Side Impact Neck Injury Criteria and Tolerances for Occupants of Sideward Facing Aircraft Seats

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Rick deWeese
Presentation overview

Initial FAA Studies

Project Methodology

Neck injury criteria literature

Test matrix

Method

Subject responses

  injury specification

  dynamics

Injury Criteria - Tolerances

Conclusions

Discussion

References
Initial FAA Research Studies

Objective: Develop certification standards for sideward facing seats that provide a level of safety and impact protection equivalent to that afforded for occupants of forward or aft facing seats.

Example Business Jet Cabin Interior
The Problem

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Project Methodology

- **Literature Review**
  - Injury Criteria and Tolerances
- **Computer Simulations with Human Models and EuroSID-2 ATD**
- **Post Mortem Human Subjects (PMHS)**
  - Lateral Impact Sled Tests
- **Validate Test and Certification Procedures**
- **Additional Sled Tests, Simulations, and Analyses to Establish Lateral Impact Tolerance Levels and Test Procedures**

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## Injury criteria and tolerances for lateral bending

<table>
<thead>
<tr>
<th>Criteria</th>
<th>AIS 1</th>
<th>AIS 2</th>
<th>Soltis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact velocity</td>
<td>&lt;40 km/h</td>
<td>30-60 km/h</td>
<td></td>
</tr>
<tr>
<td>Impact acceleration</td>
<td>5-10 G</td>
<td>10-14.7 G</td>
<td></td>
</tr>
<tr>
<td>Head angle</td>
<td>50-70 degrees</td>
<td>57-75 degrees</td>
<td>60 degrees</td>
</tr>
<tr>
<td>Head angular velocity</td>
<td>8-30 rad/s</td>
<td>32-39 rad/s</td>
<td></td>
</tr>
<tr>
<td>Head angular acceleration</td>
<td>680-1460 rad/s²</td>
<td>1588-2601 rad/s²</td>
<td>2600 rad/s²</td>
</tr>
<tr>
<td>Head linear acceleration</td>
<td>13-32 G</td>
<td>12.5-18 G</td>
<td>36 G</td>
</tr>
<tr>
<td>Neck bending moment</td>
<td>22.6-40.7 Nm</td>
<td>40.7-60 Nm</td>
<td>60 Nm</td>
</tr>
<tr>
<td>Tension</td>
<td>?</td>
<td>4170 N</td>
<td>4170 N</td>
</tr>
<tr>
<td>Compression</td>
<td>?</td>
<td>4000 N</td>
<td>4000 N</td>
</tr>
<tr>
<td>Shear force</td>
<td>240 N</td>
<td>&gt;900 N</td>
<td></td>
</tr>
</tbody>
</table>

### AIS Spine injury

1. Acute strain (no fracture)
2. Minor fracture, no cord involvement
3. Disc rupture, nerve root damage
4. Incomplete spinal cord, cord syndrom
5. Quadriplegia
## Literature since 2003

**Injury criteria and tolerances for lateral bending**

<table>
<thead>
<tr>
<th></th>
<th>AIS 1</th>
<th>AIS 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upper neck</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral bending moment [Nm]</td>
<td>132</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>47-60 Soltis (pre 2003)</td>
</tr>
<tr>
<td>Tension [N]</td>
<td>1500</td>
<td>2070</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4170 Soltis (pre 2003)</td>
</tr>
<tr>
<td>Shear [N]</td>
<td>1693</td>
<td>2797</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;900 (pre 2003)</td>
</tr>
<tr>
<td>Twist [Nm]</td>
<td></td>
<td>39</td>
</tr>
</tbody>
</table>

- McIntosh 2007  - Fréchède  - Lund 2003
# Test matrix

<table>
<thead>
<tr>
<th>Testno</th>
<th>Pulse</th>
<th>Config</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAA23</td>
<td>9 g ( \times ) 180 ms</td>
<td>Rigid seat - Side wall up to shoulder</td>
</tr>
<tr>
<td>WSU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAA26</td>
<td>16 g ( \times ) 180 ms</td>
<td>Rigid seat - Side wall up to shoulder</td>
</tr>
<tr>
<td>WSU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNSC102</td>
<td>12.5 g ( \times ) 120 ms</td>
<td>Rigid seat - Max. torso restraint</td>
</tr>
<tr>
<td>MCW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNSC104</td>
<td>12.5 g ( \times ) 120 ms</td>
<td>Rigid Seat - Max. torso restraint</td>
</tr>
<tr>
<td>MCW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNSC109</td>
<td>12.5 g ( \times ) 120 ms</td>
<td>Real seat with armrest</td>
</tr>
<tr>
<td>MCW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNSC110</td>
<td>12.5 g ( \times ) 120 ms</td>
<td>Real seat with armrest</td>
</tr>
<tr>
<td>MCW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNSC115</td>
<td>8.5 g ( \times ) 120 ms (70% ( \Delta V ))</td>
<td>Real seat with armrest</td>
</tr>
<tr>
<td>MCW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNSC116</td>
<td>8.5 g ( \times ) 120 ms (70% ( \Delta V ))</td>
<td>Real seat with armrest</td>
</tr>
<tr>
<td>MCW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental method

1. $F_{OCx} = ma_{CGx}$
2. $F_{OCy} = ma_{CGy}$
3. $F_{OCz} = ma_{CGz}$
4. $M_{OCx} = l_{Anatomy} \alpha_x - r_{OC} \times F_{OC}$
5. $M_{OCy} = l_{Anatomy} \alpha_y - r_{OC} \times F_{OC}$
6. $M_{OCz} = l_{Anatomy} \alpha_z - r_{OC} \times F_{OC}$
EuroSID and Instrumentation

Accelerometers at (■)
- Upper Rib
- Lower Rib
- Lower Spine
- Pelvis

Potentiometers at (●)
- Upper Rib
- Middle Rib
- Lower Rib

Load Cell at (▲)
- Pubic
- Lateral Abdomen
# Test Condition

<table>
<thead>
<tr>
<th>Test ID</th>
<th>% ΔV</th>
<th>Restraint</th>
<th>Seat</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 (WSU)</td>
<td>100</td>
<td>4-point</td>
<td>Rigid-wall</td>
</tr>
<tr>
<td>102</td>
<td>100</td>
<td>Full</td>
<td>Rigid</td>
</tr>
<tr>
<td>104</td>
<td>100</td>
<td>Full</td>
<td>Rigid</td>
</tr>
<tr>
<td>109</td>
<td>100</td>
<td>realistic</td>
<td>FAA</td>
</tr>
<tr>
<td>110</td>
<td>100</td>
<td>realistic</td>
<td>FAA</td>
</tr>
<tr>
<td>115</td>
<td>70</td>
<td>realistic</td>
<td>FAA</td>
</tr>
<tr>
<td>116</td>
<td>70</td>
<td>realistic</td>
<td>FAA</td>
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</tbody>
</table>
# Specimen Data

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>55</td>
<td>1.88</td>
<td>86</td>
</tr>
<tr>
<td>104</td>
<td>49</td>
<td>1.85</td>
<td>70</td>
</tr>
<tr>
<td>109</td>
<td>59</td>
<td>1.68</td>
<td>64</td>
</tr>
<tr>
<td>110</td>
<td>55</td>
<td>1.84</td>
<td>76</td>
</tr>
<tr>
<td>115</td>
<td>57</td>
<td>1.82</td>
<td>81</td>
</tr>
<tr>
<td>116</td>
<td>47</td>
<td>1.75</td>
<td>80</td>
</tr>
</tbody>
</table>
Subject Responses

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**MCW Injury Analysis**

- Biomechanical engineering
- Clinical dx – palpation, etc.
- X-ray, CT, cryomicrotomy
- Pathological assessment
- Clinical interpretation
  - Pathologist, spine surgeon, …
- Scoring and mechanism
Pre-test X-rays FNSC102
FNSC 102, rigid restraint

Widening facet joints below C4

Department of Neurosurgery, Milwaukee, WI

Triennial Int. Aircraft Fire and Cabin Safety Research Conference 2007

New Jersey 30 OCT 2007
Anterolisthesis at C3

Laxity C3-C4

Pre

Post
Cryomicrotome: ligament thinning
FNSC 109 3-point armrest

Pre

C1 pulled away
Anatomically AIS 3
Clinically AIS 5

Post

C6-C7 dislocation AIS 3
Clinical AIS 4-5 due to instability

Department of Neurosurgery, Milwaukee, WI
FNSC 109 3 point armrest
Injuries other body parts

Department of Neurosurgery, Milwaukee, WI

Femur fracture & carotid artery injury
AIS 3

Triennial Int. Aircraft Fire and Cabin Safety Research Conference 2007
New Jersey 30 OCT 2007
Autopsy: T1-T2 dislocated AIS 3,
Clinically: possible cord involvement, AIS 5
FNSC 110 3 point arm rest
Other body parts

• left distal (near knee) fracture,
  (AIS 3, clinical 3)
• clavicle fracture
  (AIS 2, clinical 2)
• flail chest
  (AIS 3, clinical 4)
• left shoulder dislocation
  (AIS clinical 2).
FNSC 115 3 point arm rest, 70% pulse

Pre
longitudinal ligament and disc C5-C6 distraction

Post
AIS2 – AIS3

subluxation C4 - C5
## Summary injuries (1)

<table>
<thead>
<tr>
<th>ID</th>
<th>Pathology</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>C4-T1 diastasis (widening)</td>
</tr>
</tbody>
</table>
| 103  | C2-3 antreolisthesis (subluxation)  
|     | C3-4 joint laxity, C6-7 ligament thinning                                                                                               |
| 109  | C2 fx/dislocation, C6-7 joint dislocation, carotid artery intimal tear, rib fractures, femur fracture                                   |
| 110  | T1-2 fx/dislocation, clavicle fx, rib fractures, left shoulder dislocation, left distal femur fx                                           |
| 115  | Ant long. ligament, disc C5-6, C4-5 subluxation                                                                                           |
| 116  | None                                                                                                                                        |
## Summary injuries (2)

<table>
<thead>
<tr>
<th>ID</th>
<th>% ΔV</th>
<th>AIS (neck)</th>
<th>Clinical (neck)</th>
<th>Other region</th>
<th>Brain (rad/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>100</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>3230</td>
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<tr>
<td>103</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>109</td>
<td>100</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>2260</td>
</tr>
<tr>
<td>110</td>
<td>100</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>2550</td>
</tr>
<tr>
<td>115</td>
<td>70</td>
<td>2</td>
<td>3</td>
<td></td>
<td>1810</td>
</tr>
<tr>
<td>116</td>
<td>70</td>
<td>0</td>
<td></td>
<td></td>
<td>1750</td>
</tr>
</tbody>
</table>
ES-2 Tension force - lateral bending moment

- Rigid Restraint Upper
- 3-point Centre Upper
- 3-point Armrest Upper
- 90% Upper
- 70% Upper
- 5-point Upper
- 4-point Upper
- X-cross Upper
- 3-point inf. Centre Upper

- Rigid Restraint Lower
- 3-point Centre Lower
- 3-point Armrest Lower
- 90% Lower
- 70% Lower
- 5-point Lower
- 4-point Lower
- X-cross Lower
- 3-point inf. Centre Lower

Z-Force (N) vs X-Moment (Nm) graph.

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Conclusions Injury risk

- Serious neck injuries (AIS4+) are likely to happen in side facing seats under FAR25 crash pulse conditions, armrest and centre location;

- Additional injuries to be expected:
  - rib fracture
  - femur /hip fractures (armrest location)
  - carotid intimal tear
- Near side wall locations will induce serious rib fractures but no gross neck injury

- Head angular accelerations are likely to cause up to one hour unconsciousness
**Conclusions injury criteria-tolerance ES2**

- Neck tension loads above 2000 N combined with a minimum lateral bending moment 20-40 Nm appears to be an AIS3+ tolerance limit in PMHS

- ES2 lower neck loads appear to be a good predictor for AIS3+ injuries, tension force ~1600-2000 N, bending moment ~ 280 Nm

- Keeping head-thorax aligned appears promising in reducing neck injury risk e.g. inflatable shoulder belt, seat integrated airbags
Discussion

• The injury patterns found in the back-to-back PMHS tests are almost identical indicating a most likely non-subject specific injury response. Although the number of specimens are statistically not significant;

• The C1-C2 injury is most unusual and seems to be caused by a different injury mechanism as the simultaneously found C6-T1 injuries;

• ES2 neck dynamics are not validated against humans, which is illustrated by the high bending moments found in ES 2 compared to the values in the PMHS;
Discussion

• Keeping head-thorax aligned appears promising in reducing neck injury risk e.g. inflatable shoulder belt, seat integrated airbags. However, timing, general application for all aircraft types etc. need to evaluated to ensure no additional injury risk induced by such systems;

• At the very moment a simulation study is done to find experimental conditions which generate a high bending moment with tension forces below ~ 1500 N to find a critical value for “bending only”
THANK YOU
References

- Association for the Advancement of Automotive Medicine, Committee on Injury Scaling (1990), *The Abbreviated Injury Scale 1990 (AIS-90)*. Des Plains, IL: Association for the Advancement of Automotive Medicine;