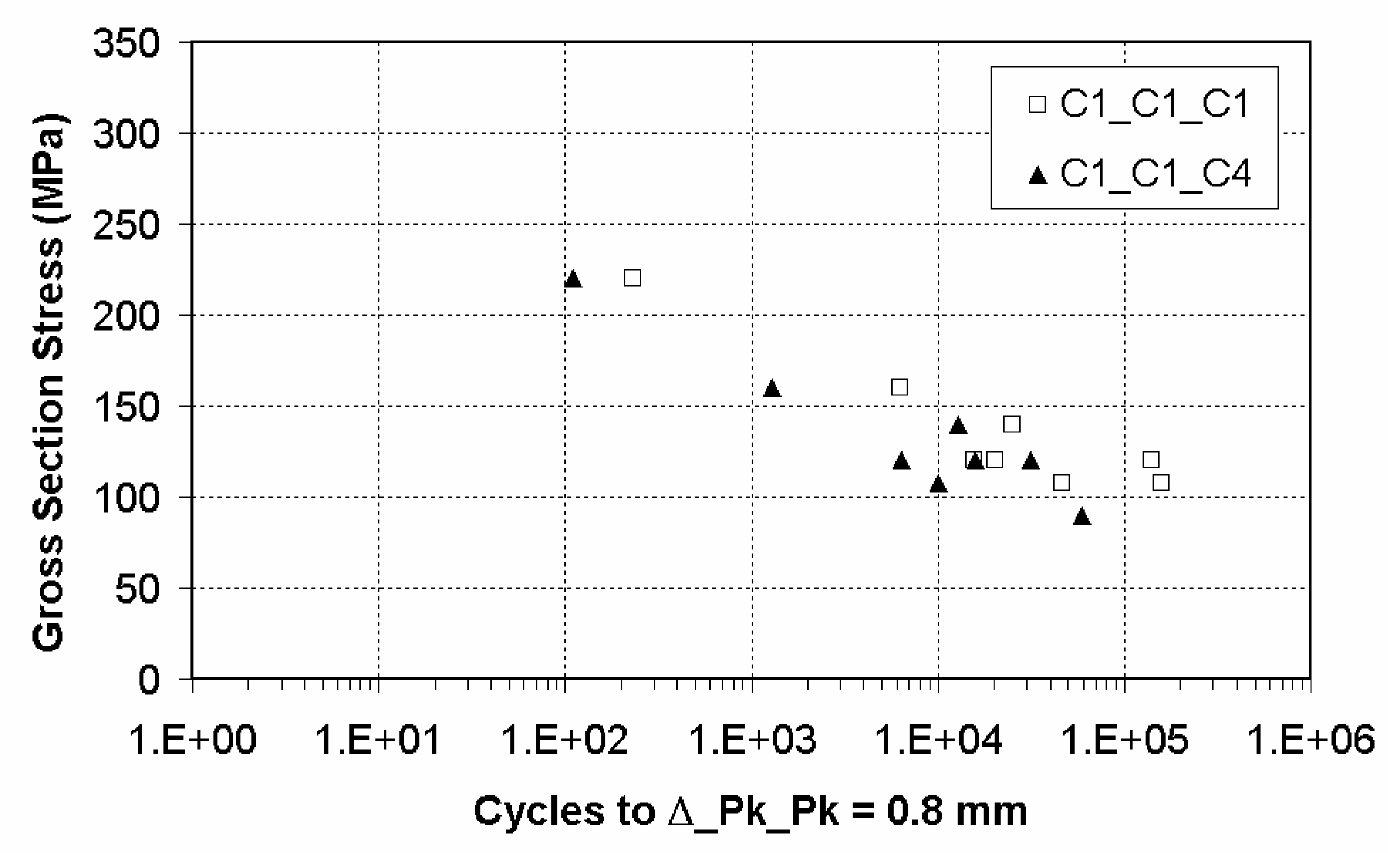


- Double-lap joints exhibited only extreme hole elongation

Ultimate Failure Cycles

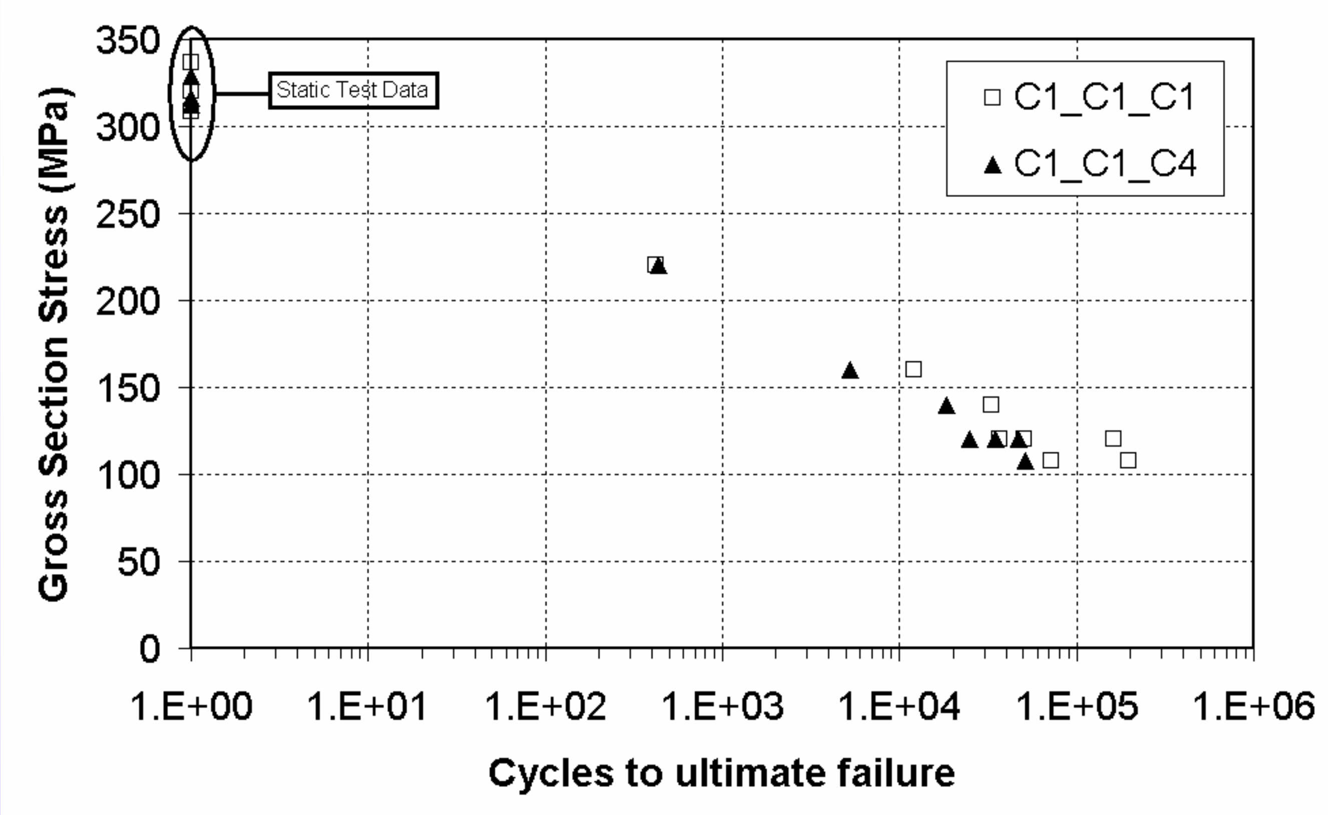
- Cycles to “ultimate failure” were also recorded
- “Ultimate failure” – displacement to + or – 10 mm
- Reached suddenly in catastrophic failure modes and gradually in extreme hole elongation cases

SL Joints – Hole Elong



Joints with loose-fit bolt have shorter fatigue life in general

SL Joints – Ult Failure



Joints with loose-fit bolt have shorter fatigue life in general

Temperature and Displ. History

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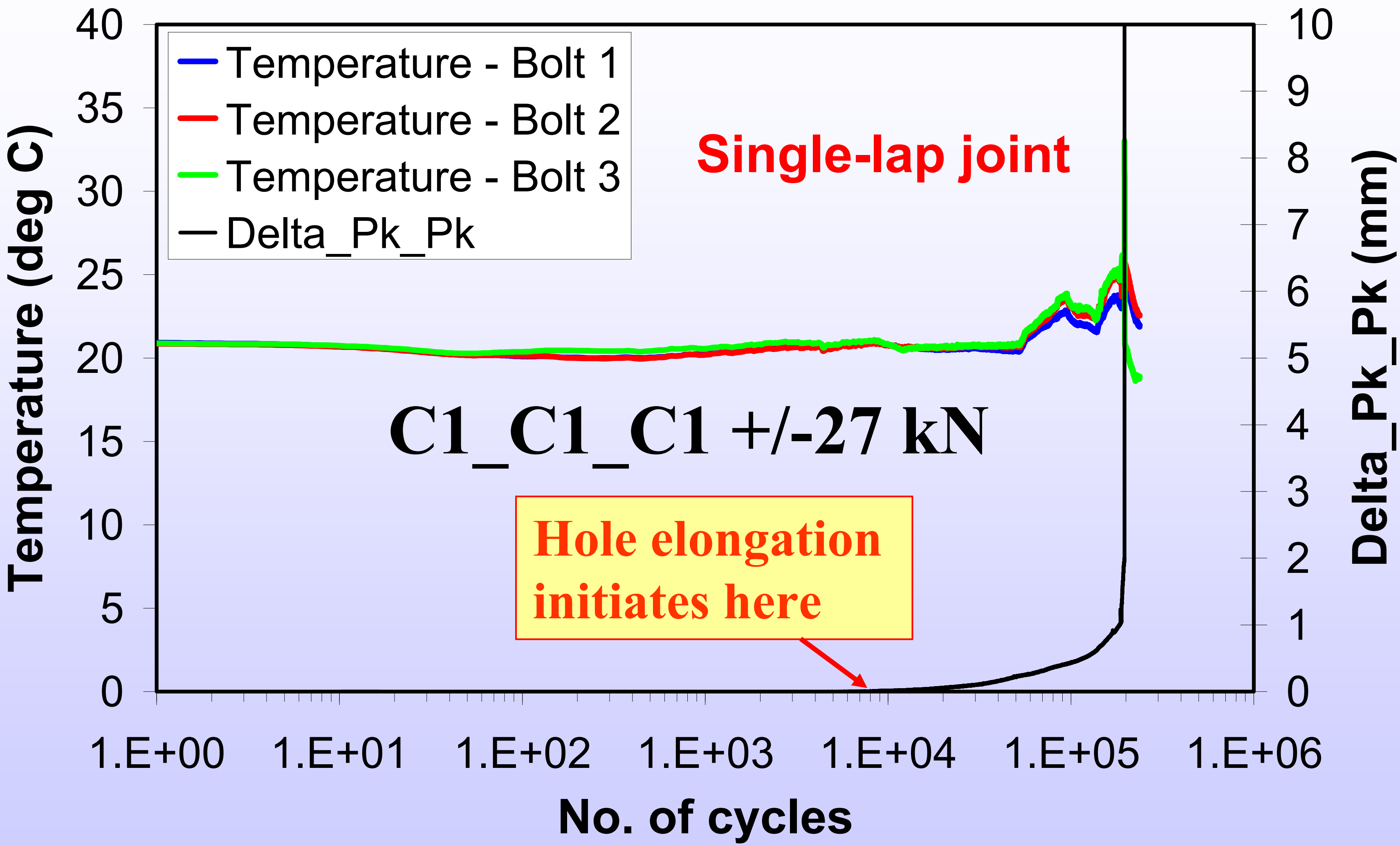
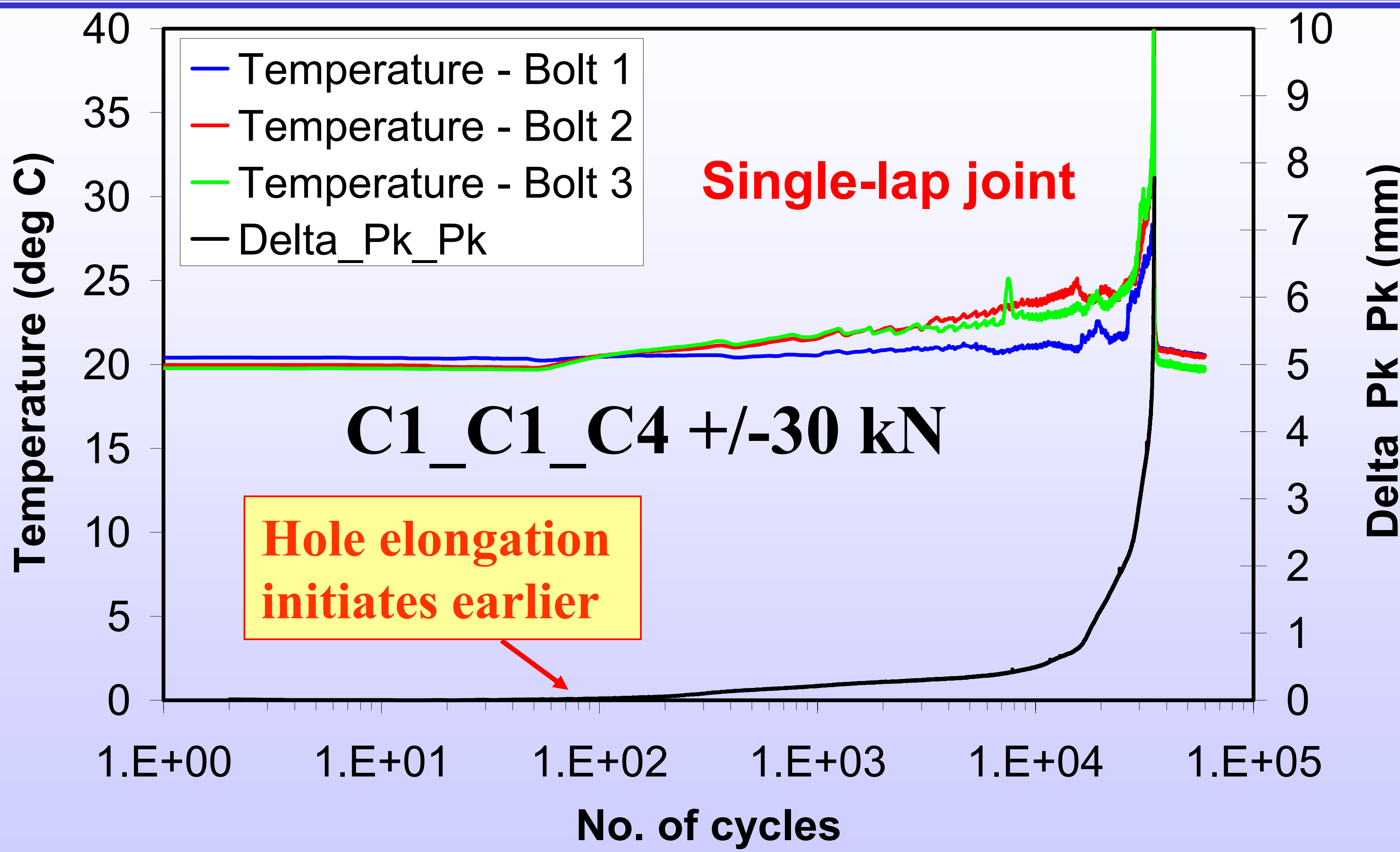
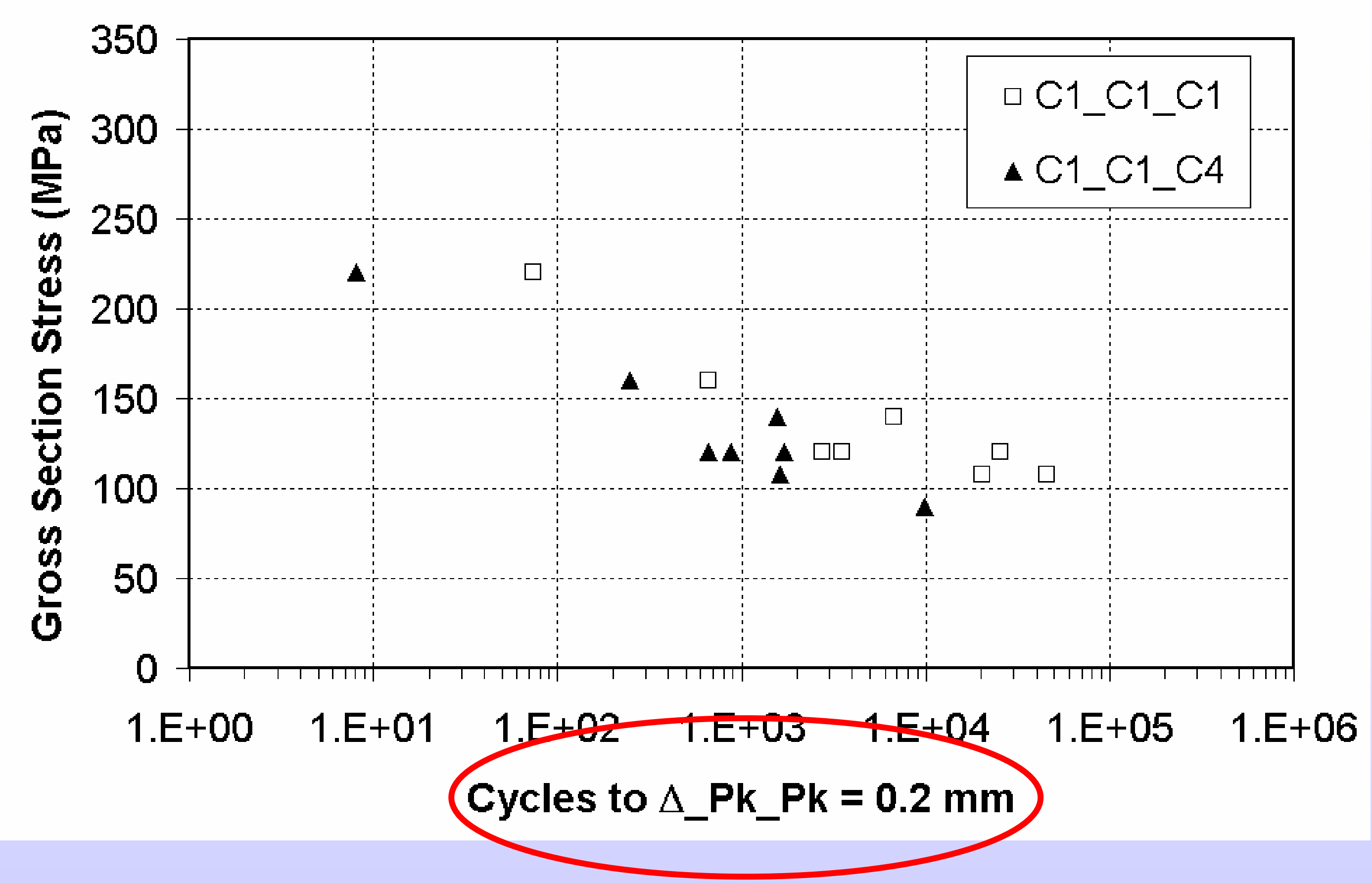


Temperature and Displ. History

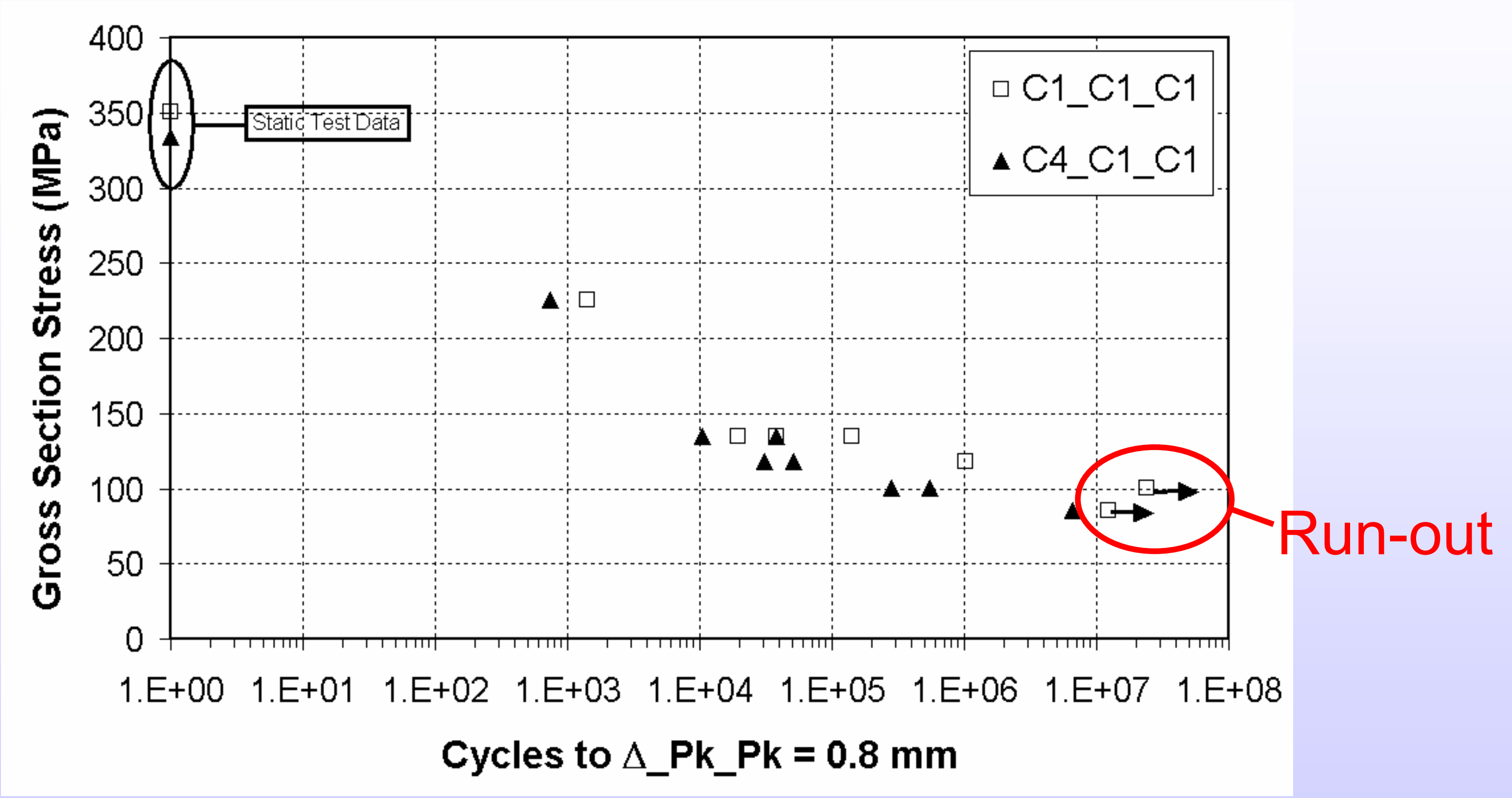


SL - Cycles to small hole elong



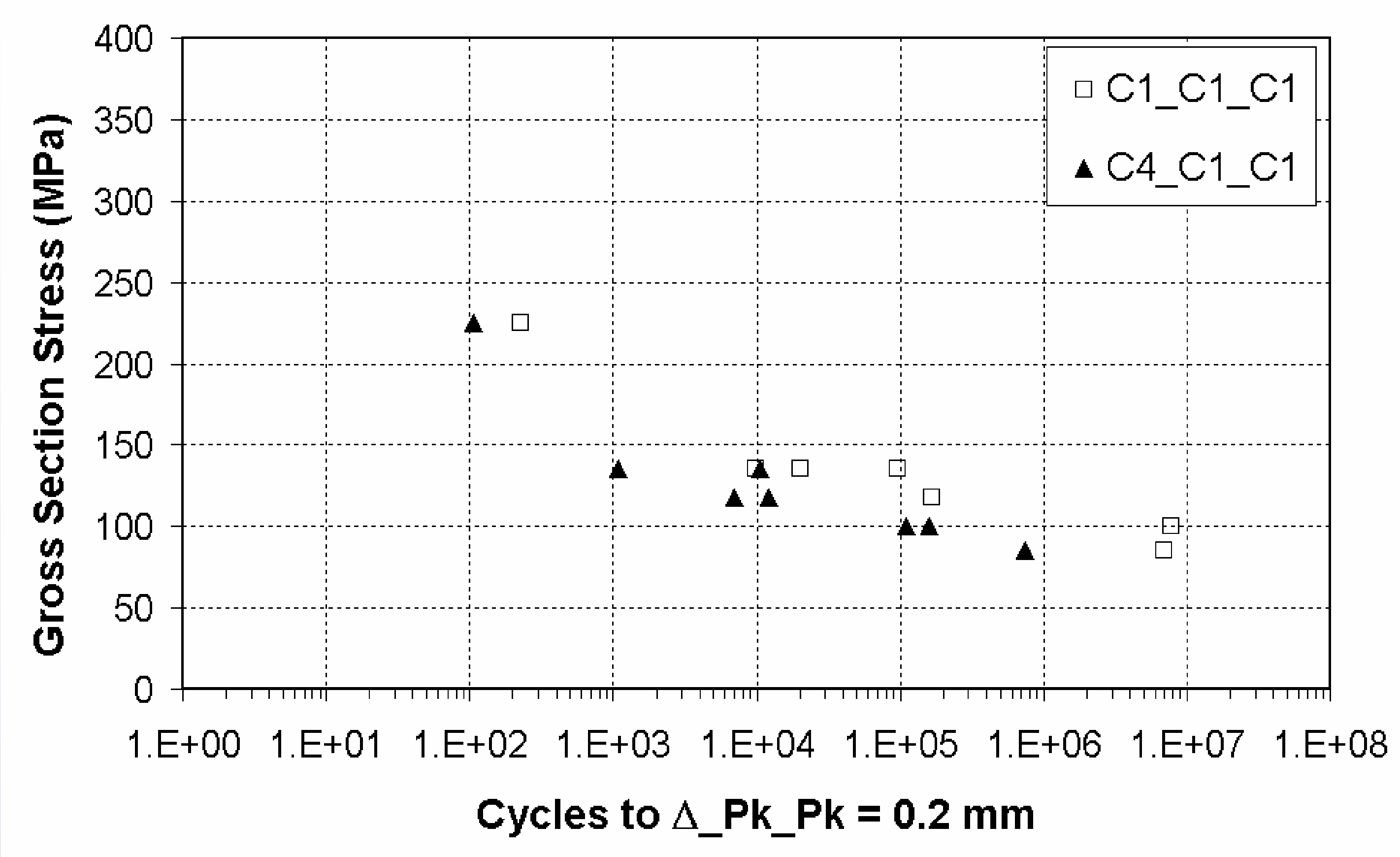
- Clearer distinction between clearance cases

DL Joints – Hole Elong



Joints with loose-fit bolt have shorter fatigue life in general

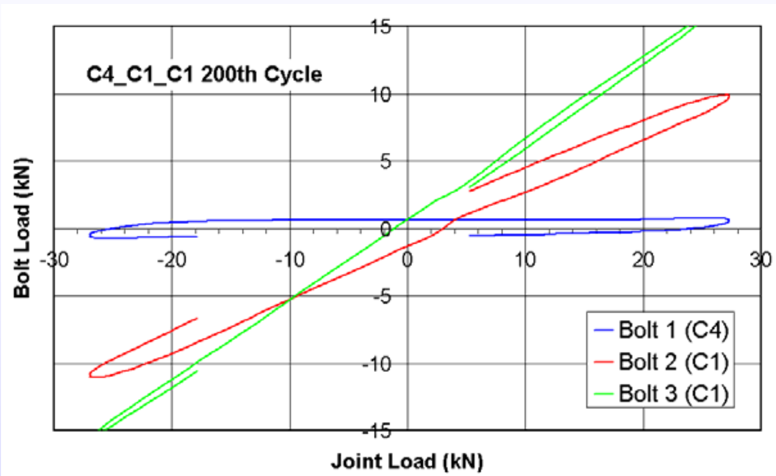
DL - Cycles to small hole elong



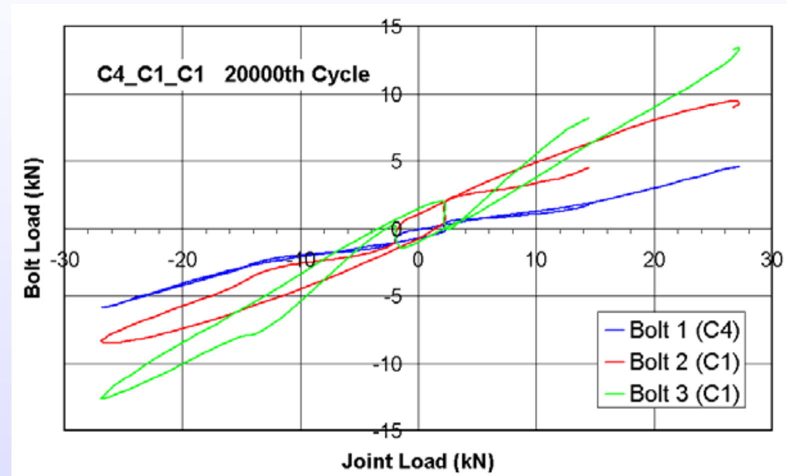
- Again - clearer distinction between clearance cases

Load distribution during Fatigue

C4_C1_C1 200th Cycle



C4_C1_C1 20000th Cycle



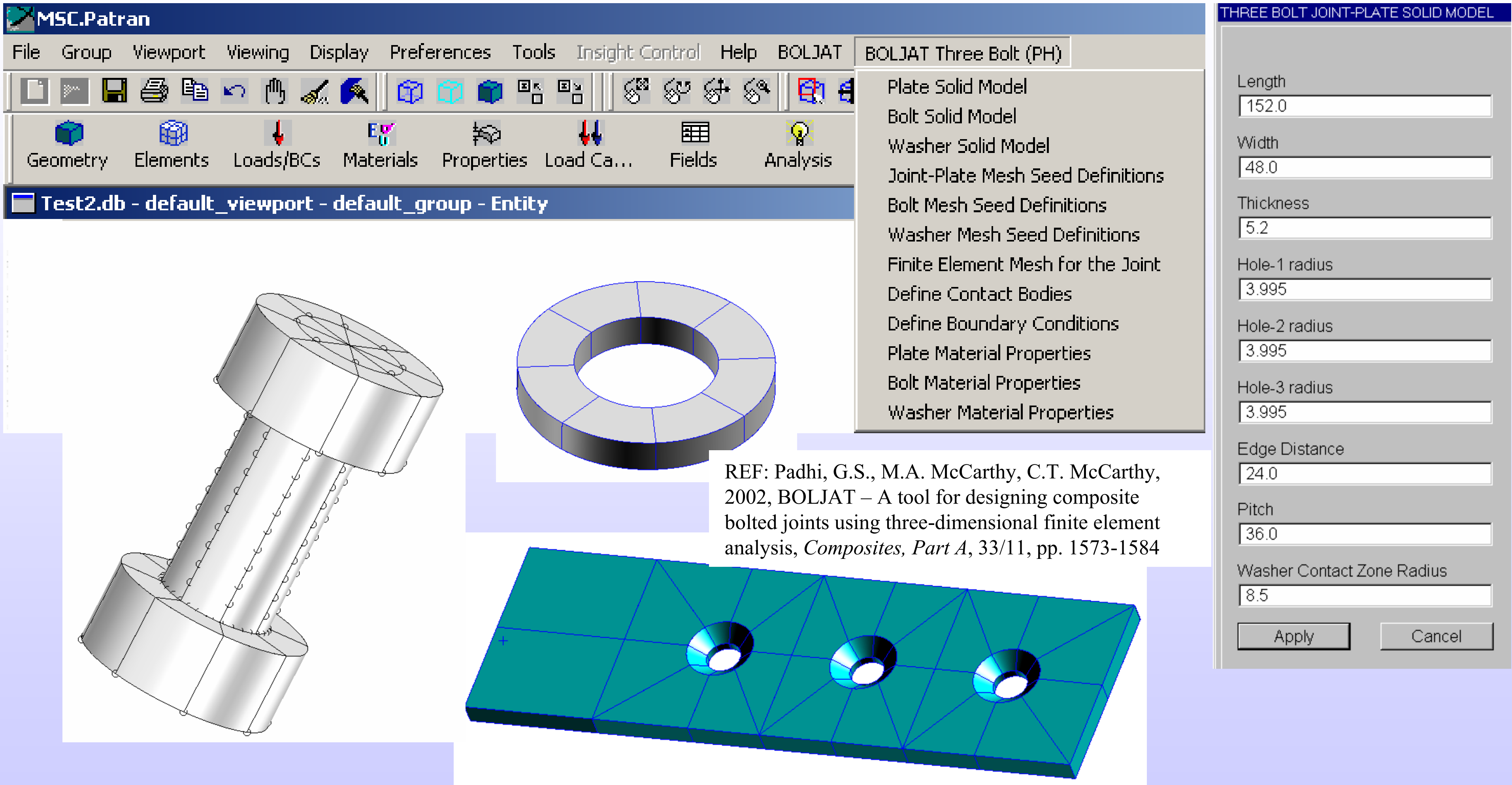
- Due to hole wear, clearance has less effect as wear progresses (load distribution evens out) ➔ clearance most affects **initiation** of failure, less effect on final failure

Conclusions – Fatigue Loading

- Joints with a loose-fit bolt had shorter fatigue lives than joints with all neat-fit bolts (SL and DL)
- Clearance had a particularly strong effect on failure initiation, i.e. cycles to a small hole elongation
- Effect of clearance less pronounced as failure progresses since failure causes elongation of the neat-fit holes in the C1_C1_C4 joint causing the clearance to even out over time

Finite element Analysis

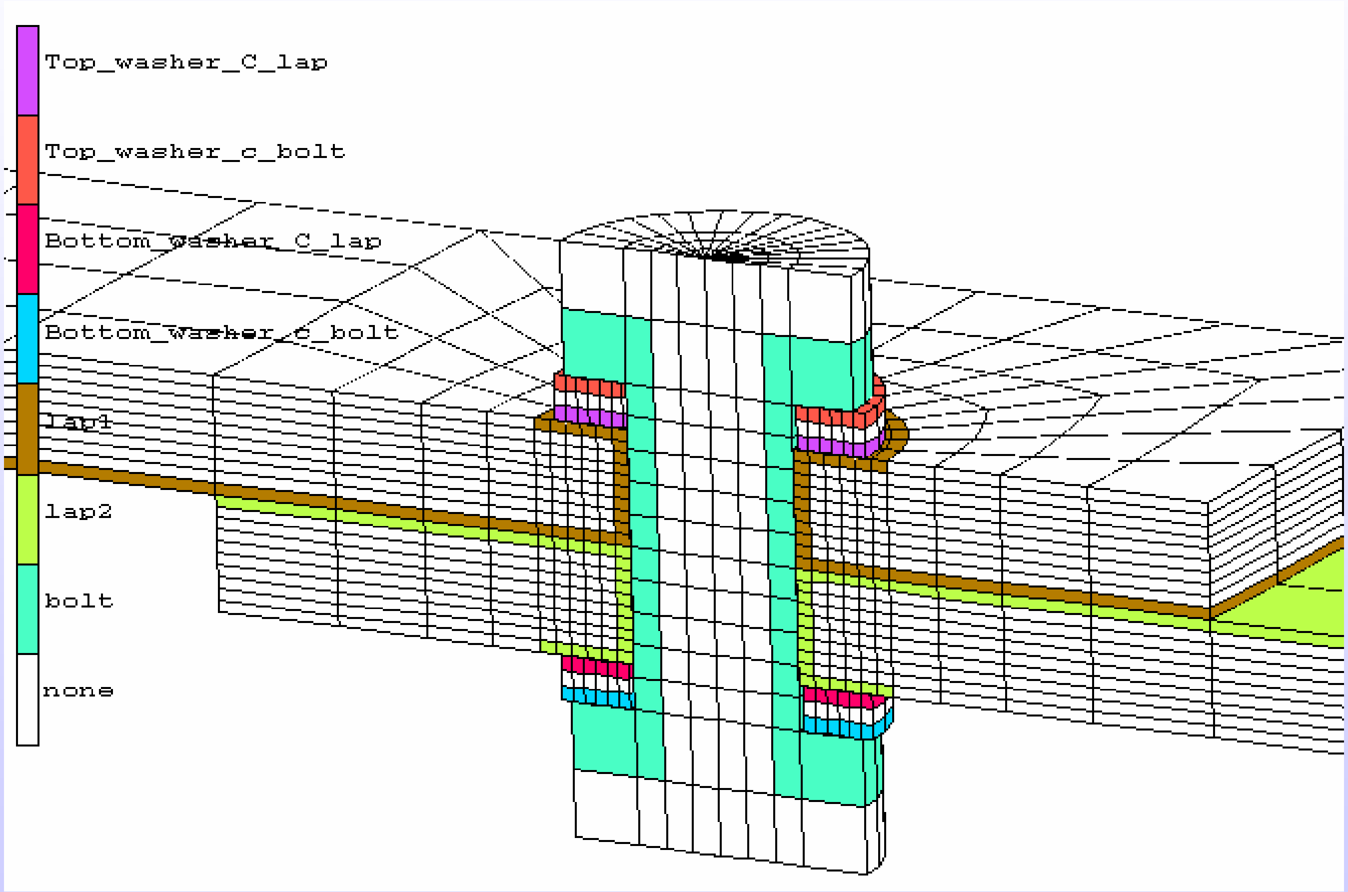
Model Creation Tool: BOLJAT



REF: Padhi, G.S., M.A. McCarthy, C.T. McCarthy, 2002, BOLJAT – A tool for designing composite bolted joints using three-dimensional finite element analysis, *Composites, Part A*, 33/11, pp. 1573-1584

Contact Analysis

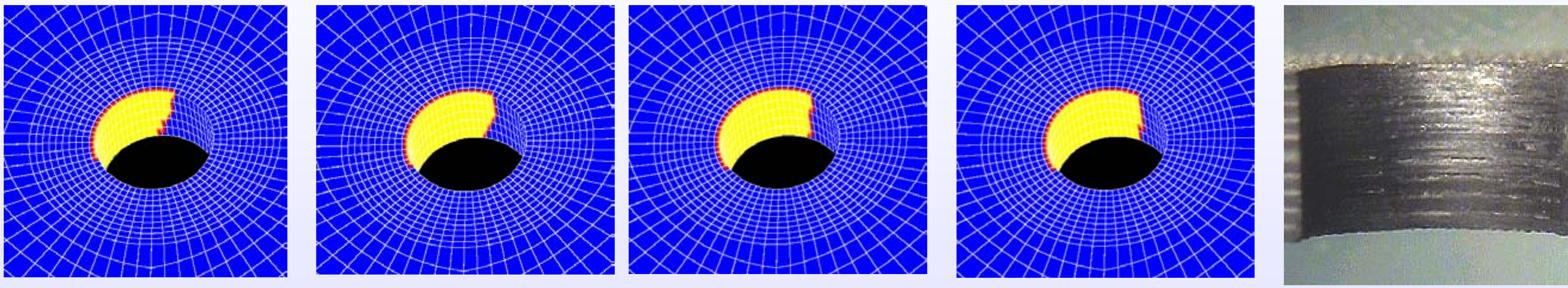
Contact analysis performed between all parts

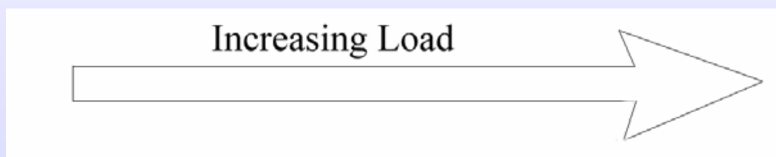


Contact Area Development

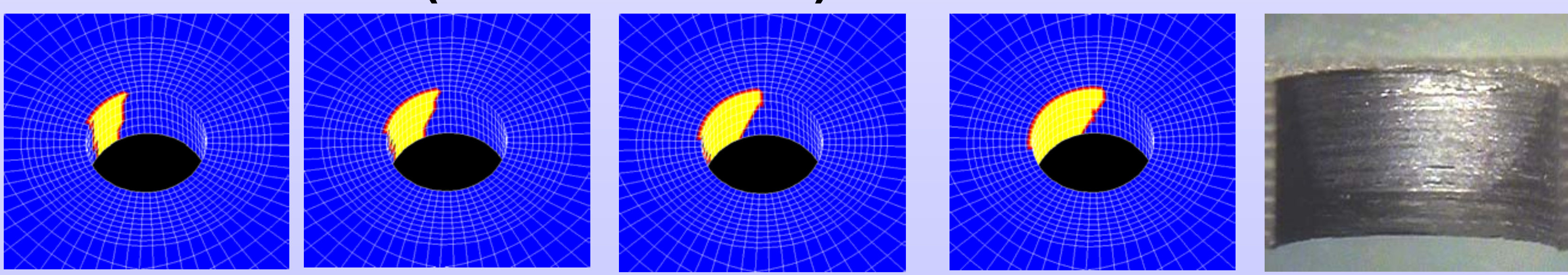
<u>Single</u>-Bolt, Single-Lap Joint

C1 Clearance (Contact Area)

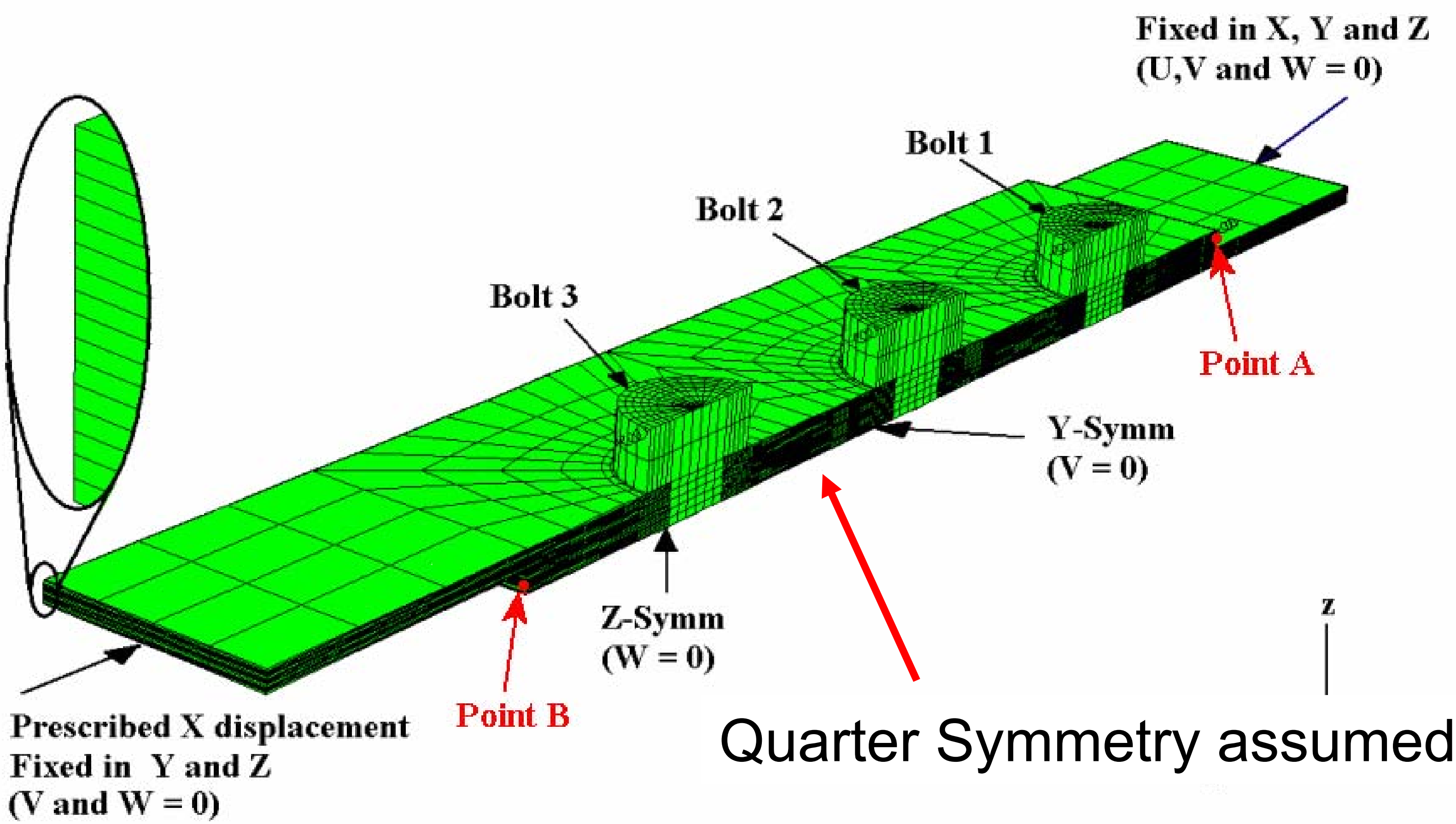




C4 Clearance (Contact Area)

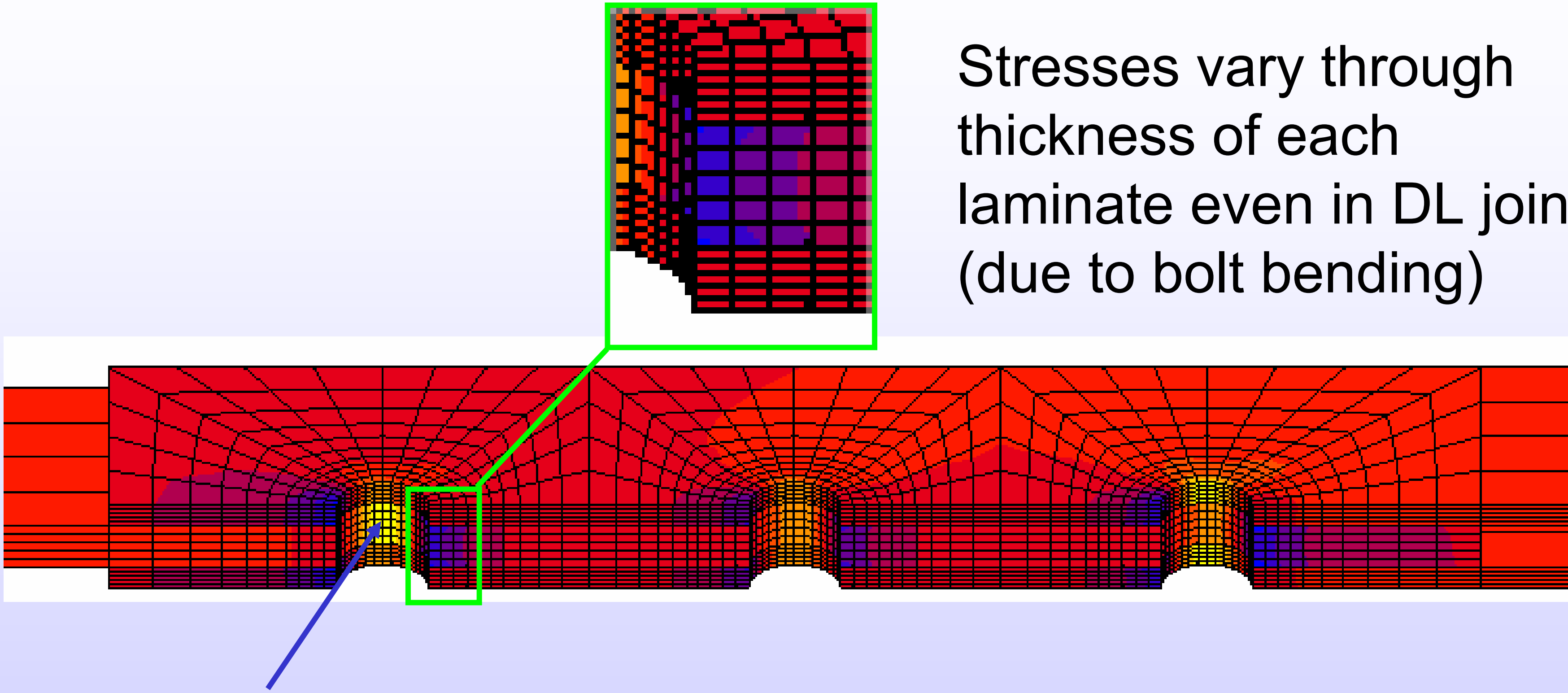


Model of Double-Lap Joint



Quarter Symmetry assumed

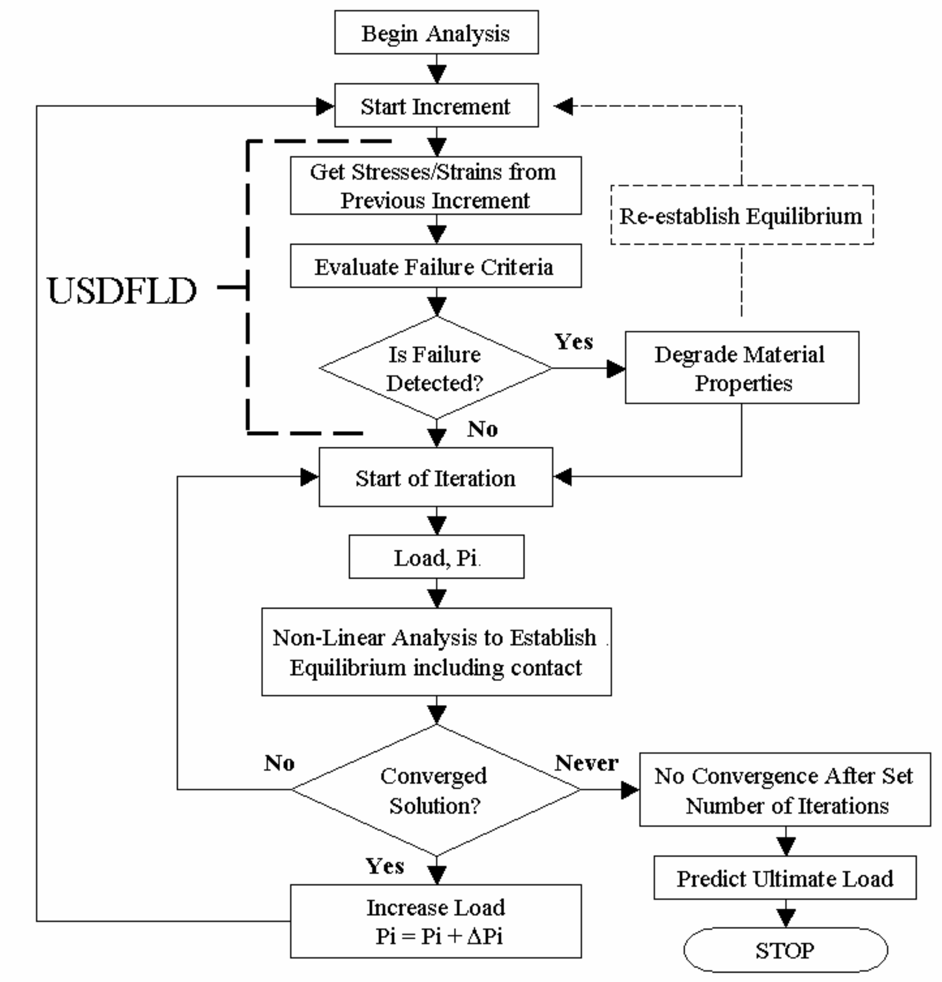
Stress Distribution



Stresses vary through thickness of each laminate even in DL joint (due to bolt bending)

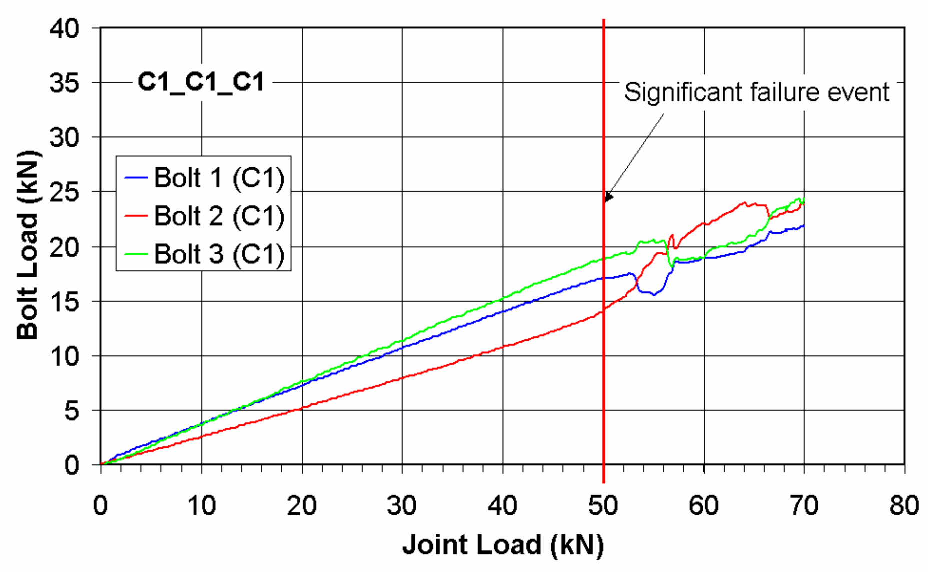
Net tension stresses in central laminate highest at this hole (i.e. bypass stresses correctly accounted for)

Progressive Damage Analysis

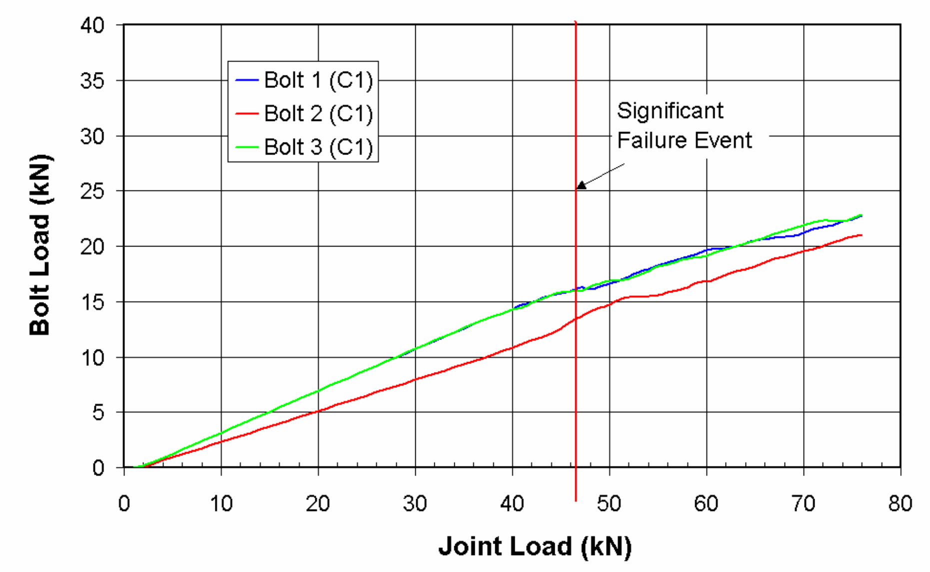


Bolt Loads (C1_C1_C1)

Experiment

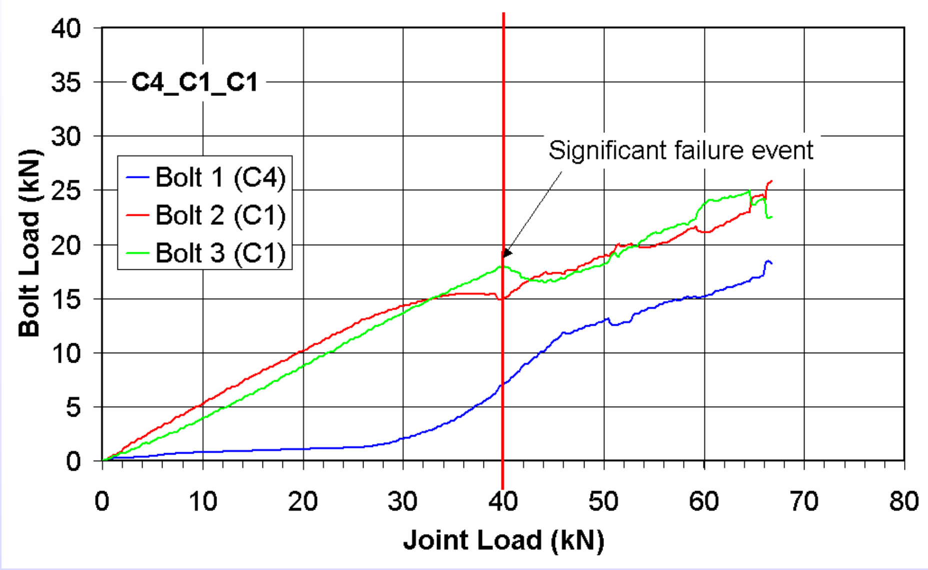


Simulation

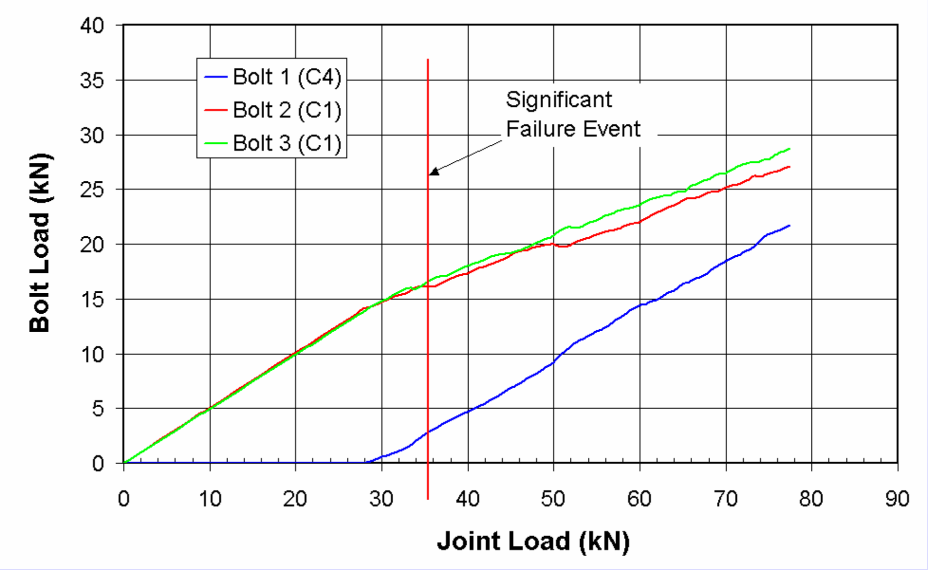


Bolt Loads (C4_C1_C1)

Experiment



Simulation



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Compressive Matrix Damage (C1_C1_C1)

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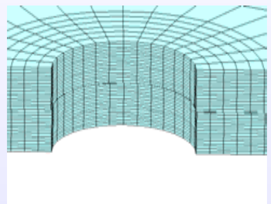
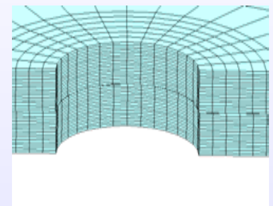
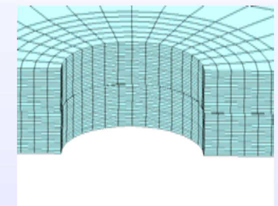
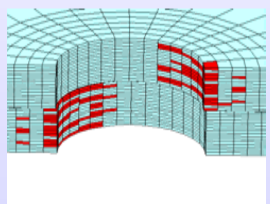
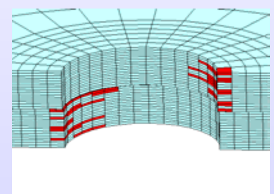
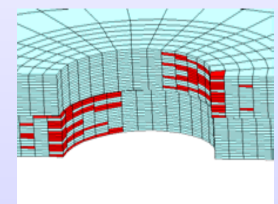
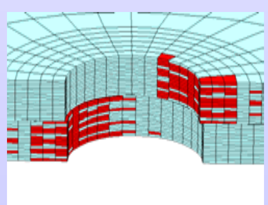
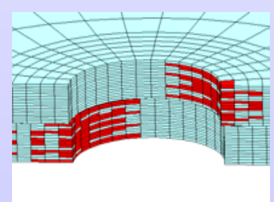
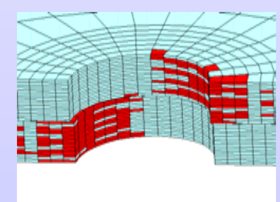
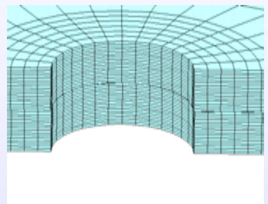
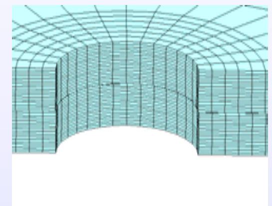
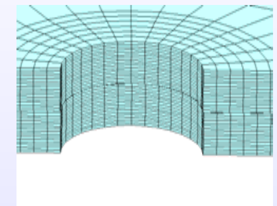
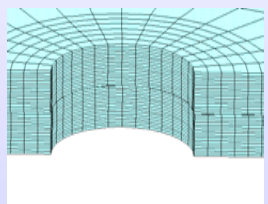
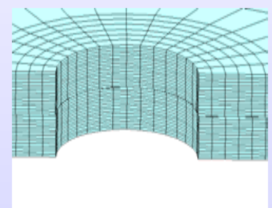
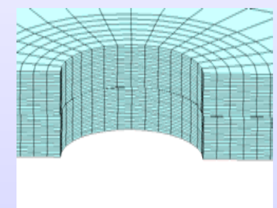
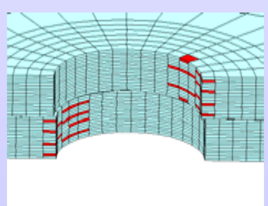
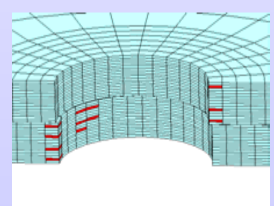
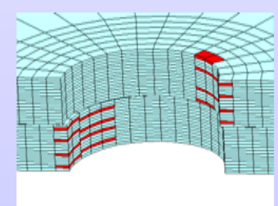
Applied Load	Hole 1 (0 μm)	Hole 2 (0 μm)	Hole 3 (0 μm)
10 kN			
30 kN			
50 kN			

Compressive Fibre Damage (C1_C1_C1)

Applied Load	Hole 1 (0 μm)	Hole 2 (0 μm)	Hole 3 (0 μm)
10 kN			
30 kN			
50 kN			

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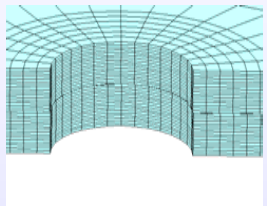
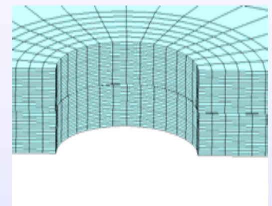
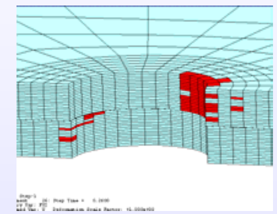
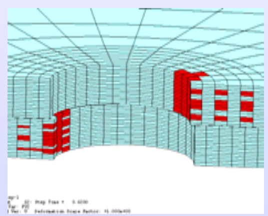
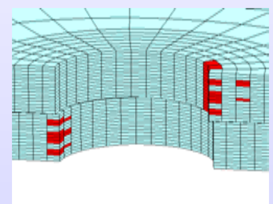
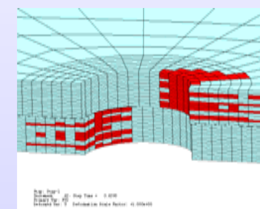
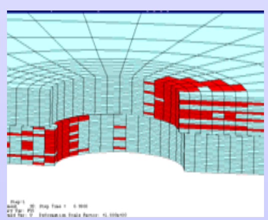
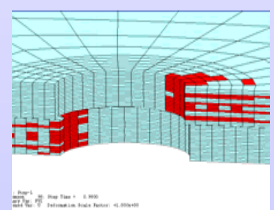
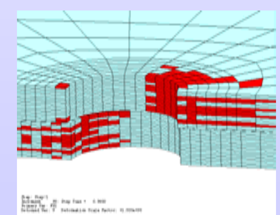
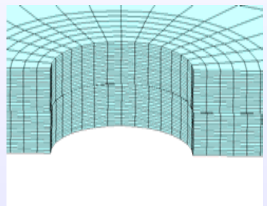
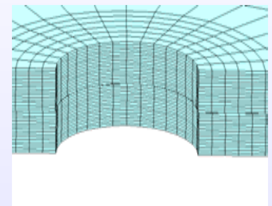
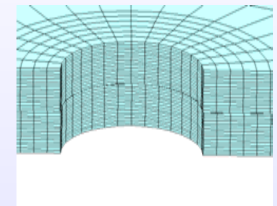
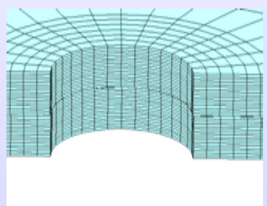
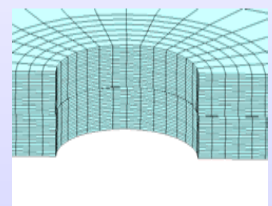
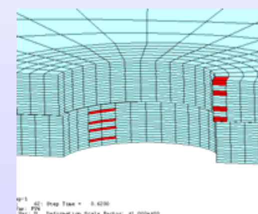
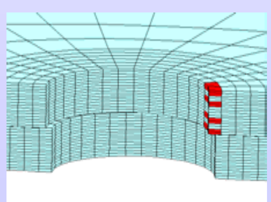
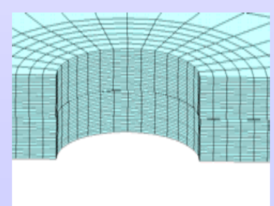
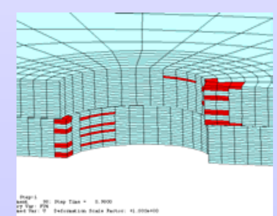
Compressive Matrix Damage (C3_C3_C1)

Applied Load	Hole 1 (160 μm)	Hole 2 (160 μm)	Hole 3 (0 μm)
10 kN			
30 kN			
50 kN			

Compressive Fibre Damage (C3_C3_C1)

Applied Load	Hole 1 (160 μm)	Hole 2 (160 μm)	Hole 3 (0 μm)
10 kN			
30 kN			
50 kN			

Conclusions – FEA

- 3D FEA with contact can account for: variable contact in each hole and through thickness; bypass stresses; non-uniform bearing stresses through thickness
- PDA gives insight into failure processes at each hole and gives prediction of initial failure (bearing failure in one hole)