Modes of physical deterioration of LLINs in different settings

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Aims

- To understand the **actual causes and modes of physical deterioration** of LLINs in field settings.

- To lay a foundation for improved LLIN **textile testing methodology** that can be used in LLIN procurement and to encourage innovation in net technology.
LLINs were Retrieved from the Field in Africa and Asia by Tropical Health LLP

- Nigeria: CDC/PMI;
- Kenya: CDC
- Uganda: Tropical Health LLP
- Mozambique: PMI
- India: WHOPES

3 separate locations within Nigeria.

- Total LLINs analysed: 526.
- Periods of use: 12, 18 and 36 months.
- LLIN types: PermaNet, Olyset, Dawaplus, Duranet, Interceptor, and Net Protect.
Analysis of all individual defects in LLINs

• Direct analysis to determine damage mechanisms resulting from use in the field.

• Multi-scale approach: individual areas of damage were visually inspected assisted by optical microscopy and Scanning Electron Microscopy (SEM).

• > 41,294 individual damage sites inspected.

• Inspection of entire LLIN structure.
Overall Profile of Structural Damage in LLINs

Results based upon 41,294 individually inspected sites of net damage.

Damage
Imperfections observed in a net that would not be present in an unused net encompassing: holes, pulls and all other defects.

- **Pulls**: 57.2%
  A structural imperfection in the fabric caused by a snagging action but not resulting in a broken yarn. Yarns in the fabric structure are displaced (pulled) resulting in a visible loop on the surface.

- **Holes**: 41.3%
  A discontinuity in the fabric structure that results in an opening greater in diameter than that associated with the mesh structure.

- **Other Defects**: 1.5%
  All other imperfections that would not be present in the unused net but which do not result in either a hole or a pull.
Pull Damage (net snags on a rigid protuberance)

No initial yarn breakage

Filament project from surface

Distortion of structure

Multifilament

Monofilament
Snag Hole Damage

- **Multifilament**
  - Approx. 5mm

- **Monofilament**
  - Approx. 6mm
  - Approx. 10mm
Tear Hole Damage

Images are from suspended nets. Arrows depict the direction of the tearing action and the resultant variation in hole morphology.

**Macro image.** Force applied in the downward direction. Distinct triangular shaped hole. No distortion around hole.

**Macro image.** Force applied in the upward direction. Triangular like shape. The 'peak' area on the right hand side corresponds roughly to the size of the blunt instrument.

**Macro image.** Force applied in the diagonal direction.

Curling edges; fibrous perimeter

Broken monofilament resulting from tearing

Broken multifilament resulting from tearing

Approx. 3cm

Approx. 3cm

Approx. 3cm

Approx. 3cm

Approx. 5cm

Approx. 10cm
Abrasion Hole Damage

Surface "fuzz" (multifilament)

Filaments broken by abrasion

Monofilament, surface abrasion

Filament flattening & deformation

Multifilament

Monofilament
Cut Hole Damage

- High aspect ratio
- Cleaved filament ends

Approx. 10cm
Approx. 5mm
Approx. 4mm
Approx. 3cm
Thermal Hole Damage

- Beads or hard polymer residue at edges
- Loss of filament structure after melting
- Charring

Approx. 1cm

Approx. 2cm

Approx. 4mm
Rodent Hole Damage

Multiple small holes in close proximity, irregularly shaped

Rodent bite breaks

Discolouration and rodent hair contamination

Notch
Secondary Damage

- Primary damage can seed larger holes as a result of unravelling and laddering.
- The degree of secondary damage is influenced by factors such as the selection of the knitted fabric structure.
Seven primary mechanisms leading to holes

<table>
<thead>
<tr>
<th>Classes of Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary (Initiation)</td>
</tr>
<tr>
<td>Snag</td>
</tr>
<tr>
<td>Yarn or part of a yarn pulled or plucked from the surface.</td>
</tr>
<tr>
<td>Tear</td>
</tr>
<tr>
<td>Tensile failure of yarns within the fabric plane in for example two opposing directions.</td>
</tr>
<tr>
<td>Abrasion</td>
</tr>
<tr>
<td>The wearing away of any part of a material by rubbing against another surface.</td>
</tr>
<tr>
<td>Cut</td>
</tr>
<tr>
<td>Yarn that is failed by slicing with a sharp object.</td>
</tr>
<tr>
<td>Thermal</td>
</tr>
<tr>
<td>Polymer that is exposed to temperatures high enough to cause shrinkage, plastic flow or degradation and failure of the yarn.</td>
</tr>
<tr>
<td>Rodent/Animal damage</td>
</tr>
<tr>
<td>Damage caused by gnawing of indigenous rodents, chewing of domestic animals or interaction with birds.</td>
</tr>
<tr>
<td>Seam Failure</td>
</tr>
<tr>
<td>Effective breakdown of a seam due to rupture of the sewing thread or yarns in the fabric, excessive seam slippage or any combination of these.</td>
</tr>
<tr>
<td>Secondary (Propagation)</td>
</tr>
<tr>
<td>Laddering</td>
</tr>
<tr>
<td>Pulling out of successive knitted loops in a wale, leaving straight segments of yarns.</td>
</tr>
<tr>
<td>Unravelling</td>
</tr>
<tr>
<td>Following yarn failure, the broken yarns allow the loops of the knit structure to un-loop creating a larger hole.</td>
</tr>
<tr>
<td>Tearing</td>
</tr>
<tr>
<td>Tensile failure of yarns within the fabric plane in for example, two opposing directions after primary damage has been initiated.</td>
</tr>
</tbody>
</table>
Damage mechanism profiles in LLINs (by hole frequency)

Mozambique:
- 8.0% Mechanical
- 40.2% Snag
- 51.4% Tear
- 0.4% Rodent
- 0.1% Abrasion
- 0.3% Cut

Nigeria Region 1:
- 3.9% Mechanical
- 44.8% Snag
- 51.2% Tear
- 0.1% Rodent
- 2.7% Abrasion
- 0.9% Cut

Nigeria Region 2:
- 4.5% Mechanical
- 66.0% Snag
- 24.5% Tear
- 41.3% Rodent
- 7.6% Abrasion
- 7.5% Cut

Nigeria Region 3:
- 17.2% Mechanical
- 78.8% Snag
- 2.6% Tear
- 1.4% Rodent
- 18.8% Abrasion
- 1.2% Cut

Kenya:
- 15.8% Mechanical
- 68.7% Snag
- 14.5% Tear
- 1.0% Rodent
- 9.5% Abrasion
- 5.3% Cut

Uganda:
- 21.7% Mechanical
- 75.1% Snag
- 3.0% Tear
- 0.2% Rodent
- 20.4% Abrasion
- 1.7% Cut

India:
- 87.9% Mechanical
- 35.8% Snag
- 48.4% Tear
- 2.0% Rodent
- 0.3% Abrasion
- 1.7% Cut
Damage mechanism profiles in LLINs (by hole area)

**Mozambique**
- Mechanical: 8.5%
- Thermal: 27.1%
- Rodent: 63.7%
- Tear: 11.6%
- Snag: 0.7%
- Abrasion: 4.3%
- Cut: 1.4%

**Nigeria Region 1**
- Mechanical: 6.0%
- Thermal: 31.1%
- Rodent: 62.7%
- Tear: 4.8%
- Snag: 0.2%
- Abrasion: 15.1%
- Cut: 4.8%

**Nigeria Region 2**
- Mechanical: 39.4%
- Thermal: 2.0%
- Rodent: 0.9%
- Tear: 14.8%
- Snag: 0.8%
- Abrasion: 14.8%
- Cut: 40.8%

**Nigeria Region 3**
- Mechanical: 21.4%
- Thermal: 1.6%
- Rodent: 0.2%
- Tear: 76.8%
- Snag: 6.3%
- Abrasion: 22.5%
- Cut: 1.3%

**Kenya**
- Mechanical: 6.4%
- Thermal: 17.4%
- Rodent: 49.6%
- Tear: 6.4%
- Snag: 2.7%
- Abrasion: 37.0%
- Cut: 1.6%

**Uganda**
- Mechanical: 0.01%
- Thermal: 11.8%
- Rodent: 17.50%
- Tear: 11.9%
- Snag: 11.9%
- Abrasion: 10.40%
- Cut: 1.70%

**India**
- Mechanical: 11.8%
- Thermal: 87.2%
- Rodent: 11.9%
- Tear: 10.4%
- Snag: 10.4%
- Abrasion: 48.4%
- Cut: 16.5%
Influence of damage mechanism on hole size

<table>
<thead>
<tr>
<th>Damage mechanism</th>
<th>Median hole size (cm)</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mozambique</td>
<td>India</td>
<td>Nigeria R1</td>
<td>Nigeria R2</td>
</tr>
<tr>
<td>Snag</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Tear</td>
<td>5</td>
<td>8.5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Abrasion</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Cut</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Thermal</td>
<td>1.5</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Rodent</td>
<td>1</td>
<td>-</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Seam</td>
<td>6</td>
<td>7</td>
<td>4.5</td>
<td>10</td>
</tr>
</tbody>
</table>

- Tearing and seam failure produce the largest holes.
- Abrasion and cutting produce holes of intermediate size.
- Snagging and rodent damage produce numerous small holes.
Proportion of LLINs in each location found to contain holes by individual damage mechanism

<table>
<thead>
<tr>
<th>Damage mechanism</th>
<th>Nets affected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mozambique</td>
</tr>
<tr>
<td>Snag</td>
<td>98</td>
</tr>
<tr>
<td>Tear</td>
<td>61</td>
</tr>
<tr>
<td>Abrasion</td>
<td>41</td>
</tr>
<tr>
<td>Cut</td>
<td>9</td>
</tr>
<tr>
<td>Thermal</td>
<td>61</td>
</tr>
<tr>
<td>Rodent</td>
<td>27</td>
</tr>
<tr>
<td>Seam</td>
<td>9</td>
</tr>
</tbody>
</table>

India\(^1\) - sample including nets with no holes (110 nets).
India\(^2\) sample excluding nets with no holes (54 nets).
Example of the distribution of holes in LLINs (Mozambique) by damage mechanism.

- **Hole location**: 
  - First Quarter
  - Lower middle Quarter
  - Upper middle Quarter
  - Top Quarter
  - Roof-outer
  - Roof-inner

- **Damage mechanisms**: 
  - snag
  - tear
  - abrasion
  - cut
  - thermal
  - rodent
Hole damage profiles in different LLINs (Kenya)

- Snagging and tearing are consistent contributors to hole formation and are likely to be related to LLIN structure.
- Thermal, cut and rodent hole damage may reflect user habits.

Time in use for all: 18-24 months
Preliminary data suggest LLIN hook strength and mechanical hole damage (snag and tear) may be related.
During use LLINs accumulate a “damage profile” with up to seven different sources of primary hole formation. All seven can be present in one net.

Mechanical damage is the most widespread and persistent source of holes across seven different study sites and five different countries. Rodent damage is also a major contributor.

Improving snag resistance (reducing the probability of snagging) is likely to result in better durability.

Currently, LLINs are particularly susceptible to holes due to cutting, thermal and rodent damage.