40+ Years of Ship Structures Advances: Opportunities Gained, Opportunities Lost

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formally of
Naval Surface Warfare Center
Carderock Division
• Introduction
  • History and Lessons
  • Platform Architecture
  • Materials
  • Processes/Criteria
• Future Challenges

Consume what you’d like. Come to your own conclusions.
Primary mission of ship structures is to *Keep the Water Out!*

- Affordably
- Reliably

Support, contain, enable other ship subsystems.

Focus of past research has usually been on reducing weight and/or cost and satisfying *structural integrity* requirements.
SHIP STRUCTURES

Three dimensional assemblage of plates normally with bi-directional support framing (grillage).
Requires prevention of structural “failure”

- “Limit” or ultimate failure
- Serviceability failure

Failure generally occurs in compression, usually from buckling, or in tension, usually from fracture or fatigue (serviceability), although shear is important for some architectures (SWATH) and some materials (composites).
SHIP STRUCTURES

Ship’s Structures are unique for a variety of reasons. For example:

- Ships are BIG!

- Ships see a variety of dynamic and random loads.

- The shape is optimized for reasons other than to resist loading.

- Ships operate in a wide variety of environments, often extreme.
NAVAL SHIP STRUCTURES

Naval Ships are unique for a variety of reasons.

• They must operate in combat and with damage.

• They operate for 30-50 years, experiencing in excess of 100 million wave encounters.

• They operate continuously for extended periods of time, typically 1-6 months but up to 12 months.

• The structure experiences reversed loading (tensions to compression and back again), unusual for most large structures.
Surface Ship Cost and Weight Considerations

Structure should provide leverage.

Other military vehicle R&D Investment 4%-5%.
Complexity of Ship Structure and Typical Systems

Naval ships have much higher density of internal systems than most commercial ships.
## Approximate Shipbuilder Labor Hours for Constructing DDG

<table>
<thead>
<tr>
<th>Craft</th>
<th>Man-Hours</th>
<th>% Of Total Man-Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PLATFORM -Hull</strong></td>
<td>1,133,000</td>
<td>28.3%</td>
</tr>
<tr>
<td><strong>DISTRIBUTIVE SYSTEMS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical</td>
<td>936,000</td>
<td>23.4%</td>
</tr>
<tr>
<td>Pipe</td>
<td>625,000</td>
<td>15.6%</td>
</tr>
<tr>
<td>Joiner and Insulation</td>
<td>248,000</td>
<td>6.2%</td>
</tr>
<tr>
<td>Ventilation</td>
<td>243,000</td>
<td>6.1%</td>
</tr>
<tr>
<td>Paint</td>
<td>374,000</td>
<td>9.4%</td>
</tr>
<tr>
<td><strong>SUPPORT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing Services</td>
<td>139,000</td>
<td>3.5%</td>
</tr>
<tr>
<td>Machine Shop Services</td>
<td>39,000</td>
<td>1.0%</td>
</tr>
<tr>
<td>Outside Machinery</td>
<td>107,000</td>
<td>2.7%</td>
</tr>
<tr>
<td>Test and Trials</td>
<td>71,000</td>
<td>1.8%</td>
</tr>
<tr>
<td>Ships Management</td>
<td>40,000</td>
<td>1.0%</td>
</tr>
<tr>
<td>Lifts</td>
<td>16,000</td>
<td>0.4%</td>
</tr>
<tr>
<td>Other</td>
<td>29,000</td>
<td>0.7%</td>
</tr>
<tr>
<td><strong>Total MHrs</strong></td>
<td>4,000,000</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Some Learning is Reflected in these Estimates. The 1st of a Class would be Much Higher - Later Ships would be Somewhat Less.*
Traditional “Design Allowable” Approach

Allowable design stress

Failure stress

Factor of Safety
Deterministic vs Probabilistic

Demand

Resistance

\[ f_X(x) \]

\[ f_Z(z) \]

\[ f_S(s) \]

\[ \mu_Z \]

\[ \mu_S \]

Mean or average

\[ \propto \text{"Probability of Failure"} \]

Joint probability

\[ \text{"Probability of Failure"} \]
Historical Review Taxonomy

Platform Architecture- the type and configuration of the hull, how it responds in a seaway and combat environment, the internal load paths resulting from geometry and structural stiffness.

Materials- the strength and stiffness of material choices in the configuration and condition installed in the ship.

Processes/Criteria- the description and methodology to assess all structural behavior and potential failure mechanisms and the associated criteria for acceptance.
Advanced Naval Vehicles

PHM

LCAC

AGEH

SES-200
FFG-7 Class Superstructure Cracking

- 20+ ships in the class experienced cracking
- Major SHIPALT resulted from several sea trials and extensive analysis

No “affordable” solution for 30 year ship life.

USS Duncan (FFG-10), December 1982
LHD-1

1995
Storm Damage
Advanced Double Hull Concept

1990’s R&D Effort for Reduced Cost/Improved Survivability of Naval Combatants
1989 Exxon Valdez/1990 OPA

Convert transverse structure to simplified longitudinal structure with minor weight penalty.
Advanced Double Hull

- Ship Structure
  - Architecture Change
  - Increased Section Modules
  - Lower Operating Stresses,
    - Increased Fatigue Life
  - Increased Inherent
    - Weapons Resistance

- Design Simplification
  - (Reduction in Piece-Parts)
  - Improved Producibility
  - Reduced Labor Costs

- $ Savings

- Increased Survivability & Reliability

- Improved Producibility
- Reduced Labor Costs
# Shipbuilder Labor Hours for Constructing DDG

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DDG-51 ADH Design Study and Cost Assessment
DDG Assembly 2110
Possible Piece-Part Reduction with ADH Design

Ship Hull - Designed for Producibility

- Items Shown in Color are Totally Deleted with Unidirectional Double Hull Design
- Reduction in Piece-Parts Translates to REDUCED COST
Piping Simplification

Conventional Framing System (Inverted)

ADH Framing System (Inverted)
Assembly 2320 Wire way Simplification
Other ADH Cost Savings Areas

Painting- 40% reduction in area

Insulation- elimination of beam wraps

Joiner bhds- simplification of curtain plates

Support Services-

- reduced rigging, transporting, parts handling, scheduling, etc. due to reduced part count and complexity
# Summary
**ADH Design vs. Conventional Ship Design**

**Man-Hour Projected Savings**

<table>
<thead>
<tr>
<th>Ship Architecture</th>
<th>Craft</th>
<th>MHrs for Total Labor</th>
<th>Percent of Total Labor</th>
<th>ADH Design Projected MHR Reduction</th>
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</thead>
<tbody>
<tr>
<td>PLATFORM</td>
<td>Hull</td>
<td>1,133,000</td>
<td>28.3%</td>
<td>246,300 (22.0% of Hull MHR)</td>
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<tr>
<td>DISTRIBUTIVE</td>
<td>Electrical</td>
<td>936,000</td>
<td>23.4%</td>
<td>164,245 (17.5% of Electric MHRs)</td>
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<td></td>
<td>Pipe</td>
<td>625,000</td>
<td>15.6%</td>
<td>147,476 (23.5% of Pipe MHRs)</td>
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<td>Joiner/Insulation</td>
<td>248,000</td>
<td>6.2%</td>
<td>84,150 (33.9% of J&amp;I MHRs)</td>
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<tr>
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<td>Ventilation</td>
<td>243,000</td>
<td>6.1%</td>
<td>43,795 (17.9% of Vent MHRs)</td>
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<tr>
<td></td>
<td>Paint</td>
<td>374,000</td>
<td>9.4%</td>
<td>136,016 (36.4% of Paint MHRs)</td>
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<tr>
<td>SUPPORT</td>
<td>Manufacturing Services</td>
<td>139,000</td>
<td>11.0%</td>
<td>88,200 (20% of Support MHRs)</td>
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<td>Machine Shop Services</td>
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<td></td>
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<td>71,000</td>
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<td>Ships Management</td>
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<tr>
<td>Reduced</td>
<td>Lifts</td>
<td>16,000</td>
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<td></td>
<td>Other</td>
<td>29,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>4,000,000</td>
<td>100%</td>
<td><strong>910,200 (22.7% MHR Reduction)</strong></td>
</tr>
</tbody>
</table>

**x $45/Hr**

$41.0M Per Ship Savings**

**Does Not Consider**

1) Material Savings
2) Shorter Schedule Savings
Advanced Double Hull - Large Scale Structural Tests
Advanced Double Hull Weapons Effects Tests

UNDEX Tests

Internal Explosion

Whipping Model
Stainless Steel Advanced Double Hull

Utilize cost reductions from geometry change coupled with material substitution to achieve affordable signature reductions.

<table>
<thead>
<tr>
<th>SHIP CHARACTERISTIC</th>
<th>BASELINE DDG-51</th>
<th>STAINLESS STEEL ADH</th>
<th>DIFFERENCE</th>
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<tbody>
<tr>
<td>DISPLACEMENT</td>
<td>6,832 L TON</td>
<td>6,696 L TON</td>
<td>+136 L TON</td>
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<tr>
<td>COST</td>
<td>$361.2 M</td>
<td>$324.6 M (HYBRID)</td>
<td>-$36.6 M</td>
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<tr>
<td>MAGNETIC SIGNATURE</td>
<td></td>
<td>FACTOR OF 9</td>
<td></td>
</tr>
<tr>
<td>IR SIGNATURE</td>
<td></td>
<td>Exceeds Goals</td>
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<tr>
<td>WEAPONS RESISTANCE</td>
<td></td>
<td>Inherent Improvement</td>
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<thead>
<tr>
<th></th>
<th>DDG-51</th>
<th>ADH 316</th>
<th>ADH AL6XN</th>
<th>ADH MIX</th>
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<tr>
<td>Labor Costs ($M)</td>
<td>180.1</td>
<td>138.8</td>
<td>138.8</td>
<td>138.8</td>
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<tr>
<td>Hull Structure Weight</td>
<td>3402</td>
<td>3421</td>
<td>3421</td>
<td>3421</td>
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<tr>
<td>Other System Weight</td>
<td>3430</td>
<td>3275</td>
<td>3275</td>
<td>3275</td>
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<tr>
<td>Hull Material Cost ($M)</td>
<td>11.6</td>
<td>23.6</td>
<td>39.6</td>
<td>31.5</td>
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<tr>
<td>Other System Cost ($M)</td>
<td>121.5</td>
<td>116.8</td>
<td>116.8</td>
<td>116.8</td>
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<td>Yard Overhead Cost ($M)</td>
<td>48.0</td>
<td>37.5</td>
<td>37.5</td>
<td>37.5</td>
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<tr>
<td>Total Costs ($M)</td>
<td>361.2</td>
<td>316.7</td>
<td>332.7</td>
<td>324.6</td>
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</table>
MHC-51 Coastal Mine Hunter

Don’t accept foreign technology without complete evaluation
High Speed Multi-Hulls

JHSV

Seafighter

LCS-2

HSV-X1

RV Triton
Materials


Materials:

- Aluminum
- Advanced Composites
- Titanium
- CRES
- HSLA
- GRP
- CRP
Fatigue endurance limit doesn't exist for welded aluminum.
HSLA Steel

Fatigue endurance limit doesn’t exist for welded steel.
Naval Composite Structures
(1980’s onward)

• High Quality
• Low Cost
Composite Primary Hulls

USCG FRC was an opportunity lost
Advanced Composite Masts

AEM/S Installed on USS Arthur W. Radford (DD-968)

Aft AEM/S Installation on USS San Antonio (LPD-17)

AEM/S System on USS San Antonio (LPD-17)

CVN 77 Mast

Effective transition requires persistence.
DDG-1000 Composite Superstructure

Success Requires:
Consistent material properties
Qualified vendors
Reliable outfitting and system integration
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<tr>
<td>Allowable Stress</td>
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<tr>
<td>Ultimate Strength</td>
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<tr>
<td>Fatigue</td>
<td></td>
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<tr>
<td>Fracture</td>
<td></td>
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<td>Loads/RAO’s</td>
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<tr>
<td>Reliability Methods</td>
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</tbody>
</table>
Fatigue-Aluminum Ship Evaluation Model
Ultimate Strength

Bending Moment

1. Ultimate Moment
2. Damage Onset Moment
3. Hog
4. Sag

Curvature

1. Liner Elastic
2. Non-Linear
3. Unloading
4. Ultimate Moment

Half-Scale Corvette Bending & Collapse Test

Welds

Plates

New Method

Existing & New Methods
Ship Structural Modeling

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>PVC Stress Modeling</td>
<td>“Full Scale” Fatigue Models</td>
<td>Component Fatigue Models</td>
<td>Panel Pressure Models</td>
<td>Large Scale Grillage Models</td>
<td>Hybrid Local-Global Loads Models</td>
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<td>Segmented Loads Models</td>
<td>Numerical Modeling</td>
<td>Physical Modeling</td>
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<tr>
<td>Numerical Modeling</td>
<td>NASTRAN</td>
<td>ABAQUS</td>
<td>PATRAN</td>
<td>DYNASTR</td>
<td>MAESTRO</td>
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<tr>
<td>Physical Modeling</td>
<td>SMP</td>
<td>SHCP</td>
<td>DPSS</td>
<td>ASSET</td>
<td>MAESTRO</td>
</tr>
</tbody>
</table>
Hydrofoil Hull Structure Stress Model
Structural Loads Physical Models

Scaled model *Hull Stiffness, El*, is necessary and achieved by *segmenting the hull* and integrating an internal *structural backspline*

*Slam panels* and/or *pressure gauges* are applied to the model to observe secondary slam and wave slap loads.
Hybrid Model-Wave Tank Tests
Grillage Strength
Hot Spot Stresses
MAESTRO Analysis of CG-47
Complex Multi-Level FEM
Integrated Design Tools

The **Trident** suite combines global ship modeling, **finite element** analysis and **seakeeping** analysis into a single integrated system. It includes standard ship design tools and leading-edge capabilities, such as fatigue and ultimate strength analysis.
Comparison of Test to LAMP simulation

Cruiser in Head Storm Seas, 10 knots
- DTMB experiment 972 – based on Hurricane Camille spectrum
- Simulation use Fourier fit of actual experimental wave

Incident Wave

Heave

Pitch

Vertical Bending Moment

Frame 174

EXPERIMENT  Time (sec.)
Body-Linear (LAMP-1) Time Domain Calculation

Nonlinear Panel Model

Experiment
LAMP Non-Linear
### Structural Monitoring Efforts Between 1985 and 2010+

<table>
<thead>
<tr>
<th>Ship</th>
<th>Year</th>
<th>Structural Channels</th>
<th>Primary Loads</th>
<th>Secondary Loads</th>
<th>Long Term Monitoring</th>
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<tbody>
<tr>
<td>USS Nicholas (FFG-47)</td>
<td>1985</td>
<td>70</td>
<td>Yes</td>
<td>No</td>
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<td>USS Carr (FG-52)</td>
<td>1986</td>
<td>70</td>
<td>Yes</td>
<td>No</td>
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<td>USS Kauffman (FFG-59)</td>
<td>1987</td>
<td>62</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<td>USS Monterey (CG-47)</td>
<td>1990</td>
<td>109</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>HMS Swan</td>
<td>1990</td>
<td>36</td>
<td>Yes</td>
<td>Yes</td>
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<td>USNS Victorius (TAGOS-19)</td>
<td>1991</td>
<td>64</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>USS Wasp (LHD-1) Sea Shadow</td>
<td>1992</td>
<td>28</td>
<td>Yes</td>
<td>Yes</td>
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<td>Joint Venture (HSV – ONR X1)</td>
<td>2001</td>
<td>27</td>
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<td>Swift (HSV-X2) ONR</td>
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<td>Sea Fighter (FSF-1) 05D</td>
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<td>LCS-1 ONR</td>
<td>2005-20??</td>
<td>105</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes^2</td>
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<td>LCS-2 PMS501</td>
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<td>E-Craft</td>
<td>2007</td>
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<td>JHSV ONR</td>
<td>2009</td>
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<tr>
<td>DDG-1000</td>
<td>2012</td>
<td>150</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes^2</td>
</tr>
</tbody>
</table>

1. Long-term monitoring for load determination
2. Long-term monitoring for fatigue damage monitoring requested by NAVSEA technical warrant or SDM
3. Long-term monitoring for TRL6

**12 sea trials conducted, 5 planned. Includes long-term monitoring**
Reliability-Based Design Criteria for Surface Ship Structures
PE063563N SHIP CONCEPT ADVANCED DESIGN

I. LOAD DETERMINATION
- Primary Loads
- Secondary Loads

II. STRENGTH DETERMINATION
- Material Properties and Local Strength
- Overall Hull Strength

III. STRUCTURAL RELIABILITY ANALYSIS
- Improved Loads for Ship Design
- Improved Strength Definition for Ship Design
- Validated Reliability Based Structural Design Criteria

Principle Product:
- Draft Load and Resistance Factor Design, LRFD, Criteria
Changes to Underlying Statistics

- Factor of Safety
- Unexpected operations
- Degraded properties
Consequence of Ignoring Underlying Statistics
Future Challenges for Ship Structures

- Safety
- Sustainment
- Cost
Safety

Systems that were once taken for granted as safe may well become unsafe during extended deployments and extreme weather.

(We now have SOE’s for systems that once “took safety for granted”.)

Rapid crack growth like occurred on FFG-10 could result in loss of contemporary aluminum hull ships.
Sustainment

Inadequate reliability adversely impacts sustainment.

Sustainment costs represent 60% of a ship's life cycle costs, if designed properly. If not designed properly, sustainment costs can be significantly higher.

Sustainment is one of the differentiating characteristics of the U.S. Navy fleet from other navies.

“More than 3,000 cracks have been found so far across the entire Ticonderoga class, which originally numbered 27 ships. Twenty-two of the ships remain in service, and Port Royal, commissioned in 1994, is the newest.”

DefenseNews
9 Dec 2010

“The determining factor for service-life of ships is the sea-frame” – RADM ECCLES, NAVSEA CHIEF ENGINEER
Cost

Reducing and managing costs is the number one priority in the Department of Defense.

The Navy is paying $100’s M in direct costs for repair of unreliable ship structure and incurring $ B’s in hidden costs of unmet Availability.

“So far, the Navy has awarded $14 million to BAE Systems in Pearl to fix the Port Royal deckhouse cracks.”

*DefenseNews*

9 Dec 2010
Meeting these future challenges will require robust investments from NAVSEA and ONR.

- Address structural risk in early stage design
- Improve, update, and replace NVR
- Enable continuous Structural Hull Monitoring
- Develop risk-based ship structural life management
Questions

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