Analysis of Fatigue Failure in D-shaped Carabiners

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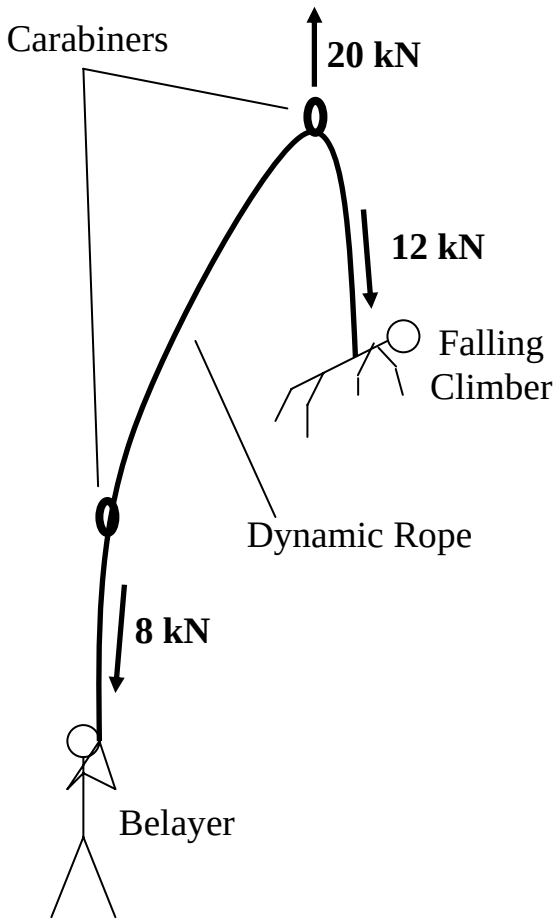
Introduction

- Current standard: Single pull to failure test (SPTF)
- Climbers need rating reflecting in-field use
  - Cyclic & Dynamic loads result from falling, hanging and lowering
  - Typical Load Range: 2- 10 kN
  - Only most severe falls approach minimum SPTF ratings
- Continued cyclic loading can result in fatigue failure of carabiners
- Current carabiner retirement guidelines do not address fatigue life

Objective

- This study characterizes the lifetime of carabiners under cyclic loads
  - Loads reflect in-field use
  - Controlled laboratory environment

Carabiner Load Analysis



- Worst case scenario is factor 2 fall
  - Factor = Distance climber falls/length of belayed rope
- Dynamic rope stretches to absorb 1/3 of the force of the climber's fall for the belayer
- Top carabiner loaded to 20 kN

Background: Climbing Loads

- Empirical studies have shown close correlation between in-field loads and those predicted by models
- Single cycle period (0.5 seconds) is in the middle of typical field-load duration
- Forces used in study are in the middle to high range of expected field loading
  - Low forces unlikely to pose danger to climbers
  - Testing at low forces prohibitively time consuming

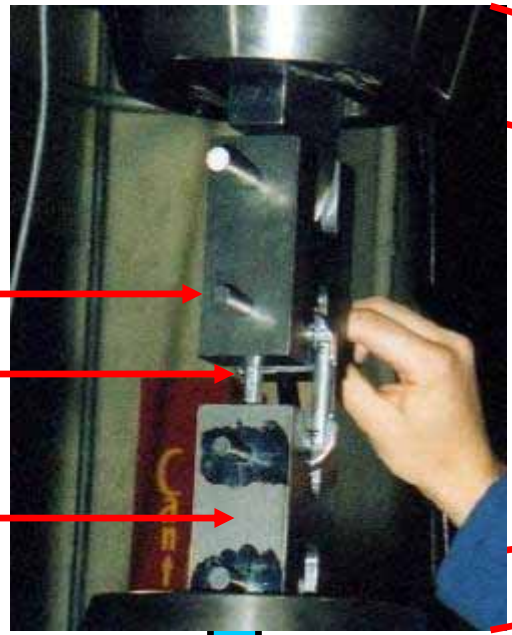
Carabiners

- All carabiners from same manufacturer
- D-Shaped 7075 Aluminum
- SPTF rating
  - 24 kN Closed gate
  - 7 kN Open gate
- Each carabiner loaded with 12 kN proof load as part of manufacturing process

Approach

- Test Design
  - ASTM Test Set-up:
    - Carabiners clipped around 2 steel dowels
    - Dowels connected to grips
- Testing: Evaluate through cyclic, dynamic loading
  - Cycles to failure
  - Carabiner Deformation
  - Crack Formation (X-ray photography)

MTS Test System

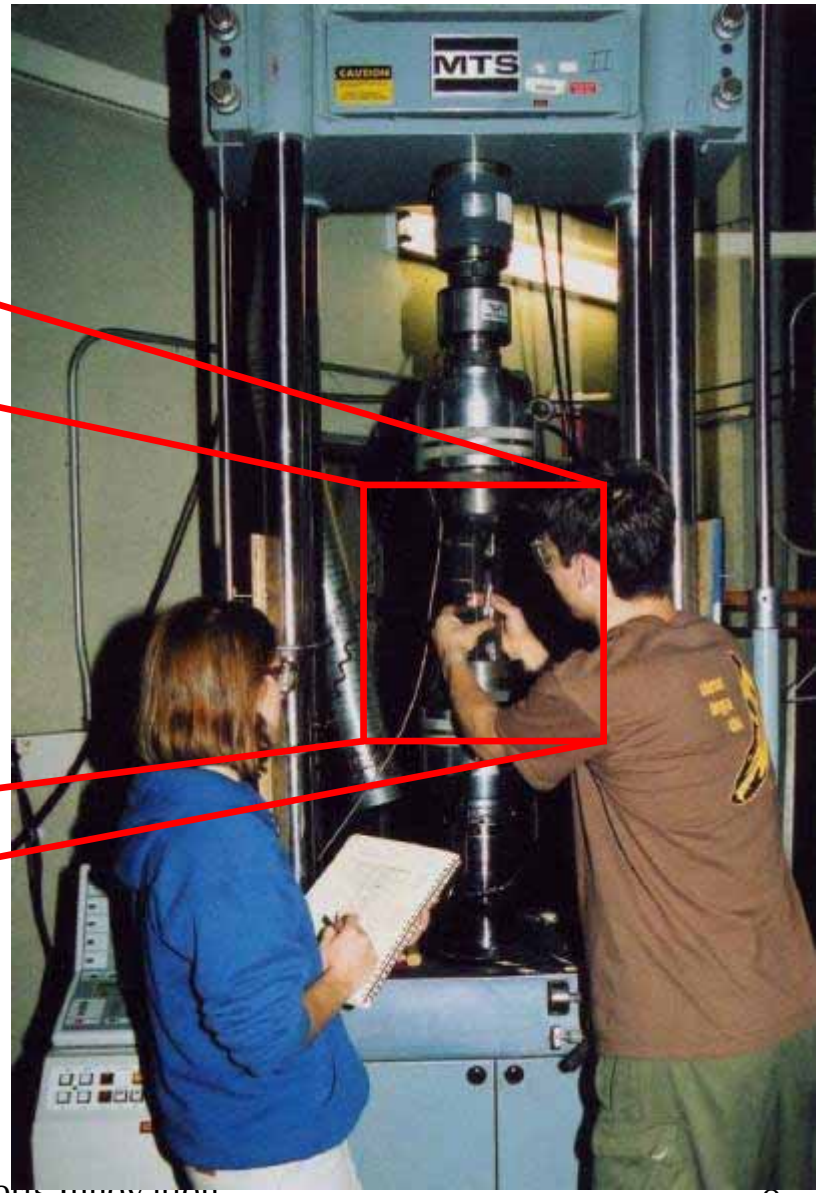


Steel Pin

Carabiner

Machined Steel Grip

Applied Load



Equipment Details

- Load and deflection
  - Measured directly from the MTS machine
  - LabView computer based data acquisition system
  - Load error ± 13 N
  - Displacement error ± 0.01 mm
- Fracture surface observations
  - X-Ray photos: Torrex 150D X-Ray
  - Photos: Zeiss Stemi 2000-C microscope

Test Matrix

	Cyclic Load Range, kN	Number Tested
Open Gate	0.5 - 4	3
	0.5 - 5	3
	0.5 - 6	3
Closed Gate	0.5 - 8	3
	0.5 - 10	3
	0.5 - 12	4
	0.5 - 14	4
	0.5 - 16	4
	0.5 - 18	4
	0.5 - 20	4

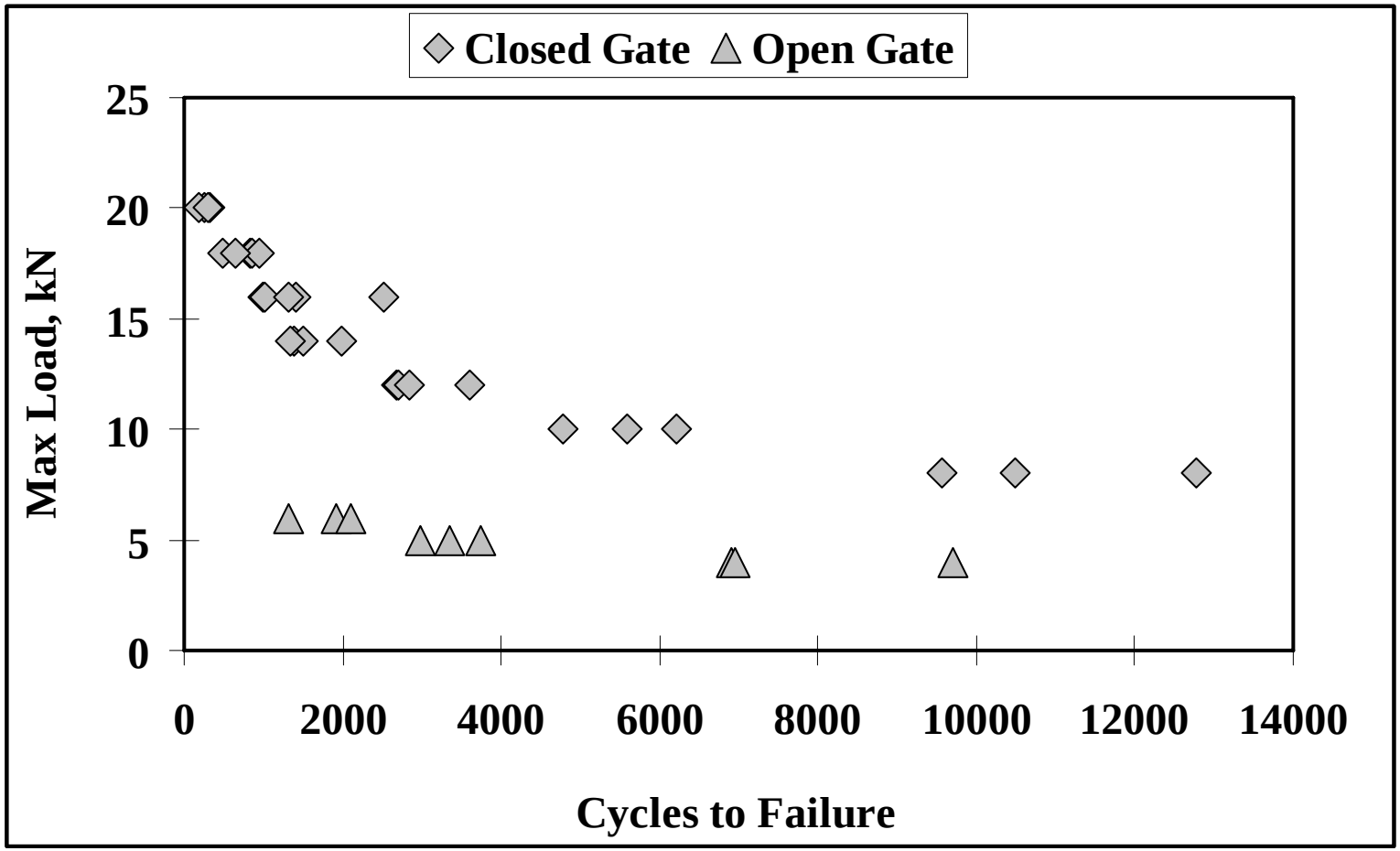
Experimental Approach

- Fatigue tests run cyclically from 0.5 kN to indicated maximum load
- Gate gap length measured periodically with micrometer throughout test
- Short exposure X-Ray photographs take periodically in 8, 10 and 12 kN tests
  - Photos copied to transparencies
  - Compared to determine deformation as a function of number of cycles

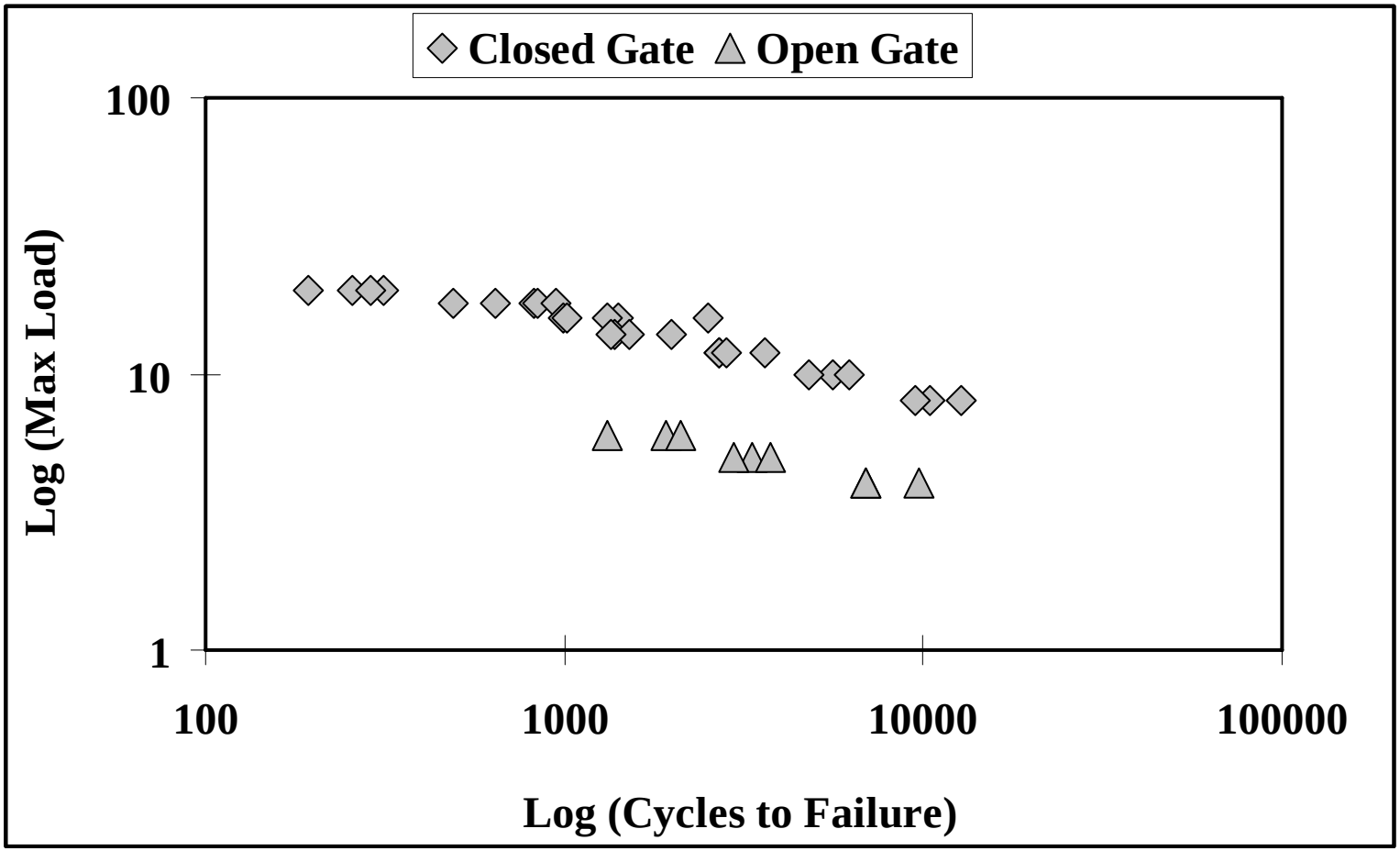
Overview of Results

- Determination of Load vs Cycles to failure curve (L-N curve)
- Carabiner deformation apparent only in high load cases
  - Majority of deformation occurs in first few load cycles
- Post failure analysis of crack surface provides information on critical crack length
- Not able to find evidence of crack formation before failure

Cycles to Failure vs. Load



Cycles to Failure vs. Load, Log Plot



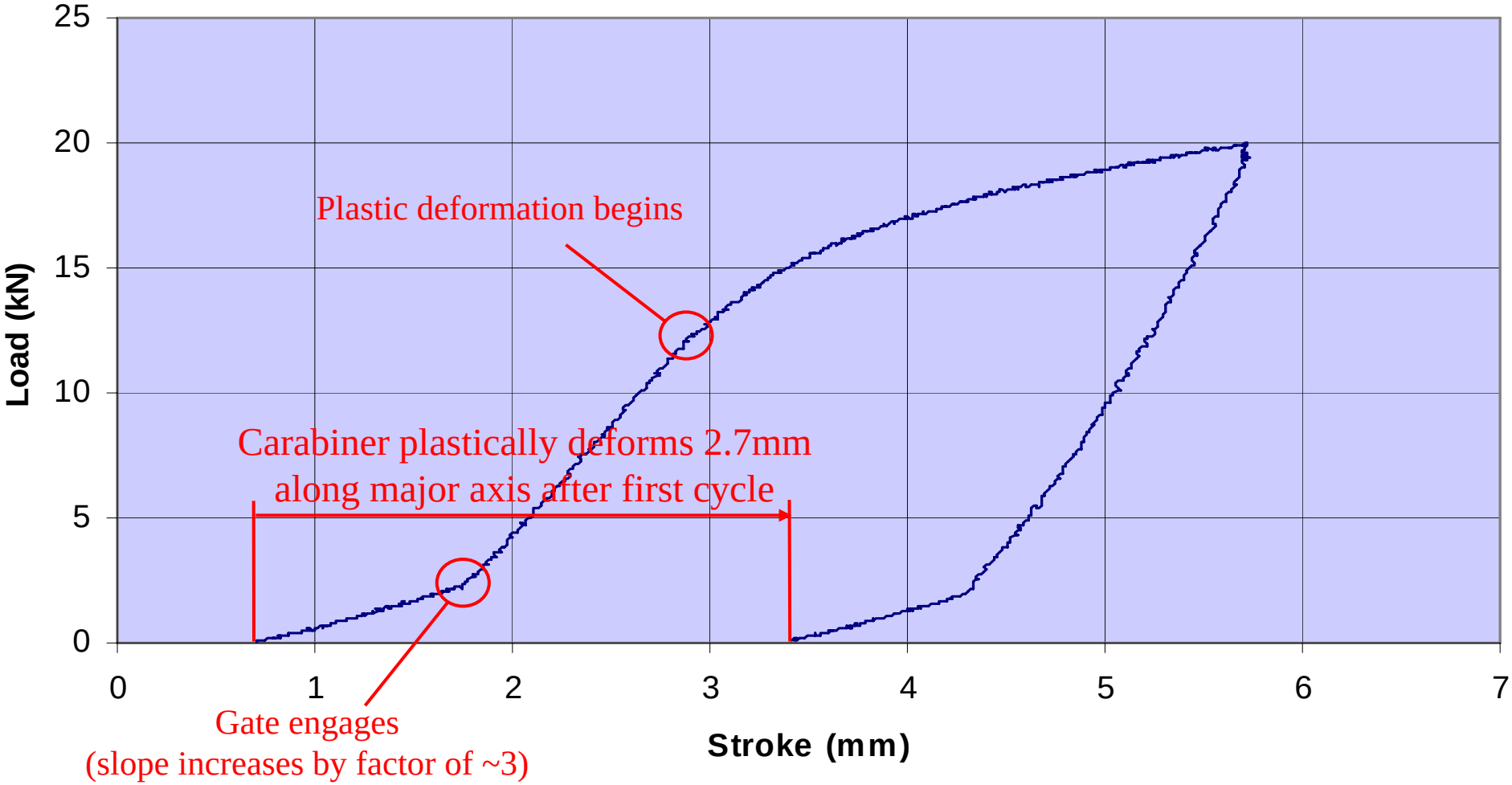
Statistical Data

	Cyclic Load Range, kN	Mean Cycles to Failure	Standard Deviation	% Variation
Open Gate	0.5 - 4	7,849	1,598	20%
	0.5 - 5	3,350	384	11%
	0.5 - 6	1,774	413	23%
Closed Gate	0.5 - 8	10,939	1,657	15%
	0.5 - 10	5,533	722	13%
	0.5 - 12	2,958	439	15%
	0.5 - 14	1,556	297	19%
	0.5 - 16	1,451	209	43%
	0.5 - 18	750	200	24%
	0.5 - 20	263	51	20%

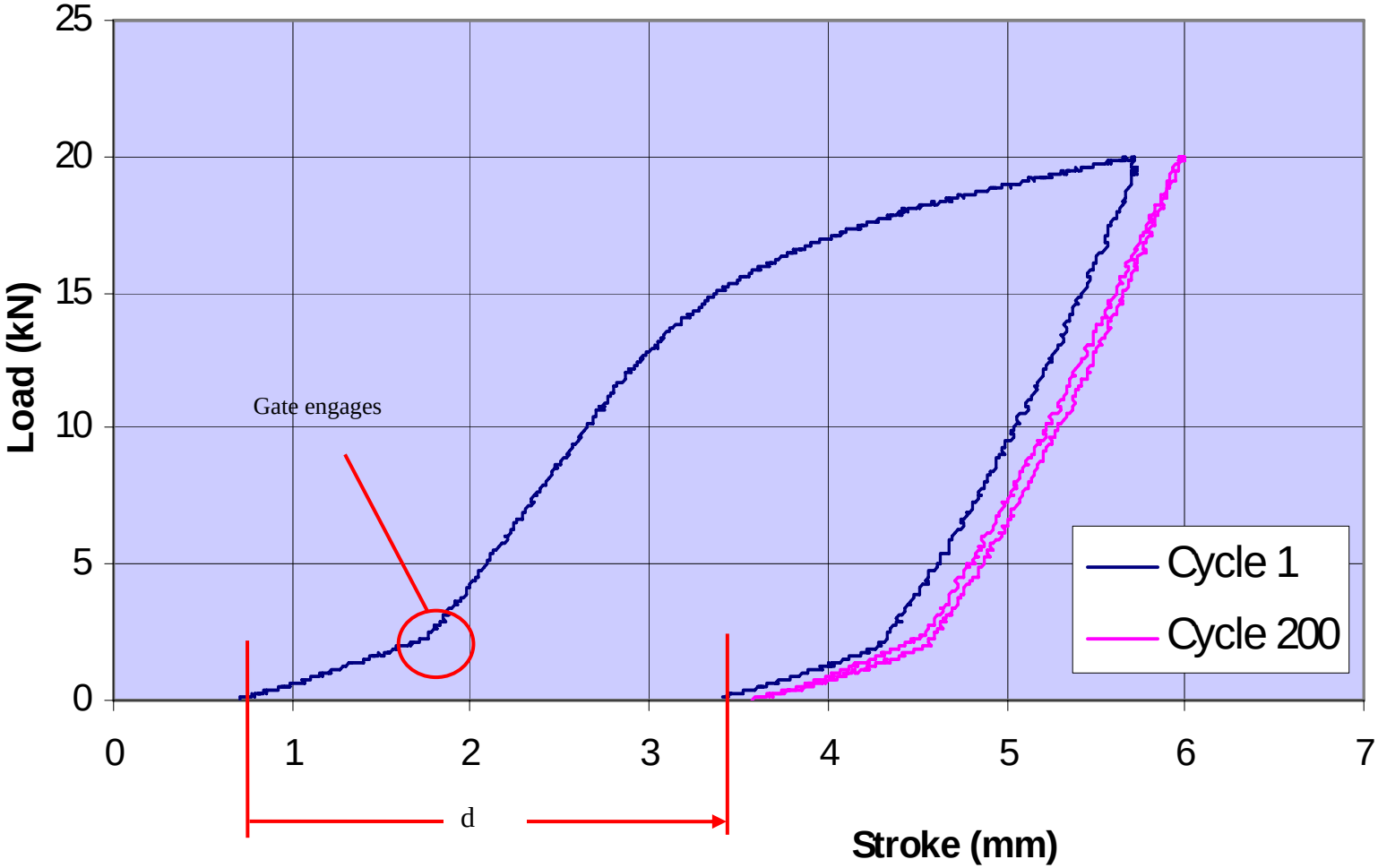
Deformation Observations

- Gate gap measurement and X-Ray photographs failed to detect deformations
- Careful measurement of carabiner length shows small deformation for large load cases (20 kN)
- Majority of carabiner deformation for large loads occurs early in life

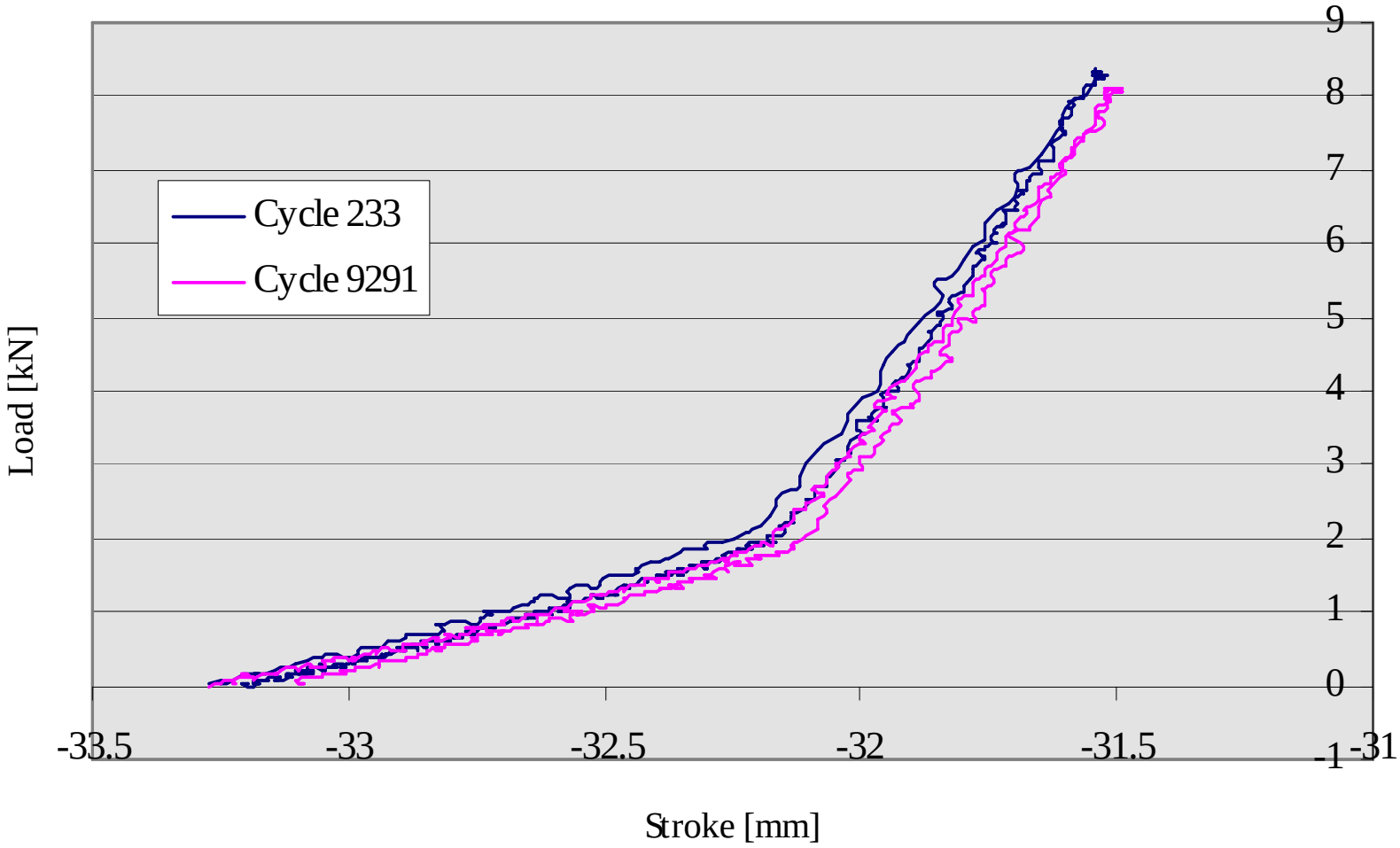
Load vs Stroke
First Cycle of 0.5-20kN Cyclic Test



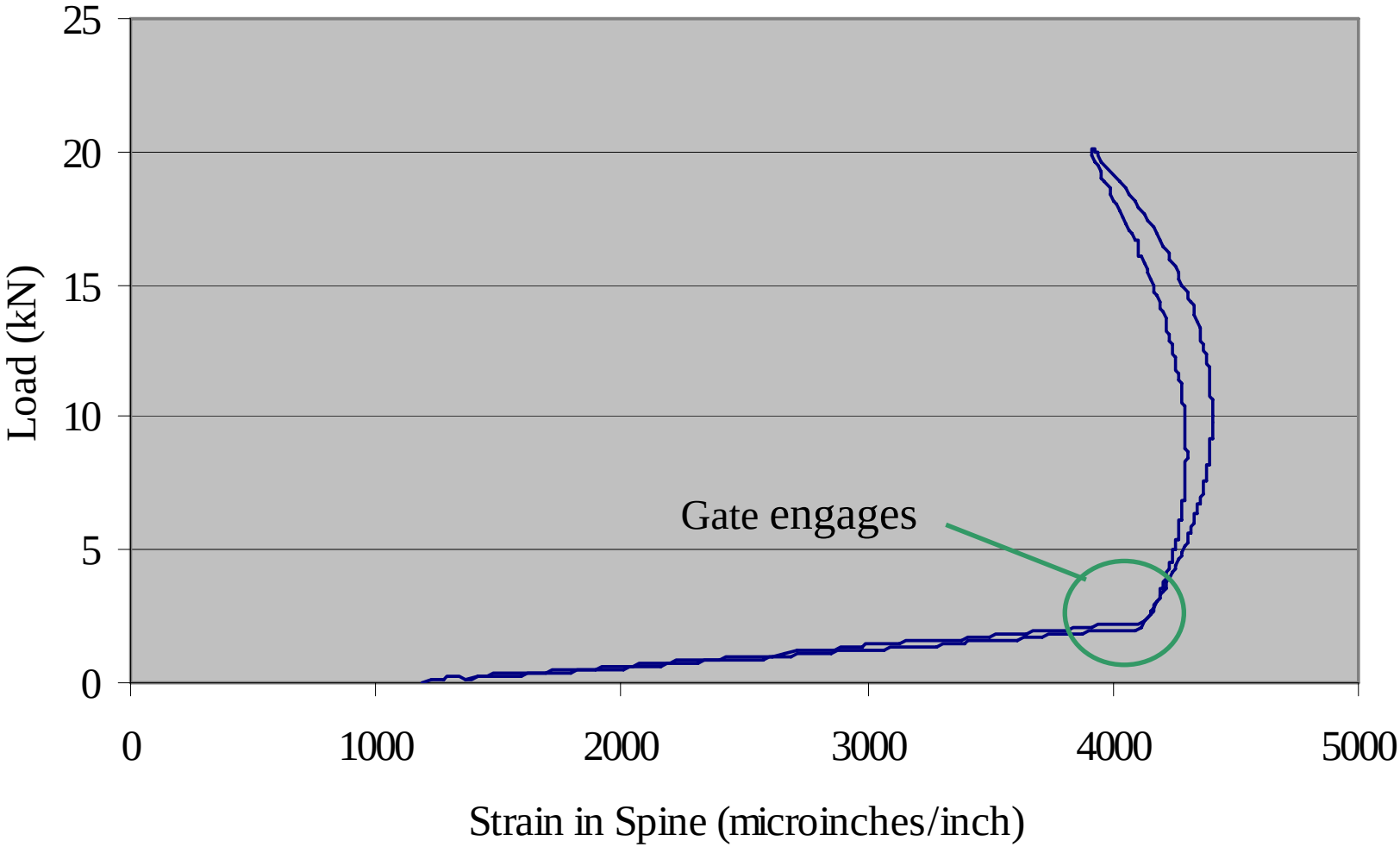
Two Cycles of Loading
0.5 -20 kN Case



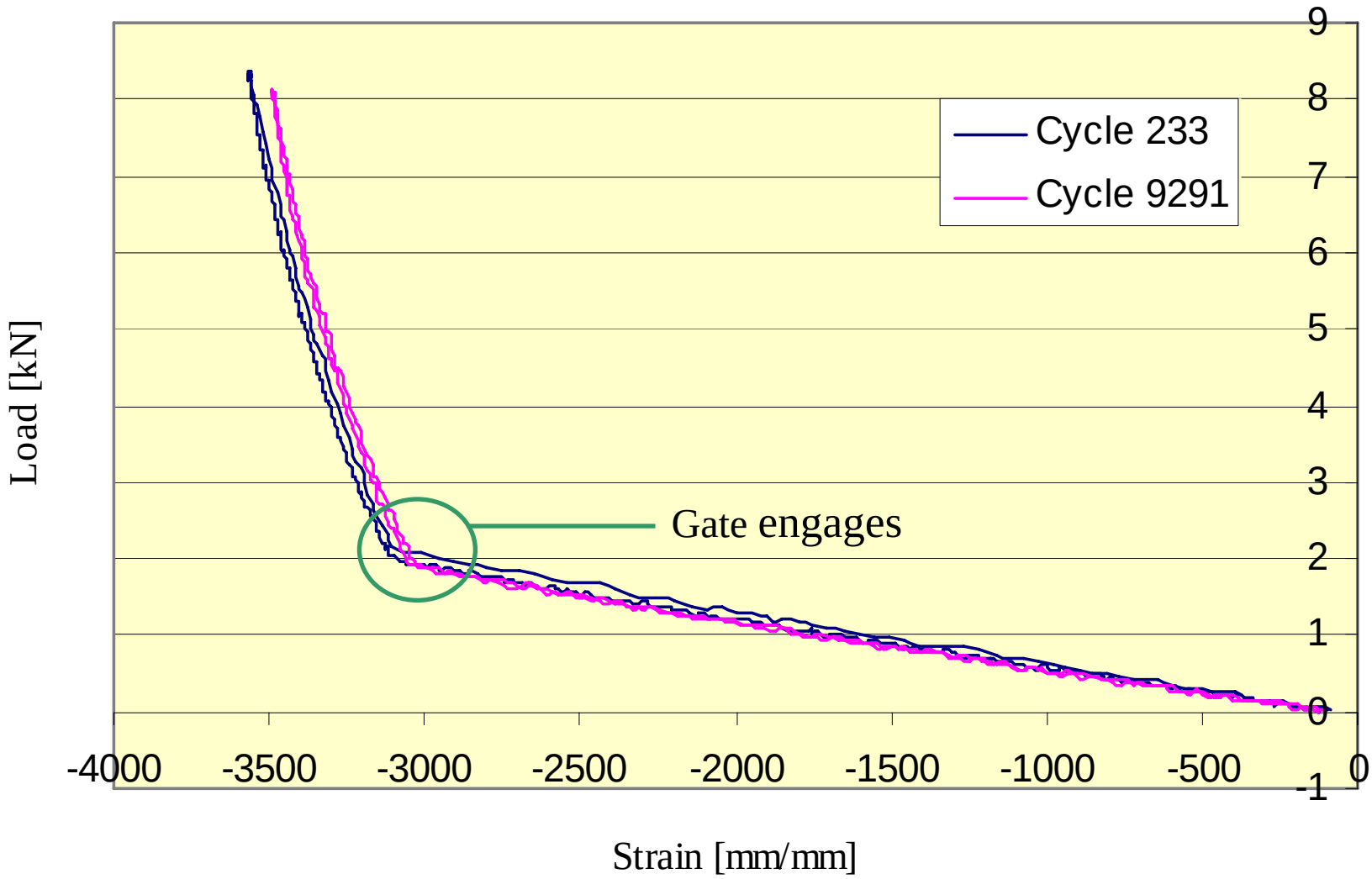
Two Cycles of Loading
0.5 - 8 kN Case



Spine Strain for 0.5 – 20 kN Test



Spine Strain for 0.5 – 8 kN Test

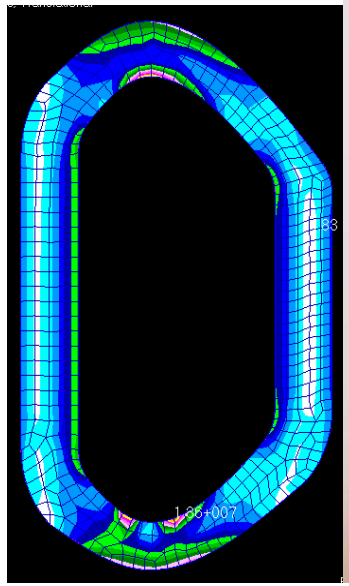


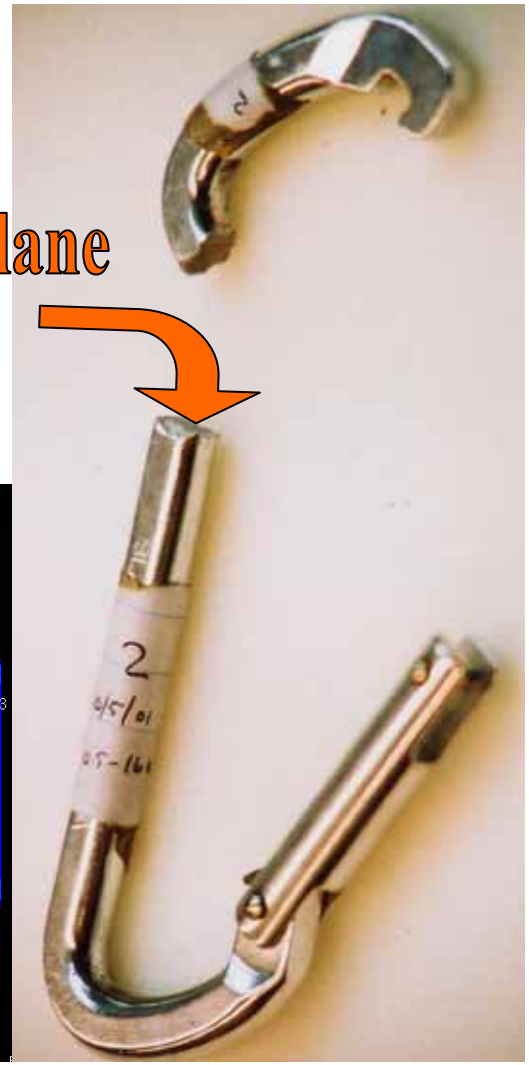
Surface Crack Formation

- Carabiners cycled at 0.5-8 kN range were X-Rayed to search for surface cracks
- X-Rays take about every 500 cycles
- No surface cracks were detected

Fracture Observations

- All carabiners break at "elbow"
  - Fits prediction made by Finite Element Model
  - Consistent with in-field failure characteristics
- Observed cross-section under microscope





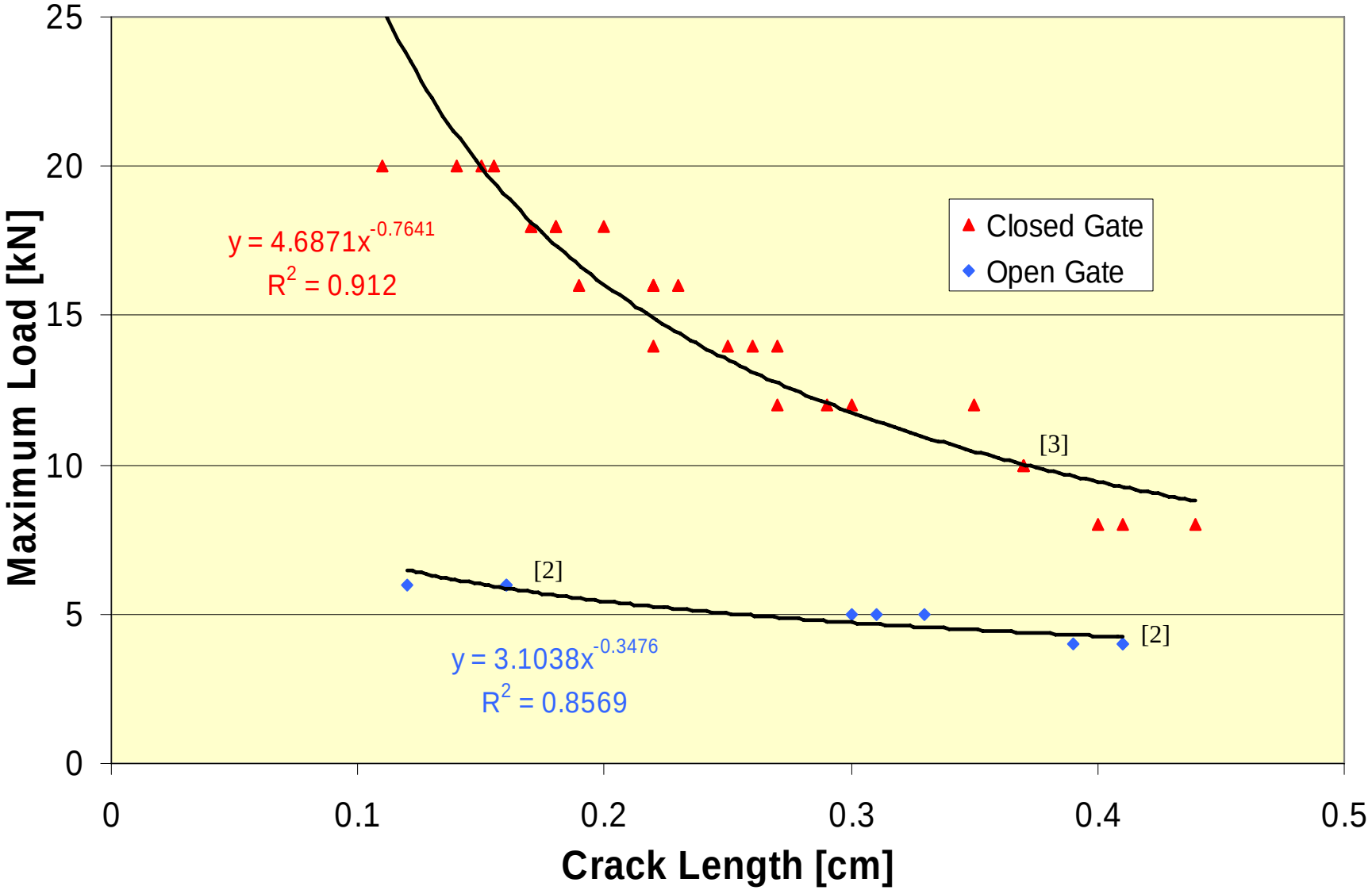
Fracture Surface Pictures

0.5 - 8 kN load cycle

0.5 - 14 kN load cycle

Magnification = 5x

Crack Size on Fracture Surface



Discussion

- Cyclic Testing
  - Even at loads representing extreme falls, this specific carabiner has long life
  - Result should be encouraging for climbers
- Deformation
  - Carabiner deformation very small and not detectable, especially for loads below the manufacturer's proof test of 50% SPTF
  - Any plastic deformation occurs in first few loading cycles
  - Data suggests that deformation can be detected using a mold

Discussion

- Crack Growth
  - No surface cracks were found during testing
  - Appears that when the carabiner is un-loaded, all surface cracks completely close
  - Crack length vs. cycles to failure trends agree with theoretical models, but direct comparison cannot be made due to complicated geometry of the carabiner

Conclusions

- Carabiner failure can be characterized with L-N data
- The carabiner tested exceeds reasonable expectations of carabiner fatigue life
- Decreasing carabiner weight will likely result in decreased life forcing the need for fatigue ratings
- Deformation cannot be used to predict fatigue failure
- Deformation can be used to detect plastic deformation due to excessive loads

Future Work

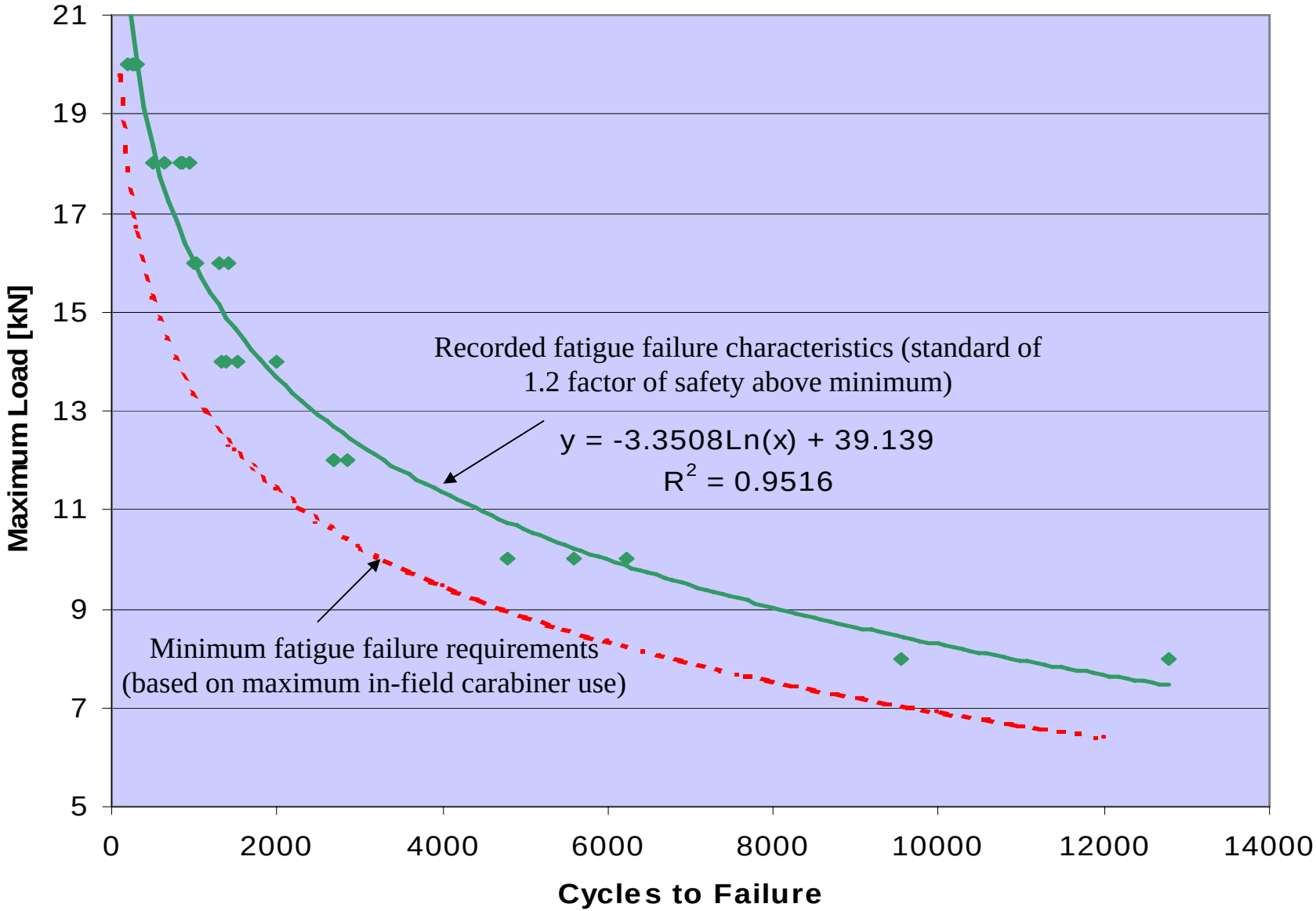
- Testing other types of carabiners would allow for more general conclusions
- Effect of load history should be studied
- Effects of surface damage on the speed of crack initiation should be investigated
- Crack initiation and propagation life should be characterized
  - Cycle carabiner at low load levels
  - Pull carabiner apart on a single load
  - Measure the length of the crack front

BACKUPS

New Testing and Rating Standard

- Based on in-field conditions, results, and current ASTM standard
  - In-field conditions
    - 0.5 sec. average loading period
    - Dynamic/sinusoidal loading
    - 20 kN maximum load (worst case scenario)
  - Results
    - Trend line for Cycles to Failure vs. Load
  - ASTM standard
    - Test minimum of 5 for 20 kN test
    - Factor of Safety = 1.2
- Rate by number of cycles to failure for 20 kN case
  - Black Diamond Light D Carabiner: ~200 cycles

Carabiner Fatigue Safety Margin



Outline

Introduction

Motivation

Objective

Approach

Results

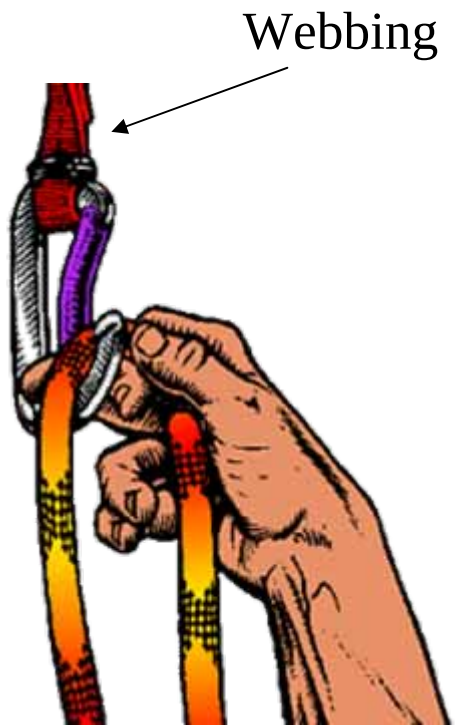
Conclusions/Future Work

Questions

Introduction

What Is a Carabiner?

- Metal link connecting climber to rope and rope to mountain side via webbing
- Features gate that climber opens to insert/remove rope or webbing under loaded & unloaded conditions
- Most common type
  - D-shaped
  - Aluminum



Climber attaching rope to carabiner.

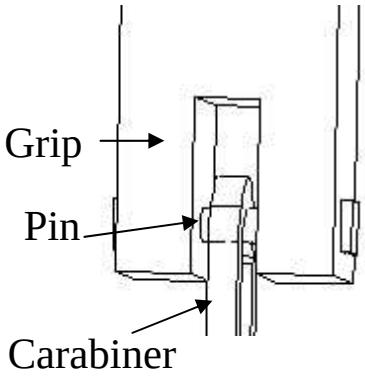
Errors

- MTS error load Error: ±13N

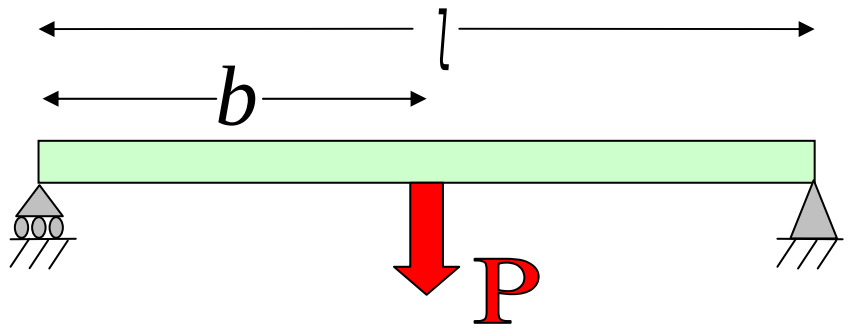
$$=> \quad 100 * \frac{13N}{8000N} = \text{0.16\% error}$$

- Carabiner manufacturing
- Negligible errors:
  - Strain Gauge
  - Temperature
  - Deformation of steel pins (see next slide)

Pin Error Analysis



Pin modeled as



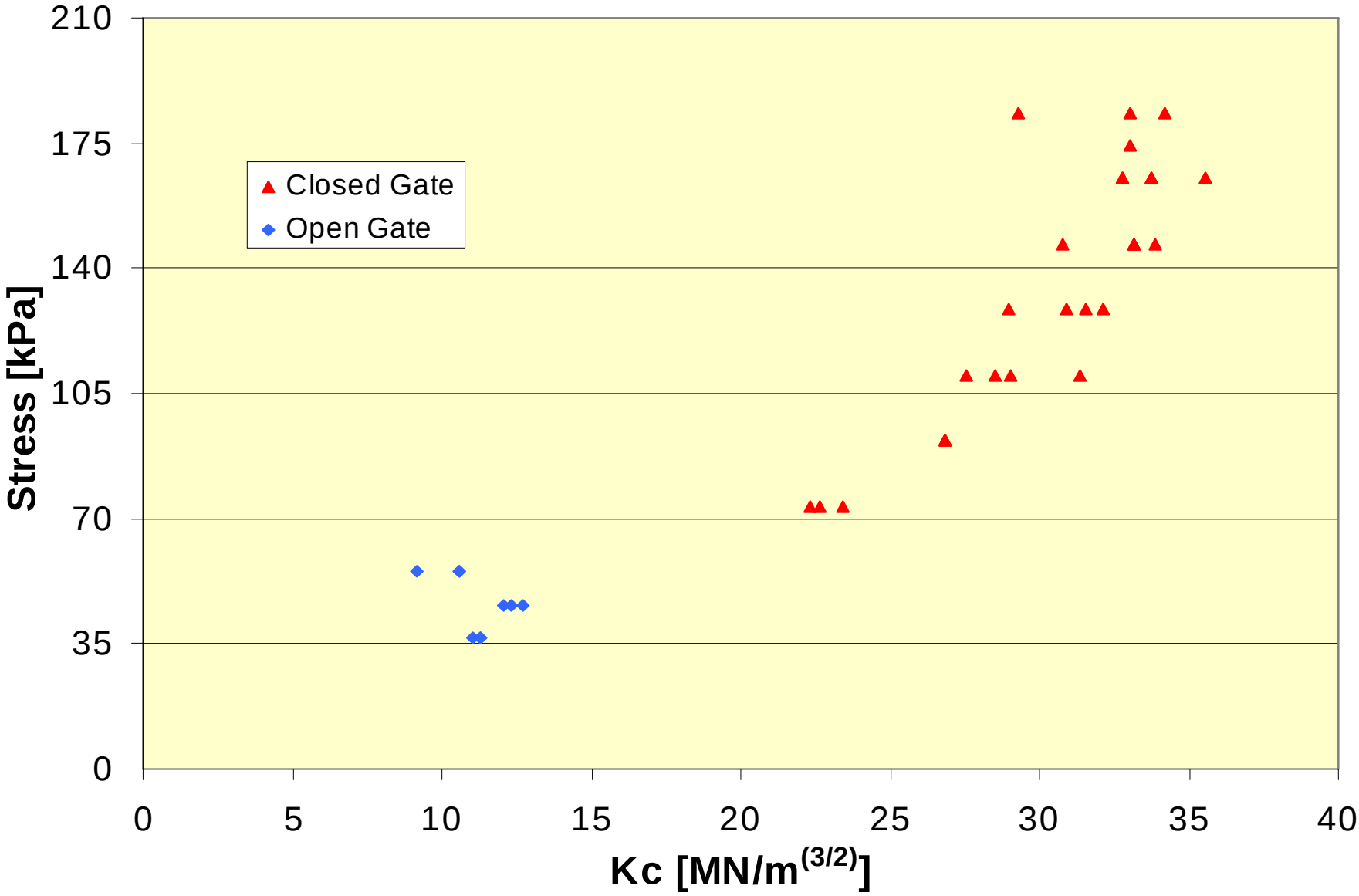
•From Crandall, Dahl, Lagner:

$$\delta_{\max} = \frac{Pb(L^2 - b^2)^{3/2}}{9\sqrt{3}LEI} = 4.97 * 10^{-6} m$$

•Smallest deflection observed: 0.0015 m at 8kN

•This represents a $100 * \frac{4.97e-6}{1.5e-3} =$ **0.33% error** (at most)

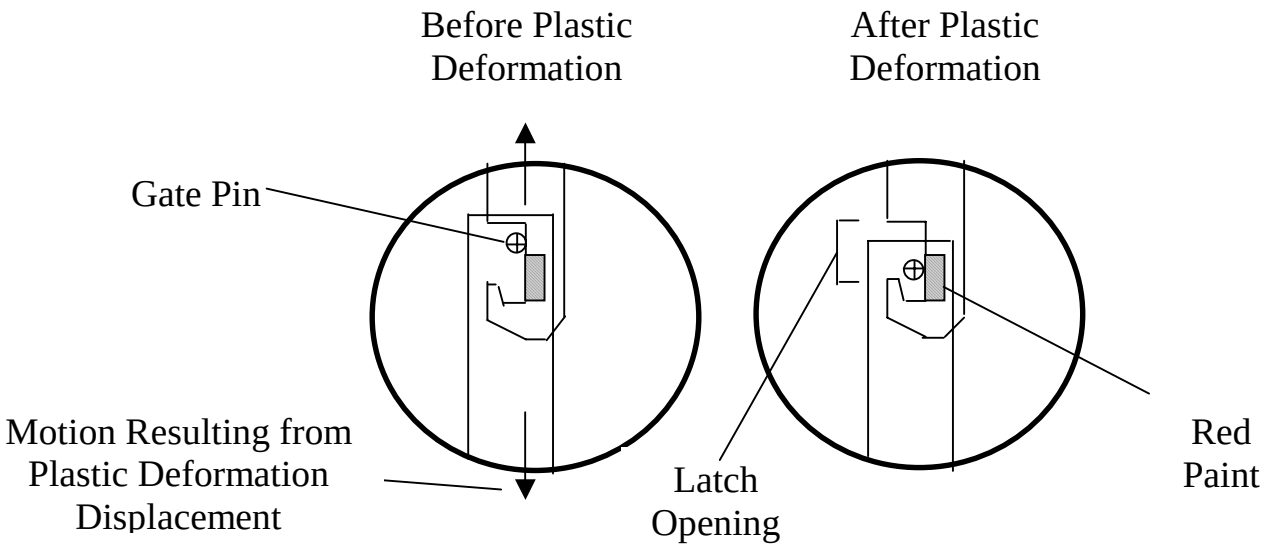
Critical Stress Intensity Factor (K_c)



Webbing Tests Eliminated

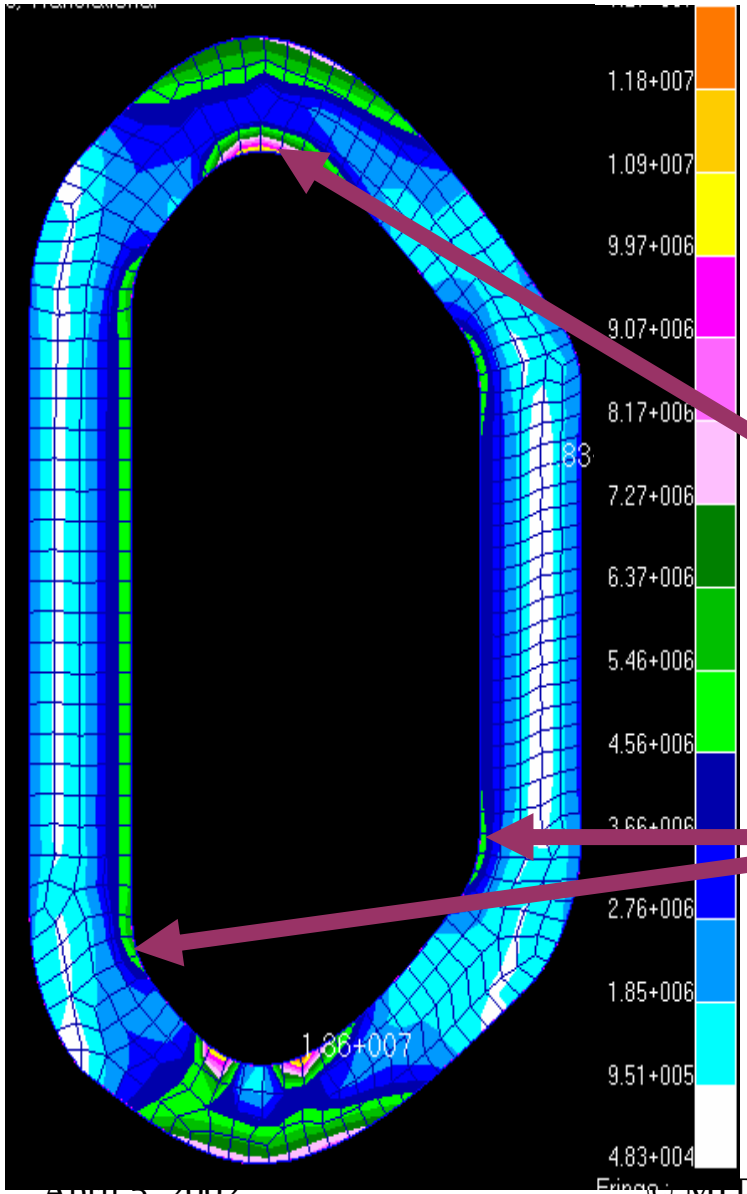
- Too difficult to accurately run tests at desired frequency
  - Desired test frequency and max. load: 2 Hz, 8 kN
  - MTS machine capabilities: 1.3 Hz, 7.3 kN
- MTS machine unable to account for stretch in webbing
- 1 test completed at lowest load, results inconclusive

Plastic Deformation



Close-up of gate latch on carabiner depicting the resulting displacement due to plastic deformation of the carabiner in an unloaded condition both before and after the carabiner is cyclically loaded.

PATRAN model



- Used to evaluate stress concentrations in carabiner to predict failure area.
- Max Stress at top and bottom of carabiner
- Stress concentrations also evident at bends

Instrumentation & Calibration

- MTS Tensile Loading Machine
  - Program load conditions
  - Mating of machined grips to vice clamps of MTS
  - Tare out zero displacement conditions
- Strain Gauges
  - Attachment to carabiner
  - Tare out zero load condition