NSRP RA Project 2017-443

“Ship Structural Design Optimization (SSDO) for Improved Producibility and Enhanced Life-Cycle Performance”

SDMT Panel Briefing
October 29, 2020
Rationale – Why Develop Multi-Objective Structural Design Space Exploration for Early-Stage Design

• **Traditional Approaches** – structural design has relied on least weight approaches, correlating with weight-based cost methods, and static design methods in early stage design

• **Resulting Structural Shortcomings** – Lightweight structures that are more complex with higher work content to fabricate, and lack robust qualities causing high in-service damage and repair costs from extreme loads and structural fatigue damage

• **Structural Design Space Exploration** – using automated 3D finite element analysis and higher-fidelity loading in early-design enables design alternatives to be engineered and compared for work content and performance through the life cycle

• **Structural Optimization** – which implements Lean Design principles offers practical tools for effective design space exploration

Lightweight structures lead to high Total Ownership Costs (TOC)
Structural Work Content

<table>
<thead>
<tr>
<th></th>
<th>CL Girder</th>
<th>P/S Bhd</th>
<th>CL Bhd</th>
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</thead>
<tbody>
<tr>
<td><strong>Traditional Design</strong></td>
<td></td>
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<tr>
<td>2 long. bulkheads, 9 IB girders, 4 horizontal stringers, and 5 web frames per 12 M tank</td>
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<tr>
<td><strong>Lean Design</strong></td>
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<tr>
<td>1 long. bulkheads, 5 IB girders, 3 horizontal stringers, and 3 web frames per 12 M tank</td>
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</table>

>50% reduction in structural work scope, >35% reduction in tank coating surface, and improved tank access with ~3% increase in steel weight.

Reduced work content & improved tank access
Ship Structural Design Optimization (SSDO) Program Team

• **Fincantieri Marinette Marine**
  • Project Lead, shipyard implementation

• **MAESTRO Marine LLC**
  • Naval architects & software developers, creators of MAESTRO

• **NSWC-CD Code 65**
  • US Navy lead organization for ship structural design

• **Ship Design USA (Bob Keane)**
  • Former US Navy Chief Naval Architect, advisor on Navy ship design & construction

• **SPAR Associates**
  • SMEs in ship cost-estimating and production planning

• **P. Jaquith & Associates (Pete Jaquith)**
  • SME in Lean Design and Design for Production
SSDO Provides Higher Fidelity Ship Structural Engineering from Concept Design through the Full Life-Cycle

<table>
<thead>
<tr>
<th>Design Timeline</th>
<th>Concept</th>
<th>Preliminary</th>
<th>Functional/Contract</th>
<th>Life-Cycle</th>
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<tr>
<td>Topology Optimization</td>
<td>Coarse global FEA model</td>
<td>Selected Topology Opt.</td>
<td>Fine mesh midbody model</td>
<td>Full Optimization</td>
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<tr>
<td>Static Global Loading:</td>
<td>- Automated optimization</td>
<td>- Secondary &amp; tertiary loads</td>
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<td>- Design space exploration</td>
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<td>- Topology search process</td>
<td>- Spectral Fatigue Analysis</td>
<td>- Life-cycle cost factors</td>
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**APPLICATION OF MAESTRO OPTIMIZATION & ANALYSIS**

**Normal Loadings:**
- Operational loads
- Extreme loads
- Spectral Fatigue Analysis
- Damage conditions

**Corrosion database**
SSDO Improvements Delivered Through the NSRP RA Project

- Concept Design/Topology Optimization Module
- Cost & Production Engineering Module
- Life-Cycle/Corrosion Module
Concept Design/Topology Optimization Module: Design Space Exploration Approach

• We have successfully developed a capability to conduct an optimization of a coarse mesh MAESTRO finite element model that automatically varies frame spacing and then, for each frame spacing, varies the global stiffener spacing with user defined min/max values.
  • For example, 3 frame spacings x 4 stiffener spacings = 12 optimized designs are automatically generated
• The capability was extended to enable the finite element analysis based automated optimization of structures that have the hull principal dimensions changed
  • Length, breadth, depth can be scaled automatically
Design Space Exploration & Structural Optimization

Optimization Settings Interface

USN safety criteria
Vary frame spacing
Scale global hull
Vary stiffener spacing

Coarse mesh mid-body
Finite element model
Original Optimization Process

- Process implements “Six Stages of Rational Ship Structural Design” as published by Professor Owen Hughes
- Uses mid-body or full ship finite element modeling and analysis with high fidelity naval architectural loading
- Automates structural failure or limit-state evaluations which serve as constraints for optimization

- Optimizes “manufacturing or design clusters” (inner loop)
- Then re-integrates revised full structure to update structural performance evaluation vs criteria
New Topology SSDO Process

- Additional nested global iterations are added to optimize changes of:
  - Stiffener spacing
  - Number of frames
  - Global scale/dimensions (length, beam, depth of hull)
- Automatically generates modified finite element models to support the geometry changes
- Optimizations automatically iterate to convergence
- Each optimized structural design is saved and has metrics extracted for review

### Diagram:

```
Define Structure
    Define Loads
      Iterate global scale, number of frames, stiffener spacing
        Finite Element Analysis (Full Ship)
          Structural Evaluation: Determine Critical panel of each Production Cluster
            Panel/Cluster Optimization
              Store Designs
                Change global scale, number of frames, stiffener spacing
                  Stop
```
Example Optimization Results
Stiffener and Frame Iterations

Topology Optimization
Level 1 global FEA

Static Global Loading:
- Automated optimization
- Design space exploration
- Topology search process

Full Matrix: 25 Optimized Structural Designs

<table>
<thead>
<tr>
<th>Property per frs 180-220</th>
<th>Original</th>
<th>Optimized Design 1</th>
<th>Optimized Design 2</th>
<th>Optimized Design 3</th>
<th>Optimized Design 4</th>
<th>Optimized Design 5</th>
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<tr>
<td>Trans. Fr. Spacing</td>
<td>80&quot;</td>
<td>96&quot;</td>
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<td>80&quot;</td>
</tr>
<tr>
<td>Stiffener Spacing</td>
<td>21&quot; - 25&quot;</td>
<td>20&quot;</td>
<td>25&quot;</td>
<td>30&quot;</td>
<td>35&quot;</td>
<td>35&quot;</td>
</tr>
<tr>
<td>Weight</td>
<td>45.1 LT</td>
<td>40.8 LT (-9%)</td>
<td>43.1 LT (-4%)</td>
<td>45.7 LT (NC)</td>
<td>47.4 LT (+5%)</td>
<td>48.3 LT (+7%)</td>
</tr>
<tr>
<td>Weld Length</td>
<td>39,791&quot;</td>
<td>42,240&quot; (+6%)</td>
<td>36,290&quot; (-9%)</td>
<td>28,920&quot; (-27%)</td>
<td>26,890&quot; (-32%)</td>
<td>28,040&quot; (-29%)</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>2.29E7 in⁴</td>
<td>2.05E7 in⁴</td>
<td>2.27E7 in⁴</td>
<td>2.41E7 in⁴</td>
<td>2.50E7 in⁴</td>
<td>2.52E7 in⁴</td>
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<tr>
<td>Max Stress deck</td>
<td>-13.3/14.0 ksi</td>
<td>-14.6/15.2 ksi</td>
<td>-12.7/13.5 ksi</td>
<td>-12.5/13.2 ksi</td>
<td>-12.3/12.7 ksi</td>
<td>-12.3/12.6 ksi</td>
</tr>
<tr>
<td>Max Stress keel</td>
<td>11.4/-15.7 ksi</td>
<td>12.5/-17.0 ksi</td>
<td>11.6/-16.1 ksi</td>
<td>10.4/-14.0 ksi</td>
<td>10.1/-13.9 ksi</td>
<td>10.2/-13.4 ksi</td>
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Best case  Worst case
Example Optimization Results, with Hull Size Changes

- This example iterates all three:
  - Stiffener spacing
  - Number of frames
  - Global scale/dimensions; this case also changes depth of hull

- Ship arrangement alternatives
- Production schedule and cost impacts
- Impact SWBS Group 100 as well as other SWBS Group production and cost factors

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<td>25&quot;</td>
</tr>
<tr>
<td>Height</td>
<td>360&quot;</td>
<td>360&quot;</td>
<td>396&quot;(+10%)</td>
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<td>360&quot;</td>
<td>360&quot;</td>
</tr>
<tr>
<td>Weight</td>
<td>46.27 LT</td>
<td>37.9 LT (-18%)</td>
<td>49.3 LT (+6.5%)</td>
<td>41.1 LT (-11%)</td>
<td>38.8 LT (-16%)</td>
<td>41.5 LT (-10%)</td>
</tr>
<tr>
<td>Weld Length</td>
<td>38455&quot;</td>
<td>37879&quot; (-1.5%)</td>
<td>43717&quot; (+13%)</td>
<td>37691&quot; (-2%)</td>
<td>42621&quot; (+11%)</td>
<td>36628&quot; (-5%)</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>2.28E7 in(^4)</td>
<td>1.75E7 in(^4)</td>
<td>3.0E7 in(^4)</td>
<td>2.27E7 in(^4)</td>
<td>1.86E7 in(^4)</td>
<td>1.93E7 in(^4)</td>
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<tr>
<td>Max Stress keel</td>
<td>11.5/-15.8 ksi</td>
<td>15.3/-20.4 ksi</td>
<td>8.9/-13.5 ksi</td>
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Cost & Production Engineering Module

A new MAESTRO software module has been designed to be used by shipyard cost and production engineers, not the structural naval architect, for defining cost and production data associated with the structural design and fabrication processes.

- Specify the plates and shapes in the yard’s “structural warehouse”
- Define structural fabrication processes, e.g. panel lines and their cost metrics
- Define the structural fabrication components and sequence of assembly
- Review results/metrics for optimized structural alternative designs

Data from this module will be used in SSDO’s work content optimization to facilitate realistic reductions/trade studies in work content and producibility enhancements
Cost & Production Engineering Module

Structural Warehouse Definition
- Global/Enterprise Warehouse
- Material Costs
- Process/Labor Content
- Project Specific Warehouse

Structural Process Definition
- Process 1, e.g. auto stiffened panel line
- Process 2
- Process 3

Define Structural Fabrication Units
- Major Blocks
- Design Clusters
- Subassemblies

Review Results & Metrics from Optimization
- Structural Weight
- Work Content Metrics, e.g. hours
- Bill of Materials

DISTRIBUTION STATEMENT: Unlimited/Approved for Public Release
Cost & Production Engineering Module

Example Structural Warehouse & Process Definition Metrics

Cost of frame/girder per unit length:
- Material
- Prep
- Welding

Labor/time to weld frame/girder per unit length (one pass, two pass, etc.)

Cost of plating per unit area

Labor to weld plating per unit length

Labor to weld stiffener per unit length
- Setup
- Manual welding
- Automated welding
- Cost of rework/straightening plate

Cost of stiffener per length:
- Acquisition
- Storage
- Prep

Labor of stiffener penetration (each)
Cost & Production Engineering Module

Production engineers work in the user friendly Rhino environment.
US Coast Guard SFLC Sponsored Corrosion Database Toolset Adaptation to SSDO Life-Cycle Assessment Objectives

- Track corrosion and other damage to a vessel’s structure in a Rhino plug-in and database
- Collect, organize, and display data spatially, temporally, and across the fleet
  - Spatially: data displayed on 3D model
  - Temporally: display progression of corrosion/damage over multiple surveys
  - Fleet: examine data across vessels of a class
- Plan future surveys and repairs
- Support structural analysis of the vessel in its corroded/damaged condition
  - Structural Response (yielding/buckling)
  - Hydrodynamic Loads Analysis (MAESTRO-Wave)
  - Extreme Load Analysis (ELA)
  - Spectral Fatigue Analysis (SFA)
Corrosion Database Tool
Conduct Life-Cycle Impact Analyses and Trade Studies

- Corrosion surveys mapped into database that correlates with ship finite element (FE) model
- Corroded/damaged conditions are automatically transferred to ship FE model for analysis
- Support in-service engineering
  - Structural integrity evaluation
  - Fatigue life forecasting
  - Structural margins assessment
  - Structural repair management
  - Damage condition assessment
SSDO Provides Higher Fidelity Ship Structural Engineering from Concept Design through the Full Life-Cycle

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- Static Global Loading:
  - Automated optimization
  - Design space exploration
  - Topology search process

**Selected Topology Opt.**
- Fine mesh midbody model
- Loading:
  - Secondary & tertiary loads
  - Basic hydrodynamic loads
  - Extreme Load Analysis
  - Spectral Fatigue Analysis
  - Life-cycle cost factors

**Full Optimization**
- Finer mesh global model
- Loading:
  - Secondary & tertiary loads
  - Full hydrodynamic loads
  - Extreme Load Analysis
  - Spectral Fatigue Analysis
  - Higher fidelity life-cycle cost factors

**In-Service Engineering**
- Fine mesh model & class database
- Loading:
  - Operational loads
  - Extreme loads
  - Spectral fatigue
  - Damage conditions

**Corrosion database**
NSRP RA Project 2017-443 Summary
“Ship Structural Design Optimization (SSDO) for Improved Producibility and Enhanced Life-Cycle Performance”

- Early-stage design can rapidly engineer and assess the effects of global changes to frame spacing, stiffener spacing, as well as for changes to hull dimensions
- Production & Cost Engineering have the ability to impact the ship’s structural design while it can still be changed during design to optimize cost, weight and production
- Life-cycle factors such as extreme load capabilities, structural fatigue life, and damage tolerance can be engineered during design to effectively improve the life-cycle performance and reduce excessive in-service structural repair costs
- In-Service Engineering can leverage the final design model throughout the ship’s life to reduce life-cycle costs, engineer structural repairs, assess damage conditions, and ensure ship structural integrity with minimum downtime and repair costs