Design and Fabrication of a HIC Compliant Bulkhead

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The compliance with the Head Injury Criteria (HIC) poses a significant problem for aerospace industry.

\[
HIC = \max \left[ \left( \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \, dt \right)^{2.5} \right]
\]

Where, \( a(t) \) is the head resultant acceleration of the Part 572 Hybrid II ATD in g’s and \( t_1 \) and \( t_2 \) are the response times to maximize the function.

Non-injurious if: \( HIC < 1000 \)

HIC problems encountered in:

- **Bulkhead**
- **Cabin Furnishings**
- **Cabin Side Walls**
- **Instrument Panel**
- **Wind Screen Posts/Side Posts**
- **Class Dividers**
- **Cockpit Glare Shields**
- **Row-to-Row**
- **Entry Door Steps**
Goal

- *Proof of concept:* It is possible to arrive at a potential solution for bulkhead seating problem that is acceptable to the industry such that $HIC < 1000$

$$
HIC = \left[ \left( t_2 - t_1 \right) \left\{ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t) dt \right\}^{2.5} \right]_{\text{max}}
$$

Benefit

- Project contributes to aircraft safety by providing potential solution(s) for occupants head injury protection

Products

- A prototype HIC compliant bulkhead
- Methodology and guidelines for industry

Correlation between tests and analytical models

Static Testing

Dynamic full-scale sled testing
Energy - Absorbing Panels

Aluminum sheet Panel

Thin Panel designs consistently produced HIC below 1000
Baseline Tests – Typical Production Bulkhead

Dynamic sled test

16g dynamic test pulse

Analysis of head impact

HIC >1000
Modification Of Production Bulkheads

Initial stiffness 470 lb./in

Initial stiffness 212 lb./in

30-in. vertical slits at 4 in. apart on the face sheet and carpet

Vertical cuts reduced the stiffness of the panels and HIC < 1000
### Dynamic Test Results Comparison

<table>
<thead>
<tr>
<th>Results</th>
<th>Aluminum Bulkhead</th>
<th>Unmodified Bulkhead</th>
<th>Modified Bulkhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Head Accl.(g)</td>
<td>111</td>
<td>156</td>
<td>92</td>
</tr>
<tr>
<td>HIC</td>
<td>653</td>
<td>1395</td>
<td>881</td>
</tr>
<tr>
<td>HIC WINDOW (ms)</td>
<td>49</td>
<td>12</td>
<td>31</td>
</tr>
</tbody>
</table>
Biodynamic models were developed and validated against dynamic sled tests.

Static tests were conducted to obtain load-deflection properties of the bulkhead.
Sample Analytical and Dynamic Test Results Comparison

Modified Production Bulkhead
Comparison of Head CG Resultant Acceleration of Sled Test 97204 - 002 and Analysis

<table>
<thead>
<tr>
<th>Head C.G Average Acceleration (g's)</th>
<th>Head C.G Peak Acceleration (g's)</th>
<th>Δt (ms)</th>
<th>HIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 42</td>
<td>Analysis 41</td>
<td>Test 93</td>
<td>Analysis 91</td>
</tr>
</tbody>
</table>
## ATD Response for Different Seat Setbacks

### Dynamic Sled Tests on Aluminum Panels

<table>
<thead>
<tr>
<th>Seat setback (In.)</th>
<th>Head Impact Velocity (ft/s)</th>
<th>Head Impact Angle (deg)</th>
<th>Head C.G Peak Accel. (g’s)</th>
<th>HIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Analysis</td>
<td>Test</td>
<td>Analysis</td>
</tr>
<tr>
<td>33</td>
<td>46</td>
<td>45</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>35</td>
<td>46</td>
<td>47</td>
<td>34</td>
<td>40</td>
</tr>
<tr>
<td>38</td>
<td>48</td>
<td>48</td>
<td>67</td>
<td>60</td>
</tr>
</tbody>
</table>

*Fire & Cabin Safety Research Conference*
Validated biodynamic model was used for the development of the design guidelines.

Parametric studies were conducted to study the variation of HIC by varying crush strength and stiffness values.
**Fabrication of test rig**

- The existing test rig was modified to replicate proper attachment points.
- Modifications were made to the rig to ensure that no additional support was provided to the bulkhead.
Bulkhead Materials

Bulkhead panel composition

- Honeycomb core
- 2-ply Epoxy fiberglass face sheets
- Covered with carpet used typically in aircraft installations

Selected based on design guidelines and from sled tests conducted at NIAR and CAMI

- Both metallic and non-metallic cores were studied for the design of the bulkhead

Metallic cores

Non-Metallic cores
## Composition and Properties of Bulkhead Panels

### Bulkhead Panel Composition

<table>
<thead>
<tr>
<th>Bulkhead Series</th>
<th>First Series</th>
<th>Second Series</th>
<th>Third Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>Nomex Honeycomb</td>
<td>Nomex Honeycomb</td>
<td>Aluminum Honeycomb</td>
</tr>
<tr>
<td>Facings</td>
<td>2-ply Phenolic Fiberglass</td>
<td>2-ply Epoxy Fiberglass</td>
<td>Fiberglass</td>
</tr>
<tr>
<td>Carpet</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Properties of the acquired panels

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>First Series</th>
<th>Second Series</th>
<th>Third Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>in</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Weight</td>
<td>lb/sq ft</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>Facings</td>
<td>in</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Core</td>
<td>in</td>
<td>1/8</td>
<td>1/8</td>
<td>3/8</td>
</tr>
<tr>
<td>Flat wise Compression</td>
<td>psi</td>
<td>310</td>
<td>275</td>
<td>240</td>
</tr>
<tr>
<td>Density</td>
<td>psi</td>
<td>3.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Dynamic sled tests were conducted at NIAR on the first series of bulkheads, the stiffest ones, to evaluate the performance of these bulkheads for accelerations in the head of 49 CFR Part 572, Subpart B of the ATD.

**Test Results**

<table>
<thead>
<tr>
<th>Seat Setback</th>
<th>HIC</th>
<th>Δt (ms)</th>
<th>Avg. Accl. (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>1550</td>
<td>69</td>
<td>55.1</td>
</tr>
<tr>
<td>35</td>
<td>1450</td>
<td>71</td>
<td>52.8</td>
</tr>
</tbody>
</table>

∴ First series of bulkheads failed
Dynamic sled test was conducted on the second series of bulkheads to determine head accelerations.

Bulkheads less stiff than the first series bulkheads

### Test Results

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<tr>
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<th>HIC</th>
<th>Δt (ms)</th>
<th>Avg. Accl. (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>1321</td>
<td>21.4</td>
<td>82.4</td>
</tr>
<tr>
<td>35</td>
<td>781</td>
<td>4.9</td>
<td>118.8</td>
</tr>
</tbody>
</table>

*: Second series of bulkheads failed
Sled tests conducted at both smaller and larger seat setback distances

HIC values obtained below the threshold value of 1000 for both seat setback

**Test Results**

<table>
<thead>
<tr>
<th>Seat Setback</th>
<th>HIC</th>
<th>$\Delta t$ (ms)</th>
<th>Avg. Accl. (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>935</td>
<td>22</td>
<td>62.8</td>
</tr>
<tr>
<td>35</td>
<td>165</td>
<td>23.3</td>
<td>35.3</td>
</tr>
</tbody>
</table>

∴ The proof of concept is demonstrated

Resultant head acceleration
Design Methodology

1. Utilizing hybrid analytical methods
2. Perform FEM analysis
3. Conduct Static tests to obtain load-deflection characteristics
4. Design a bulkhead based on the required cabin configuration and previous experience
5. Modify Design
6. Estimate the stiffness of the bulkhead
7. Compare the stiffness to Design Curve
8. Utilization or analysis tools (occupant model) to obtain design curves
9. Fabricate and conduct dynamic full-scale sled tests
10. Fabricate and install the bulkhead in an aircraft

Decision Points:
- Is Stiffness < 300 lb/in? (Yes/No)
- Is HIC < 1000? (Yes/No)
Hybrid Analytical Method to Estimate Stiffness

SIMPLY SUPPORTED RECTANGULAR PLATE:

-Stiffness value at any point \((x,y)\):

\[
k = \frac{P}{W} = \frac{\pi^4 abD}{4 \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sin \left( \frac{m \pi x}{a} \right) \sin \left( \frac{n \pi y}{b} \right) \sin \left( \frac{m \pi x}{a} \right) \sin \left( \frac{n \pi y}{b} \right)}
\]

Where:
- \(P\) : Load
- \(W\) : Deflection
- \(D = EI\) : Bending Rigidity
- \(E\) : Young’s Modulus
- \(I\) : Second Moment of Area
- \(m, n = 1,3,5…\) (convergence for three or four terms)

- e.g., the stiffness at the center of a square plate:

\[
k = \frac{D}{0.0112 a^2}
\]

- The estimated stiffness is compared to the values in the design curve(s)
- Other boundary conditions yield similar formulations for the stiffness values

Stiffness of a simply supported plate under concentrated load at any point
COMPOSITE PLATES:

For each ply (lamina), stiffness $Q$ in the fiber and transverse directions:

\[
\begin{align*}
Q_{xx} &= mE_x \\
Q_{yy} &= mE_y \\
Q_{xy} &= m \nu_y E_x \\
Q_{yx} &= m \nu_x E_x \\
\end{align*}
\]

where, $m = \left[ 1 - \nu_x \nu_y \right]^{-1}$

Transforming to direction 1 – 2

For $0^\circ$ ply : $Q_{11} = Q_{xx}$
For $45^\circ$ ply : $Q_{11} = \frac{1}{4} Q_{xx} + \frac{1}{4} Q_{yy} + \frac{1}{2} Q_{xy} + Q_{yx}$
For $90^\circ$ ply : $Q_{11} = Q_{yy}$

Equivalent stiffness / Bending Rigidity for the combined laminate:

\[
D_{11} = \int Q_{11} z^2 \, dA
\]

The value of $D$ is replaced by $D_{11}$ in the previous plate stiffness calculation
The estimated stiffness is compared to design curve(s)
Finite Element Analysis can be performed on a bulkhead design to estimate the stiffness at the vicinity of the head impact.

The estimated stiffness is compared to the design curve(s).
Static testing on bulkheads to obtain load-deflection characteristics

For more complex compositions of the bulkhead materials and geometries, the bulkhead needs to be fabricated first.

Static test is conducted on a fabricated bulkhead to evaluate the stiffness at the point of impact.

The stiffness value is compared to the design curve(s).

Load Vs Deflection

Load Curve

Unload Curve

K

Sample load-deflection characteristics and bulkhead stiffness
Concluding Remarks

- HIC compliant bulkheads were designed, fabricated and tested for aircraft interior installation.

- A design methodology was developed for the development of HIC compliant bulkheads.

- The methodology requires estimation of the stiffness of the designed bulkhead. The estimated stiffness will be compared to the ones from the design curve(s) for HIC attenuation.

- Stiffness of the Teklam panels will be estimated/evaluated and plotted vs. the design curve(s).

- Project highlight’s the FAA’s main objective of enhancing passenger safety.