DEVELOPMENT OF NEW RAFT TECHNOLOGIES FOR THE BC SHELLFISH AQUACULTURE INDUSTRY
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Project Report

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Executive Summary

The necessity of creating better culture raft designs to effectively modernize the shellfish farming industry has been a significant priority to the BC shellfish culture industry. Recently, it has become apparent that the vast majority of industry infrastructure is in need of redesign, upgrades and new investment.

The goal of this project was to respond to industry need and to develop a new shellfish aquaculture raft design using current state-of-the-art materials and techniques. The resulting "open" design will hopefully create high quality rafts for the BC Shellfish Farming industry and improve industry economic profitability and environmental sustainability. Having long-life raft designs that will withstand significant loads from high wind and wave action will reduce industry's contribution of debris on beaches and subsequently save farmers time and money to replace lost and broken equipment.

The Centre for Shellfish Research conducted an open-source development process with industry, component manufacturers and experts. Two workshops were held, one at the beginning of the project to engage the industry and allow the opportunity for the exchange of ideas and needs to be incorporated into the design. The second industry workshop was held after preliminary designs were complete allowing the opportunity for feedback before final design decisions were made. In addition numerous conversations were conducted with industry members in BC and the US throughout the project.

Expert engineers (Dynamic Systems Analysis) were engaged to work with the project team to assist in developing prototype designs and to provide design recommendations to independent industry efforts. Virtual dynamic systems modelling was employed to simulate how various materials and structures would perform in a dynamic marine environment and greatly accelerated the range of materials and concepts that could be analyzed prior to physical prototyping.

Existing industry standard trimaran and catamaran rafts were modelled to determine weaknesses and safety factors and used as a guideline in new designs. A wide variety of materials were simulated to determine which would be most suitable as potential component materials in terms of both minimum strengths and cost effectiveness.

After testing more than 30 designs virtually, four final designs based on two styles (A & B) were developed for physical prototyping. Final designs use a combination of primary structural beams (steel) and secondary interstitial beams. The supporting structure of the rafts is a combination of galvanized steel 4" steel 'T' and 'I' beams, assembled with galvanized bolts in order that rafts can be bolted together onsite with simple tools. Standard steel stock comes in 40' lengths and to maximize the use of steel, the raft dimensions were extended to 27.6’ x 27.6’ (2/3d’s) of a standard beam. Rotomolded dock floats (billets) manufactured by ACE Plastics were selected. A summary comparison is shown in the following table.
Comparison of styles.

<table>
<thead>
<tr>
<th>Main cross beam component</th>
<th>Raft dimension (feet)</th>
<th>Main beam dimension (in x in x ft)</th>
<th># Main cross beams</th>
<th># Floats</th>
<th>Min # Drop lines</th>
<th>Max # Drop lines</th>
<th>% Submergence (Max)</th>
<th>% Submergence (Min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - galvanized I beam unequal spacing</td>
<td>27x27</td>
<td>4x4x27</td>
<td>6</td>
<td>6</td>
<td>77</td>
<td>121</td>
<td>87</td>
<td>64</td>
</tr>
<tr>
<td>B - galvanized I beam equal spacing</td>
<td>27x27</td>
<td>4x4x27</td>
<td>5</td>
<td>6</td>
<td>96</td>
<td>144</td>
<td>97</td>
<td>72</td>
</tr>
</tbody>
</table>

Overall, we believe we have been successful in achieving the project objectives. The prototype designs meet the project goals and criteria establish during industry discussions. Both raft styles are approximately 1m x 1m larger than existing designs (8m x 8m), with more capacity (>80 tray droppers and >12,000 lbs floatation).

In summary these designs:

- May be able to be moored in a similar fashion to existing designs
- Are as simple as possible with few “custom parts” and structures that could be assembled by farmers with a minimum of tools on-site.
- Have integral structure constructed from non biodegradable materials virtually tested to be capable of withstanding normal to significant weather conditions.
- Isolate the structure of the raft from the components that physically suspend the culture stock so that failure of components suspending stock does not contribute to overall raft failure.
- Have durable components that do not degrade and/or can be maintained or repaired in situ.
- Have commercially available plastic foam filled billets as floatation that will not degrade in the marine environment if damaged.

Prototypes are now being tested and demonstrated at the Deep Bay Field Station in Baynes Sound, BC. Shop drawings of prototypes are available to industry for construction, further testing and continuing advancement.
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1.0 Introduction

1.1 Projective objectives:
The necessity of creating a better raft to effectively modernize the shellfish farming industry has been a significant priority to the BC shellfish culture industry. Recently, it has become very apparent that the vast majority of industry infrastructure is in need of redesign, upgrades and new investment. Having new raft designs that will withstand significant loads from high wind and wave action will reduce industry’s contribution of debris on beaches and subsequently save farmers time and money to replace lost and broken equipment. As a result the BC Shellfish Growers Association (BCSGA) has included testing new raft designs on their working list of industry research and development priorities1.

The goal of this project was to respond to the industry need and develop new shellfish aquaculture raft designs using current state-of-the-art materials and techniques. The resulting open source designs can be used to create high quality rafts for the BC shellfish farming industry which will in turn improve industry economic profitability and environmental sustainability. This occurred by bringing much needed engineering support to this issue and engaging industry in a multi-disciplinary collaborative design process. Funding from the Aquaculture Innovation and Market Access Program (AIMAP)2 has allowed us to design, test and build alternative rafts to the current designs being used by industry.

The specific objectives of this project included:

1. Conduct and facilitate an open-source development process with industry, component manufacturers and experts.
2. Engage expert engineers to work with industry to develop prototype designs and to provide design recommendations to independent industry efforts.
3. Maintain a project communications strategy through information on BCSGA and CSR websites, trade journal articles, industry presentations and press releases.
5. Model and test in-situ various prototypes at the Deep Bay Field Station under commercial culture situations while making rafts available for demonstration purposes.
6. To develop and test up to four prototype designs for “next generation” shellfish rafts.
7. Provide a report for dissemination to industry outlining manufacture detailing, design and capital costs.

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2 http://www.dfo-mpo.gc.ca/aquaculture/sustainable-durable/index-eng.htm
1.2 **Background:**

The current state of the art in deepwater shellfish aquaculture is to use 8 metre² rafts constructed of lumber and either unprotected or coated/covered Styrofoam for the cultivation of shellfish such as oysters and mussels. Generally, these rafts have been built using the expertise and the materials readily available to the farmers. In the last four years with particularly severe wind storms, it has become apparent that more durable rafts are needed as many rafts have broken up and been destroyed resulting in loss of valuable equipment and environmental/community concerns about debris.

![CSR Computer model of existing trimaran design and production raft destroyed by storm (December 2006)](image)

Figure 1. CSR Computer model of existing trimaran design and production raft destroyed by storm (December 2006)

The CSR has estimated that losses from a single storm damaged raft can include the following:

- tray oysters = $12,000 – $18,000
- trays = $8,000
- raft = $2000
- Total approx. = $25,000
Key facts about the current designs

- Catamaran and Trimaran designs
- Framework and decking - wood; wood and steel
- Dimensions - 24’ x24’, using 2”x6” and 2”x8” lumber to accommodate a two foot square shellfish tray hung at two different depths
- Floats - Styrofoam blocks wrapped in tarpaulin, some use of roto molded plastic. Flotation costs range from $400 for plain Styrofoam, to $1800 for roto molded foam
- Useable life of approximately 5 years.
- Approx 80-88 tray stack droppers per raft.
- Design approach: “if it breaks build it bigger”.
- Estimated >1000 over “shelf life” in BC.
- Cost - Large trimaran design costs $6500 + manpower. Smaller trimaran rafts (24’x 24’) cost $1400 - $2000 + construction costs.

During a single storm in December 2006, it was estimated that as many as 100 rafts were severely damaged or lost. In years following, anecdotal reports are that losses continue. This estimate does not take into account the costs of salvage, removal and disposal of ruined equipment or the social and environmental costs of marine debris lost to the marine environment. This has resulted in significant media attention and social issues related to marine debris washing up on local beaches.

Globally shellfish farmers are developing new designs specific to their area and culture methods based on better and more durable materials. This advanced development has so far excluded much of the BC industry. Since winter storms devastated a large number of farms in December 2006, the CSR and the BCSGA have made the development of new more durable technologies a specific research priority and have engaged industry and experts in a collaborative design process that has suffered for lack of resources to develop and test prototypes and then introduce these to the industry at large.

1.3 Prior work

The CSR has worked opportunistically on responding to industry requirements for new raft designs since spring of 2007 when the CSR hosted a one day industry workshop to discuss the issue, bring experts together with industry and engage in a discussion to move the industry forward. This highly successful workshop was funded by the BC Ministry of Agriculture and Lands.

Subsequent to the workshop, the CSR with the UVIC Innovation and Development Corporation (IDC) hosted a working luncheon...
to discuss the issue. This first workshop included CSR staff, representative of 6 shellfish companies, an engineer from Camosun College, representatives from two commercial float companies and a business specialist from UVIC Innovation and Development Corporation (IDC). Participants in this workshop shared and identified a number of key criteria for moving forward including:

- Issues and common points of failure with current raft designs
- Design considerations for a new raft design?
- What the necessary attributes of a good raft are in terms of operational characteristics, size, flotation, stability, modularity, and service lifetime etc.?
- How much they would be willing to spend for a raft, and what cost benefits would be necessary to justify new raft designs?

Figure 2. Raft design workshop at Centre for Shellfish Research

1.4 Partners
This project was conducted with the BC Shellfish Growers Association (BCSGA). The shellfish industry has been engaged in preliminary discussions prior to this project and a model for industry involvement was established. Co-leadership on this project with the BCSGA ensured that industries concerns were heard and met during the process.
1.5 Potential Benefits to Industry and Commercialization

Commercialization potential
Industry estimates collaborated with site development information provided by BC Ministry of Agriculture and Lands have indicated that there are in excess of 1000 rafts in British Columbia, the majority of which are estimated to be more than five years old or past the half-way mark of normal lifespan. Assuming that 100 rafts at a very minimum are replaced per year with next generation rafts this would removed approximately 22,000 cubic feet of Styrofoam per year from risk of loss to the marine environment per year. Construction of another 100 new rafts per year for industry growth would prevent an equivalent amount of Styrofoam from being placed into the marine environment.

Better designs will allow the industry to reduce risk of product and equipment loss due to storm damage during climax changed which may result in more severe weather events on the British Columbia coast. New more environmentally sustainable and aesthetically less intrusive designs will also contribute to the shellfish industry achieving more “social license” from coastal communities and thus adding to overall development potential.

Production from an anticipated 1000 new rafts introduced over the next five years would produce wholesale product values of between 12–18 million dollars annually.

Secondary component fabricator/manufacturers and raft assembly firms will benefit by production of the necessary parts, integrating existing manufacturer's floats and sell the shellfish rafts as part of their product line, either selling the entire raft or selling the individual components. Over the next five years it is anticipated that over 1000 rafts could enter service with a materials (secondary supplier) opportunity of 4–5 million dollars based on what industry has stated total capital costs for new rafts should be.

Open licensing is expected to promote commercialization. Prototype designs produced through this project are being made publicly available to the BC shellfish industry through the Centre for Shellfish Research and the BCSGA.
2.0 Methodology and objectives

2.1 Industry involvement
A goal of the project was to conduct and facilitate an open-source development process with industry, component manufacturers and experts. Two workshops were held, one at the beginning of the project to engage the industry and allow the opportunity for the exchange of ideas and needs to be incorporated into the design. The second industry workshop was held after preliminary designs were complete allowing the opportunity for feedback before final design decisions were made. In addition, numerous conversations were conducted with industry members in BC and the US throughout the project.

2.2 Engagement of experts
Expert engineers were engaged to work with the project team to assist in developing prototype designs and to provide design recommendations to independent industry efforts.

Vancouver Island University conducted an open Request for Qualifications among engineering firms and retained Dynamic Systems Analysis of Victoria. Dynamic Systems Analysis, Ltd. (DSA) specializes in risk management in marine environments. DSA primarily focuses on the following industries: renewable energy, submersibles & subsea robotics and ocean engineering: moorings & riser design. DSA is located on the University of Victoria campus in a partnership with the UVIC technology transfer office and the Innovation and Development Corporation.

The core technology used by DSA is an advanced engineering analysis tool called ProteusDS®. This proprietary software was developed by DSA and is used to rapidly construct accurate virtual prototypes of marine assets or operations. The response of the constructed system to ocean wind, waves, and current conditions allows DSA to intelligently assess system performance and prevent catastrophic structural failure.

2.3 Modeling a series of prototypes using computer simulations

Concept of simulation based design

In terms of mechanical engineering, dynamics analysis is the study of forces and their relationship to the motion of bodies. If the nature of loading on a body is understood and a model of the body can be created, dynamic analysis will predict the motion of the body through time. An accurate understanding of the dynamics of a mechanical system is critical to ensure reliable and efficient design.
Computer simulations were utilized by Dynamic Systems Analysis (DSA) to virtually test a wide variety of prototypes developed by the project team. The conceptual theory behind this approach is that to analyze the dynamics of a system, the relationships between the system components must be defined. Traditional analytical techniques and linearized analysis can become too onerous, time consuming, and even impossible. However, the use of nonlinear numerical simulations allows the motions complex mechanical systems of any size to be predicted in a reliable and economical fashion. Examples of the elastic forces calculated and modeling during dynamic analyses are shown in the following diagram.

![Diagram of Forces Acting on a Cable and Raft Beam]

**Figure 3.** Factors utilized in dynamic cable modeling showing forces acting on a cable and a raft beam.

**Simulation plan**

The goal of conducting dynamic analyses on virtual prototypes is to remove design weaknesses (optimize) without having to physically construct prototypes. The internal stresses of the raft beams are a function of the dynamic internal forces of the elastic joints in the model. Once the internal stresses exceed the yield strength of the material (incorporating an appropriate safety factor), failure of the object, in this case a culture raft is anticipated.

A standard virtual model of shellfish mooring for raft simulations was developed with mooring properties and
schematics based on industry norms. In order to establish internal forces of the raft during environmental forcing, a series of virtual raft models were developed with a series of rigid beam segments with elastic joints. In order to facilitate parametric studies on different materials, geometries, and raft configurations computer scripts were generated in order to quantify the stiffness and inertias of the raft components given fundamental material properties such as density, stiffness, and characteristic dimensions.

Once failure conditions of the raft have been anticipated, materials and raft geometry can be varied to address the design issues. The parametric study was constrained by the allowable materials and geometry dictated by industry feedback, which was determined by the project team staff and took into account numerous “workability” decisions. Raft materials of PVC, wood, steel, and other materials were be incorporated in the simulation model as allowed by constraints.

In summary, this procedure allowed the design team to model elastic virtual rafts, anticipate failures and try many beam shapes & materials.

The specific design process included:

1) Setting the environment (depth, sea state)
2) Establishing safety factors based on the standard industry trimaran raft
3) Simulating to benchmark beam shapes + materials
4) Repeating 3)!

The simulation-based design tested the following:

- Shapes: I-beam, pipe/tube, rectangular beams
- Structural materials: aluminum, steel, fiberglass, HDPE, plastic wood, wood
- Rafts styles: trimaran, catamaran, 'frame' catamaran

The following definitions are important in understanding the results of the simulations.

**Yield stress** - the internal pressure level a structure can sustain at the verge of failure. Yield stress is a known value for many different materials. Steel for example has a significantly higher yield stress over wood.

**Safety factor** - the ratio of the yield stress over the applied stress of a structure. A safety factor of 1 or lower implies the structure has failed. A design with a larger safety factor will be more tolerant to uncertainties in loading and material imperfections. Safety factors are affected by the material as well as the situation in which it is used. For our usage, a safety factor of 10 is desirable based on the American Bureau of Shipping’s
Guide for Building and Classing Floating Production Installations for critical non-field repairable members on offshore structures.

Wing beam- the amount of overhang (unsupported beam length) on the outside of the floats in current designs.

Bending axes- the raft beams can flex in two ways, specified by the primary bending axis (flexing up and down) and the secondary bending axis (flexing side to side). The most important difference between these two bending axes is in their resistance to bending. The resistance to bending about the primary axis increases cubically with beam height, whereas the resistance to bending about the secondary axis increases linearly with beam height. This means that failure is occurring in the secondary bending axis, increasing the beam height will do little to improve the failure and resulting overall safety factor of the raft.

Figure 4. Diagrammatic representation of bending axes
2.4 Simulation process

Step 1: Determine environmental conditions

Weather data from 2 stations in the Strait of Georgia (Stations 46131 and 46146) was used to generalize worst case scenario wind and wave action in the area. From this data it was determined that a 3m, 8 second period wave would be used in initial simulations.
Step 2: Model industry standard rafts

Existing industry standard trimaran and new catamaran raft designs were modeled to determine weaknesses and safety factors to use as a guideline in new designs.

In order to establish a design starting point both Catamaran (2 rows of floats) and Trimaran (3 rows of floats) versions of rafts used in the shellfish industry were simulated by DSA. For each variant, a series of materials were examined with simulated wave propagations hitting the side of the rafts (beam waves) and at an angle of 45 degrees (Beam head waves). Predicted safety factors, the axis of failure and the safety factor of what we termed to be wing beams, the section that hangs out over the beam were calculated.

Step 3: Simulations of new and materials

Simulations and calculations of safety factors were conducted of new components tested with beam-head waves with 2m, 6 second period for rafts of different sizes and made of different materials. The results of these extensive simulations are summarized in Appendix 2.
Step 4: refinements and production of designs

Based on calculations on materials and dimensions outlined in Table 4., further refinements were made in concept. It was decided to increase the size of the raft from 24’x24’ which is determined by the maximum available size of dimension 2x6” lumber to 27’x27’. This was based on maximizing recovery from standard steel stock sizes which come in 40’ lengths by using 2/3’s of a standard 40’ length. The remaining thirds can be joined to create 27’ lengths.

Having made this assumption, various materials were then simulated to determine which would be most suitable as a frame material. During this design iteration, materials were examined to determine both minimum strengths and cost effectiveness.

2.5 Project communications

This project has provided updates to industry through the BCSGA website and print newsletter Tidelines. The CSR developed a PBWiki site https://shellfishraft.pbworks.com/ during which materials and news of the project was maintained. Many producers, manufacturers and interested parties have requested access to this site. Presentations have been made about the project at conferences such as the Aquaculture Association of Canada Annual meeting in Nanaimo in May 2009, the Pacific Coast Shellfish Growers Association annual meeting in Portland, Washington in September 2009 and at the 2009 BCSGA meeting.

The project received print coverage in Northern Aquaculture Magazine and the University of Victoria produced a print article on DSA and their role in the project. Additional print media arose from the announcement of funding at VIU by local Member of Parliament, Dr. James Lunney.

Video simulations of raft designs were placed on YOUTUBE at:

http://www.youtube.com/watch?v=NDcAeFNSCdU

An summary article of the project was included on the Deep Bay project blog at:


This final report has been added to the Deep Bay project blog at:


2.6 Development of prototypes

After narrowing down designs through virtual modelling, shop drawings were produced for two separate styles of prototype rafts. A Request For Proposals was issued for construction of raft components by the purchasing office of Vancouver Island University. A contract for prototypes was awarded to Advanced Integration Technologies Canada – Fabrication in Abbotsford (http://www.aint.com).
3.0 Outcomes and results

3.1 Consultation outcomes
Design considerations raised at workshops which guided further design included the following:

Operations

- Some farmers move their rafts around regularly, others do not. Rafts must be capable of being moored in semi-permanent or easy to release moorings
- Linkage- Rafts are generally chained together with a spacing between the rafts of 4’-20’, larger rafts having more space between them. This is not ideal.
- Modularity- Would be ideal, as it would allow growers to build a new fleet of rafts that work together over a period of years. New designs must be able to be incorporated into existing farm layouts and resemble the existing dimensions as much as possible. Note: This had a significant impact on overall design.
- Ladders and walkways must be able to be mounted on the raft for safety. Most pre-existing industry rafts have wood walkways integral on the structure of rafts, but crews must still work across exposed 2x6 beams which present issues for worker safety. Overboard ladders are typically not built into raft designs but are commercially available. This led to a discussion of whether every raft should have walkways and working platforms built into the raft or should these be separate from the raft design?

Structure

- Raft structure must be constructed out of materials that will not degrade in weather – This had significant effect on design
- Raft design must match the weather conditions. Existing designs when new generally meet weather requirements and this be used as a baseline for design
- Loading- When overloaded a single stack of trays can weigh up to 300 lbs in air (100 lbs in water).
- As a raft moves up and down during ocean swells, significant shock loading from the suspended trays occurs, effectively increasing the weight that must be sustained by the structure
- Flootation- A 24’ industry standard beam raft would require 12,000 lbs of floatation to support the trays of a standard mature crop.
- Flootation must be sufficient enough not to cause the break-up of the raft if floats are lost
Redundancy- A rafting/anchoring system that will not break up as soon as one problem occurs. **Note:** *Existing designs share structural integrity across the entire raft and when a single beam breaks the entire structure weakens often resulting in cascading failures.*

Materials- must be readily available and repairable or replaceable on site by workers.

**Cost**

Cost- must be cost effective. Existing rafts are “inexpensive” to build but have a relatively short operational lifespan (5-7 years). Cost effectiveness must be determined as a component of life cycle.

### 3.2 Local and international design review

Local BC designs were reviewed from the original catamaran rafts constructed on Cortes Island by Redonda Seafarms and descendant modifications of this design. Trimaran wood and foam rafts designed by Odyssey Shellfish using wood and wrapped Styrofoam and a recent catamaran raft designed by Odyssey Shellfish Ltd. using a wood structure with steel connections and roto-molded plastic floats and a combination steel and wood raft design used by Taylor Shellfish in Okeover Inlet.

A comprehensive review of other international raft designs was conducted including (Maine, Puget Sound, Scotland and Spain). This included a field trip to Puget Sound to examine and discuss the pros and cons of an aluminum raft developed by Taylor Shellfish Ltd.

It was noted from the design review that most other jurisdictions where shellfish culture is more established as an industry, are trending to steel structures and moulded plastic floats (Figure 7). This generally replicates the growth of the fin fish industry which moved form wood cages to more weather resistant galvanized steel structures.
Figure 7. **Steel and wood mussel raft designs**

Upper left – Explora galvanized steel and wood beam mussel raft – Loch Fyne, Scotland
Upper right – Aluminium and wood mussel raft – Taylor Shellfish, Puget Sound, Washington USA.
Bottom - 40x40’ galvanized steel and wood beam mussel raft – Maine Aquaculture Equipment, Maine USA.
3.3 Summary of design requirements

As a result of the industry consultations and existing design review the following design criteria were established:

- Must approximate the existing footprint (24’ x 24’), capacity (>80 tray droppers and >12,000 lbs flotation).
- Be able to be moored in a similar fashion to existing designs.
- A simple design including: as few “custom parts” as possible, structures that could be assembled by farmers with a minimum of tools on-site.
- Have integral structure constructed from a non biodegradable material (i.e. not wood) and capable of withstanding normal to significant weather conditions.
- Isolate the structure of the raft from the components that physically suspend the culture stock so that failure of components suspending stock does not contribute to overall raft failure.
- Have durable components that do not degrade and/or can be maintained or repaired in situ.
- Have commercially available plastic foam filled billets as floatation that will not degrade in the marine environment if damaged.
- Separate the work platform from the overall raft design in favour of more comprehensive and modular “work-safe” structures similar to standard construction scaffolding that can be moved from raft to raft.  

The use of existing rotomolded dock floats was determined to be an objective.

Figure 8. Cut-away view of ACE Rotomolded float

This aspect of the design remained controversial within the project. We decided that the addition of walkways into the structure of the raft would significantly add to individual cost and engineering of the rafts. Integral walkways in most cases did not meet emerging worker safety requirements and contributed to poaching and theft as unattended rafts could be accessed. Future work will explore modular work platforms that can be moved from raft to raft.
3.4 Simulation results
The simulation was enhanced by first conducting engineering analyses of the existing wood raft designs being used by industry including trimaran and catamaran designs using 2”x6” wood and newer designs utilizing 2”x10” lumber.

The team also tested the hypothesis of keeping existing designs but substituting wood lumber with non-degradable materials such as plastic wood. The results are summarized in the following tables.

**Existing wood trimaran raft designs**

**Table 1.** Wave propagation hitting the side of the raft (beam waves)

<table>
<thead>
<tr>
<th>Material</th>
<th>Predicted Safety Factor</th>
<th>Failure Axis</th>
<th>Predicted Wing Beam Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x6 hemlock</td>
<td>3.8</td>
<td>1</td>
<td>5.7</td>
</tr>
<tr>
<td>2x6 plastic wood</td>
<td>4.4</td>
<td>1</td>
<td>4.4</td>
</tr>
<tr>
<td>2x10 hemlock</td>
<td>7.9</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>2x10 plastic wood</td>
<td>7.2</td>
<td>1</td>
<td>13.5</td>
</tr>
</tbody>
</table>

**Table 2.** Wave propagation hitting the raft at a 45° angle (beam-head waves)

<table>
<thead>
<tr>
<th>Material</th>
<th>Predicted Safety Factor</th>
<th>Failure Axis</th>
<th>Predicted Wing Beam Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x6 hemlock</td>
<td>2.5</td>
<td>2</td>
<td>6.2</td>
</tr>
<tr>
<td>2x10 hemlock</td>
<td>3.8</td>
<td>2</td>
<td>14</td>
</tr>
</tbody>
</table>

It was determined from the Trimaran raft simulations that:

- Increasing wood height from 2x6 to 2x10 doubles the safety factor (3.8 to 7.9) when encountering beam waves. The failure axis continues to be the primary axis, so the design has been improved by adding beam height.
- Beam-head waves (45°) cause devastating secondary bending.
- Increasing the height from 2x6 to 2x10 **does not** significantly increase beam strength in secondary bending (2.5 to 3.8).
- There is little difference in safety factors between the plastic wood and hemlock.
**Existing wood catamaran raft**

**Table 3.** Wave propagation hitting the side of the raft (beam waves)

<table>
<thead>
<tr>
<th>Material</th>
<th>Predicted Safety Factor</th>
<th>Failure Axis</th>
<th>Predicted Wing Beam Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x10 hemlock</td>
<td>4.2</td>
<td>1</td>
<td>4.8</td>
</tr>
<tr>
<td>2x10 plastic wood</td>
<td>4.2</td>
<td>1</td>
<td>4.1</td>
</tr>
</tbody>
</table>

It was determined from the Catamaran raft simulations that:

- Because of the large unsupported masses hanging off the wing beams, the wing beam safety factor is very similar to the internal safety factor for either material (plastic wood or hemlock).

**Findings**

- Plastic wood and hemlock have very similar safety factors in the simulations.
- Plastic wood is less stiff (more pliable) than wood and simulations show significantly larger beam curvatures. Using fibreglass reinforced plastic wood is not expected to improve safety factors because any imperfections in the bonding will compromise the strength of the beams and will likely fail from fatigue (cyclical) loading.
- To increase the safety factor of a trimaran raft under beam-head waves (45°), it would be necessary to increase the width, as an increase in height does not significantly affect the failure on the secondary axis where the damage is predicted to occur under simulation.
- Under the same beam sizes, the catamaran raft safety factor was significantly less than that of the trimaran. This difference is due to the larger unsupported span of the catamaran raft.

Computer simulations of the existing wood trimaran and catamaran rafts provided details on structural weaknesses and provided a reference point for relative safety factors. Because of the extreme weather conditions that were used (3m waves with 8 second period), future simulations were based on 2m, 6 second period waves, still extreme waves for the majority of the industry’s locations, but a more likely scenario.

The results of these extensive simulations are summarized in Appendix 2.
3.5 Final design and prototype development

After testing more than 30 designs virtually, four final designs based on two styles were developed for physical prototyping and shop drawings to aid construction were produced.

Figure 9. Example shop drawing

Key to the final design is that there are primary structural beams (steel) and secondary interstitial beams. The supporting structure of the rafts is a combination of galvanized steel 4” steel 'T' and 'I' beams, assembled with galvanized bolts in order that rafts can be bolted together onsite with simple tools. Relatively simple fabrication of the steel was required involving only the drilling of holes and welding of small tabs prior to galvanizing the assemblies.

Standard steel stock comes in 40’ lengths and to maximize the use of steel, the raft dimensions were extended to 27.6’ x 27.6’ (2/3’s) of a standard beam. The remaining 1/3’s were then spliced together to make new full (27.6’) beams. This resulted in an expansion of the capacity of the raft while still resulting in a raft that has approximately the same size as a standard raft.
Rotomolded dock floats (billets) manufactured by ACE Roto-Mold and sold by locally Barr Plastics\(^4\) were selected. Six billets (8’x3’x2’) met the requirement for flotation. These were arranged in two groups of 3 to produce a catamaran raft. As no structural advantage was observed in producing a “wing” style raft, the billets were located at the outside of the raft primary cross beams.

The “T” beams are bolted directly to the plastic billets these then are used to support the primary steel cross members which are bolted perpendicular to the T beams. Two styles of raft were designed, one using 5 primary I beams and the other 6 beams.

Tabs welded on the vertical surface of the I beams support “interstitial beams” which extend between the primary beams and are nested within the I-beams. Two types of interstitial beams are being tested, standard wood lumber and plastic wood.

The design intent of the interstitial beam is that the secondary beams provide a designed "weak point". In the case of extreme weather conditions leading to failure these will break losing only a portion of the crop but not the entire raft. As mentioned previously, most traditional rafts use structural beams to deploy product and when they start to fail, the entire structure loses integrity leading to catastrophic failure. This design also allows for a raft to be repaired over its lifetime, another challenge with prior raft designs.

---

\(^4\) [http://www.barrplastics.com/foam_filled_plastic_floats.htm](http://www.barrplastics.com/foam_filled_plastic_floats.htm)
Figure 10. CAD drawing of raft and components

Top: 6 beam raft  
Bottom Left: End view of float and attachment  
Bottom Right: Detail of bolt structure.
3.6 Comparison of prototype styles

Four shellfish raft prototypes have been constructed and deployed at the Deep Bay Field Station, 2 of each version (Raft A and B). A summary comparison is shown in the following table. This analysis includes the potential number of drop lines using just interstitial beams and from the perimeter T beams as well. As well as calculated float submergence for the range of anticipated loading.

Table 4. Comparison of raft prototype styles.

<table>
<thead>
<tr>
<th>Main cross beam component</th>
<th>Raft dimension (feet)</th>
<th>Main beam dimension (in x in x ft)</th>
<th># Main cross beams</th>
<th># Floats</th>
<th>Min # Drop lines</th>
<th>Max # Drop lines</th>
<th>% Submergence (Max)</th>
<th>% Submergence (Min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A -galvanized I beam unequal spacing</td>
<td>27x27</td>
<td>4x4x27</td>
<td>6</td>
<td>6</td>
<td>77</td>
<td>121</td>
<td>87</td>
<td>64</td>
</tr>
<tr>
<td>B -galvanized I beam equal spacing</td>
<td>27x27</td>
<td>4x4x27</td>
<td>5</td>
<td>6</td>
<td>96</td>
<td>144</td>
<td>97</td>
<td>72</td>
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</table>

Computer generated images of the two raft styles showing the locations of shellfish trays below the rafts are shown in the following figures. Full shop drawings are shown in Appendix 4.

3.7 Projected Raft Costs

The component costs of the rafts will be variable on the costs of steel (variable with construction industry) and oil (which affects plastic costs) over time and the number of units purchased at in any order. We also found significant differences in the price of fabrication when bids for our request for tender were received with bids for a single raft ranging from approximately $4,000 to $10,700 per raft...Based on our results we estimate that the prototype designs will cost the following to build (not including HST).

Table 5. Estimate of construction costs per raft.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Steel Fabrication and Galvanizing</td>
<td>$4,000</td>
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<tr>
<td>Hardware</td>
<td>$275</td>
</tr>
<tr>
<td>Floats 6 x 3'x8'x2' Ace Roto-mold'</td>
<td>$2,550</td>
</tr>
<tr>
<td>Lumber – 2x6 lumber</td>
<td>$540</td>
</tr>
</tbody>
</table>

$7,365

<table>
<thead>
<tr>
<th>Construction</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication</td>
<td>$500</td>
</tr>
<tr>
<td>Materials Freight Central Vancouver Island (variable)</td>
<td>$600</td>
</tr>
</tbody>
</table>

$1,100

Total per raft est. $8,465

Note this does not include cost of plastic wood which is estimated to add approximately $1500/raft.
Figure 11. Raft “A” – 6 Beam raft CAD image

Figure 12. Raft “B” – 5 Beam raft CAD image
Figure 13. Photographs of raft construction, launching and installation on research farm.
4.0 Discussion

4.1 What we like about the prototype designs

Achieving goals
Overall, we believe we have been successful in achieving the project objectives. The prototype designs meet the project goals of:

- Both raft styles are approximately 1mx1m larger than existing designs (8mx8m), with more capacity (>80 tray droppers and >12,000 lbs).
- May be able to be moored in a similar fashion to existing designs
- The design is as simple as possible with few “custom parts” and structures that could be assembled by farmers with a minimum of tools on-site.
- Have integral structure constructed from a non biodegradable materials virtually tested to be capable of withstanding normal to significant weather conditions.
- The designs of the isolate the structure of the raft from the components that physically suspend the culture stock so that failure of components suspending stock does not contribute to overall raft failure.
- Have durable components that do not degrade and/or can be maintained or repaired in situ. We expect the lifespan of this raft to be more than 3x the current wood based designs.
- Have commercially available plastic foam filled billets as floatation that will not degrade in the marine environment if damaged.

Overall Comments
The virtual design process proved to be highly effective to work through a range of options without having to build and test and allowed us to analyze existing designs and use them as benchmarks. This greatly informed the design process.

Overall the design meets our intent of remaining as consistent as possible with existing sizes while increasing the size slightly to maximize the use of materials. We believe that the combination of steel structural beams and “weaker” interstitial beams provides a good compromise between required structural strength (expensive) and keeping costs to a minimum (replaceable wood interstitial beams).

Any such design exercise such as this is a series of compromises. Cost as expressed by the industry consultations was repeatedly raised by the most critical factor that would prohibit industry uptake. The design process therefore resulted
in the design that utilized the minimum amount of materials that would still result in the required strengths and rejected more elaborate designs or more expensive materials that would have significantly increased safety factors.

As discussed previously, the prototype designs differ from most existing designs in that we have chosen to separate the work platform from the overall raft design. This will require that separate work platforms are either affixed on a permanent or temporary basis to the rafts. We decided that the addition of walkways into the structure of the raft would significantly add to individual cost and engineering of the rafts and perhaps were not the best design solution.

During the project we noted that this design approach was consistent with the approach taken with other advanced international designs. We also noted that worker safety issues have not received much significance in prior raft designs. Like salmon pens which now have railings and other safety features, we believe that this will be an emerging issue in the advancement of the industry. Integral walkways in most cases did not meet emerging worker safety requirements and may contribute to poaching and theft, as unattended rafts may be more easily accessed.

As a result, the final design approach rejected integral walkways in favour of modular "work-safe" work platforms that can be moved from raft to raft. Future work will explore the adaptation of standard scaffolding style components used in the construction industry and their adaptation to raft work platforms that can be moved from raft to raft as required.

4.2 What we don’t like about the prototype design

The following observations have been made to date during the testing process.

- Engineering specifications indicate that 2x4 standard lumber is suitable for the secondary interstitial beams. It is our opinion that 2x6 material with the ends notched to fit within the inner portion of the I beam is more suitable.

- We believe that the tabs which hold the interstitial beams may be improved by having a larger connection to the wood and that bolts may be more appropriate than screws. Alternately placing short pieces of 2x4 within the I-beam between the secondary beams can be used to “lock” the secondary beams into place.
Plastic lumber provided the strength and the durability required. However we noted that it added substantially to the cost (>\$1500/raft). As well, we noted that the 2x4 plastic lumber was prone to excessive bending in the secondary axis and do not recommend it as a result.

To date both raft styles have performed equally well in testing. Our personal preference is for the five beam version as it only uses one length of interstitial beam and has less steel. This raft does have reduced capacity.

We have noted that the addition of integral vessel tie-up cleats to the T-beams would assist when working with the rafts. We recommend adding this to future rafts as an option.

4.3 Future work

Our future work will be to continue testing of the rafts over long term and demonstrate these to industry. Feedback received from testing and from industry comments will be used to inform future iterations of these prototypes and the adoption of these designs into standard industry use.

As discussed previously, developing a modular “work-safe” platform that can be easily moved from raft to raft will facilitate the use of these designs. Our future work will investigate options for platforms that are guided by standard construction industry scaffolding technologies which meet worker safety standards.
### Appendix 1 – Summary material analysis:

<table>
<thead>
<tr>
<th>Main cross beam component</th>
<th>Raft dimension (feet)</th>
<th>Main beam dimension</th>
<th># Main cross beams</th>
<th># Floats</th>
<th>Min # Droplines</th>
<th>Max # Droplines</th>
<th>Frame beam lateral stress &gt;50% total</th>
<th>Interstitial beam</th>
<th>Whole raft</th>
<th>% Submergence (Max)</th>
<th>% Submergence (Min)</th>
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<tr>
<td>standard wood trimaran</td>
<td>24x24</td>
<td>2x6x24</td>
<td>N/A</td>
<td>Variable</td>
<td>80</td>
<td>80</td>
<td>1.7</td>
<td>N/A</td>
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<td>Main beam dimension</td>
<td># Main cross beams</td>
<td># Floats</td>
<td>Min # Droplines</td>
<td>Max # Droplines</td>
<td>Frame beam Initial beam</td>
<td>Whole raft Frame beam lateral stress &gt;50% total</td>
<td>% Submergence (Max)</td>
<td>% Submergence (Min)</td>
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</tbody>
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**Appendix 2: Materials tested for frame component suitability for a 27’x27’ raft**

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<th>Material and form</th>
<th>Dimension</th>
<th>Suitability as frame component</th>
</tr>
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<tbody>
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<td><strong>Aluminium</strong></td>
<td></td>
<td></td>
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<tr>
<td>H beam</td>
<td>4”x4”</td>
<td>Cost prohibitive</td>
</tr>
<tr>
<td></td>
<td>5”x4”</td>
<td>Safety factor too high</td>
</tr>
<tr>
<td></td>
<td>6”x3.5”</td>
<td>Safety factor too low</td>
</tr>
<tr>
<td><strong>Steel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe</td>
<td>3”x0.125”</td>
<td>Lateral strength excess</td>
</tr>
<tr>
<td></td>
<td>3”x0.375”</td>
<td>Lateral strength excess</td>
</tr>
<tr>
<td></td>
<td>4.5”x0.375”</td>
<td>Lateral strength excess</td>
</tr>
<tr>
<td></td>
<td>4.5”x0.75”</td>
<td>Lateral strength excess</td>
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<td>Lateral strength excess</td>
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<td>12”x0.25</td>
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<td><strong>S beam</strong></td>
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### Hemlock

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<tr>
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<td>5”x10”</td>
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### Structural plastic wood

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<td>2”x8”</td>
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<td>2”x10”</td>
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<td>3”x6”</td>
<td>Safety factor too low</td>
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<tr>
<td>3”x7”</td>
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<tr>
<td>3”x10”</td>
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<tr>
<td>4”x8”</td>
<td>Safety factor too low</td>
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Appendix 3: Fabrication pictures

![Fabrication pictures](image)

**Figure 14.** Raft components being fabricated at Advanced Integration Technologies
Appendix 4; Raft Plan documents

(attached as PDF)

**PLEASE NOTE**: The designs which follow are prototypes still under testing and are provided "as is" and without warranties of any kind whether express or implied. Vancouver Island University disclaims all warranties express or implied and does not make any warrantees or representations regarding the use of the designs in terms of their correctness, accuracy, adequacy, usefulness, timeliness, reliability or otherwise. Vancouver Island University may not be held liable for any damages (including, without limitation, incidental and consequential damages, personal injury/wrongful death, lost profits, or damages resulting from the use of these designs.)
Description:
These drawings are for the fabrication of prototype shellfish cultivation rafts.
There are two raft designs, Raft A, and Raft B.

Because the only difference between the raft designs are the layout of the
"Frame Beams," the only raft-specific parts are the "T Beams" that have the
bolt holes for Frame beam mounting. To save on material costs, the rafts utilize
structural members that are 2/3 of standard 40ft lengths. Extra 1/3's of the 40ft
lengths are utilized by splicing two 1/3 lengths into 2/3 lengths. The Frame beam
splice is a welded joint with caps on the flanges.

All material is to be galvanized. Assembled onsite.

For Technical Questions Please Contact
Scott Beatty, Research Engineer,
Dynamic Systems Analysis,
250 472 4323,
scott@dsla-ltd.ca

For Administrative Questions Please Contact
Joy Wade
Centre for Shellfish Research
Vancouver Island University
250 740-6399
Joy.Wade@viu.ca

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Barr Plastics Float Drums x 6
Part Number: 3624-96

Detail A: Frame Beam Connection
3/4 in Thru Holes
4 per side of raft for mooring shackles

Detail B: Pontoon End View

Updated to reflect series of changes
R3 Added location dims for shackle hole in Detail A

2009.12.09
MAT'L: Hot Rolled ASTM A572 GR50/A992
Wide Flange W8x13 split into T Beam

**All Hole Loc. Dims Symmetric about Mid-Span**

Reference dims for hole to edge clearance given in Detail A

**Details:**
- 12 FB clamp holes diameter increased to 27/32" (0.8438) THRU TYP x 12
- 15 Float mount holes specified to 9/16" (0.563) THRU TYP x 15

**Reference Dimensions for Hole to Edge Clearance:**
- 5.50 (REF) TYP

**Scale:** SJB 2009.12.09
Hole Locations and Sizes
Identical As per Drawing 06A

Detail B:
Splice Side View

MAT'L: Hot Rolled ASTM A572 GR50/A992
Wide Flange W8x13 split into T Beam

ALL DIMS IN INCHES UNLESS OTHERWISE SPECIFIED

07A - TBeam Spliced

R2 SJB 2009.12.09
**Hole Locations and Sizes**

Identical As per Drawing 06A

**Description**

Flange and Web Splice Plates removed

Splice Joint as butt weld all around.

**Dimensions**

- Flange: 320
- Web: 160

**Material**

Hot Rolled ASTM A572 GR50/A992

Wide Flange W8x13 split into T Beam

**Scale**

SJB 2009.12.09

**Notes**

- All dims in inches unless otherwise specified.
Description:
These drawings are for the fabrication of prototype shellfish cultivation rafts. There are two raft designs, Raft A, and Raft B. Because the only difference between the raft designs are the layout of the “Frame Beams,” the only raft-specific parts are the “T Beams” that have the bolt holes for Frame beam mounting. To save on material costs, the rafts utilize structural members that are 2/3 of standard 40ft lengths. Extra 1/3’s of the 40ft lengths are utilized by splicing two 1/3 lengths into 2/3 lengths. The Frame beam splice is a welded joint with caps on the flanges. All material is to be galvanized. Assembled onsite.

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For Administrative Questions Please Contact
Joy Wade
Centre for Shellfish Research, Vancouver Island University 250 740-6399, Joy.Wade@viu.ca

Numbering Scheme:
##A denotes a drawing specific to Raft A,
##B denotes a drawing specific to Raft B,
## denotes a drawing shared by both Rafts.

RAFT A Specific Drawings:
00A_Raft_A_Bill_of_Materials
00A_Raft_A_Overview
06A_TBeam_Basic
07A_TBeam_Spliced

RAFT B Specific Drawings:
00B_Raft_B_Bill_of_Materials
00B_Raft_B_Overview
06B_TBeam_Basic
07B_TBeam_Spliced

Drawings Shared by Raft A and Raft B
01_Basic_Frame_Beam
02_Spliced_Frame_Beam_Assy
03_Splice_Flange_Plate
05_FB_Clamp_Plate

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<td>As Per Dwg 01-Basic Frame Beam</td>
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<td>3</td>
<td>Frame Beam Full (W4x13 Structural Steel) 26.67ft - 2/3 of a 40ft length.</td>
<td>2.0</td>
<td>As Per Drawing: 03-Splice Flange Plate</td>
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<tr>
<td>6</td>
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<td>Frame_Beam_Splice_Cap</td>
<td>2.0</td>
<td>As Per Drawing: 05 - Clamp Plate</td>
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<tr>
<td>8</td>
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<td>Frame Beam Clamp Plate</td>
<td>2.0</td>
<td>As Per Drawing: 06B- TBeam Basic</td>
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<td>16</td>
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Detail A:
Frame Beam Connection

3/4 in Thru Holes
4 per side of raft for mooring shackles

Detail B:
Pontoon End View

Barr Plastics Float Drums x 6
Part Number: 3624-96

ALL DIMS IN INCHES UNLESS OTHERWISE SPECIFIED
**Details A**

- **Drilled Through hole sizes updated**
  - See Detail A

- **Fixed small error in Ordinate Dimensions**
  - For frame beam clamp holes. Dimes are now symmetric about midspan

**Specifications**

- **Material:** Hot Rolled ASTM A572 GR50/A992
- **Wide Flange W8x13 Split into T Beam**

**Dimensions**

- **320.0 (26.67 ft or 2/3 of Std 40ft length)**

---

**Notes**

- **ALL DIMS IN INCHES UNLESS OTHERWISE SPECIFIED**

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**Revisions**

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<td>2010.01.15</td>
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**Drawing Information**

- **DRAW NO.**
- **REV DESCRIPTION**
- **SCALE**
- **DATE**
- **APPROVED**
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<td>Flange and Web splice plates removed, replaced with butt weld all around (see Detail B)</td>
<td>2009.12.09</td>
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<td>Drilled hole sizes increased (see Detail C)</td>
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<td>R3</td>
<td>Fixed small error in frame beam clamp holes: Ordinate dimensions are now symmetric about mid-span as intended</td>
<td>2010.01.15</td>
<td>SJB</td>
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### Details

**Detail B:**
- Splice Side View
- Ø 9/16" (0.563) THRU TYP x 15 Holes
- Ø 27/32" (0.8438) THRU TYP x 10
- 5.50 REF
- 0.750

**Detail C:**
- 5.50 REF
- 0.25

**Notes:**
- Flange and Web splice plates removed, replaced with butt weld all around (see Detail B).
- Drilled hole sizes increased (see Detail C).
- Fixed small error in frame beam clamp holes: Ordinate dimensions are now symmetric about mid-span as intended.

**Sheet:**
- **07B - TBeam Spliced**
- **R3**
- **SJB 2009.12.09**
- **Sheets**
Weld-on Tabs placed on both sides of web (as per Detail A).
Fillet Welds all around web/tab interface (sealed for galvanization).
Tab locations dimensioned to inboard edges.
18 Tabs, 18 Fillet Welds.

MAT'L: Hot Rolled W4x13 Steel Beam

*DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED

**REVISIONS**

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320 Two W4x13 x 160in segments spliced at midspan.

Flange Splice Plates x 2
Hot Rolled 3/8 x 3.5 x 16in

*Weld-on Tabs x 8, only on one-side of spliced beams

Detail A: Weld-on tab locations
given to inboard edges
Placement symmetric about mid-span

Detail B: Beam Splice
Welded butt joint: beveled edges with a 1/8" root gap
100% weld penetration with back grinding.
Welded Splice plates on flanges: 1/4" fillet all around

*ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED

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All drilled holes removed, material width reduced from 4.5 to 3.5in to accommodate fillet weld.

MATERIAL: HOT ROLLED 3/8 x 4.5 ASTM A-36 Steel

*ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED*
Drilled hole sizes increased from 0.75 CLR to 27/32 to accommodate galvanization thickness

HOTROLLED ASTM A-36
3/8 X 1.5 STEEL

ALL DIMENSIONS IN INCHES