Fiberglass and Aluminum Ladder Performance Under Dynamic Loading Conditions

James Glancey
Jack Vinson
University of Delaware

G. A. Snyder
National Forensic Engineers

Our Work . . .

- Analysis of Accidents

- Examinations of Failed Ladders

- Engineering Analysis of Ladders
  - Characterize structural failures and identify modes of failure
  - Model the ladder structure
    - Buckling analysis of the side rails
    - FEA models
  - Estimate factors of safety for current ladder designs

- Ladder Testing
  - Instrumented Ladders used to Measure Stresses
  - Dynamic Loads
  - Much, Much more to do . . .
Motivation

• The authors (primarily Vinson and Snyder) have been involved with many ladder accident cases in litigation.

• Failures include step, extension, and articulated ladders.

Ladder Standards

- ANSI 14.x, OSHA 1926.1053, BSI 2037.
- In general, used to qualify new designs.
- Quality control and user tests limited at best.
- Not required to be used in a formal quality control program to assess manufacturing and material variations.
Terminology

ANSI 14
Type II – 225 lbs
Type III – 200 lbs

Forensics of Accidents/Failures

- Climber Falls
  - Lost his or her balance; improper setup; etc.
  - Landed on the ladder during the fall, thus inducing mechanical damage
  - Often the theory proposed by the ladder manufacturer

- Ladder Deficiencies
  - Design defect – inherently poor design
  - Material strength defects
  - Manufacturing defects
    - Rivets
    - Improper Lay-up (Composites)
    - Front and rear side rails
      - Curvature
      - Eccentric loading
Side Rail Model

- New ladders often have curved, eccentrically loaded siderails.
- Artifact of ladder company's poor design & manufacturing practices.
Measuring Dynamic Loads and Stresses

- Standard 6 ft aluminum Type III step ladder
- 30 rosettes/linear gauges
- Dynamic stresses measured for a variety of users and tasks

\[ \sigma = \frac{P_z}{A} + \frac{M_x c_y}{I_x} + \frac{M_y c_x}{I_y} \]
Stepping down onto the 2\textsuperscript{nd} step

Test Subject
Weight = 800 N

Stepping onto the 2\textsuperscript{nd} step . . .
Peak Stress Situation - Repetitive Task

Dynamic Stresses - Descending
Effect of a 2.5% Slope

Descending while ladder is leaning to the left

Experimental Summary

*Test Results*

- Small Supporting Slopes = Big Effects
- Peak Dynamic Load Factor ~ 3
- Peak Stress = 140 MPa.
- Yield Strength (6061-T6) = 240 MPa
- Buckling Strength:
  - Curvature = 150 MPa
  - Eccentric Loading = 175 MPa
- Apparent Factor of Safety = less than 2
Experimental Summary

Observations

- Loads rapidly change in magnitude AND direction.
- Complex loading on the siderails.
- Under normal use, step ladders become three-legged structures.
- Stability and balance require 3 points of contact.
- Forces exerted by climber can be briefly transmitted to 2 or 1 siderails.

Implications for Ladder Designs

- ANSI requires factor of safety of 4.
- Actual dynamic load compared to the rated load accounts for a factor of almost 3.
- Remaining factor must account for ladder setup, material properties, geometry, manufacturing and assembly variations.
- This situation has most likely led to the structural failure of some ladders.

*ANSI testing protocol is not sufficient to properly evaluate ladder designs and loading conditions.*
Back to ANSI . . .

- Revised to incorporate some findings from the CPSC study conducted by Fox (mid 70’s)
- Loads are static in nature
- Uniformly distributed loads
- Uni-directional loads
- No compound loads
- Large limits (e.g. deflection) acceptable
- Tests design to generate reproducible results
- Can repeat tests that fail using statistics
- “Ladder Use Survey” leads to one of two conclusions regarding accidents: abuse or misuse.

Some Components of a New/Revised Standard . . .

- Design requirements for structural members.
- Component qualification as well as ladder assembly qualification.
- Compound, dynamic loading.
- Limits
  - Siderail curvatures
  - Eccentric loads
  - Material properties
  - Realistic deflections
  - Material properties

*These changes will be costly and met with significant opposition by the ladder industry.*
Questions?

Comments?

The U of D Human Performance Lab
On-Going Work . . .

- Combined Effects of Curvature, Eccentric Loading, and Bending on the Side Rail Strength
- Other Ladder Types
- FEA Animation of Failures
- Alternate Designs

Experimental Procedure . . .

- Additional testing on 6 degree of freedom force plates.
- Measured dynamic reactions \((x,y,z)\) at the bottom of the side rail.
Finite Element Modeling

Effects of Curvature on Buckling Strength

- Euler Curve
- Tangent Modulus Curve
- Alcoa

Slenderness Ratio (l/r) vs. Buckling Failure Stress (MPa)
Dynamic Vertical Reaction

Failure Statistics

- On average, about 157,000 people make emergency room visits due to ladder mishaps each year. *Underwriters Laboratories Inc.* (2000).

- Annually, accidents involving ladders cause an estimated 300 deaths and 130,000 injuries requiring emergency medical attention. *National Safety Council.* (1996)
Presentation Overview

- Overview of Ladder Accidents
- Forensics of Failures
- Structural Analysis
- Human Testing and Dynamic Loading
- Implications Regarding Current Ladder Designs
- Summary

Concept:
A Polymer Capped Chisel

Cap
Cap Holder
Hex Shank
Steel Chisel
Work

\[ \theta \]
Reducing Vibration Transmitted to the Hand From Struck Tools

- Introduce a material with poor transmission characteristics
  - Polymer Cap

Automated Hammer
The World’s Most Comfortable Struck Tool.
Prototype Designs

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