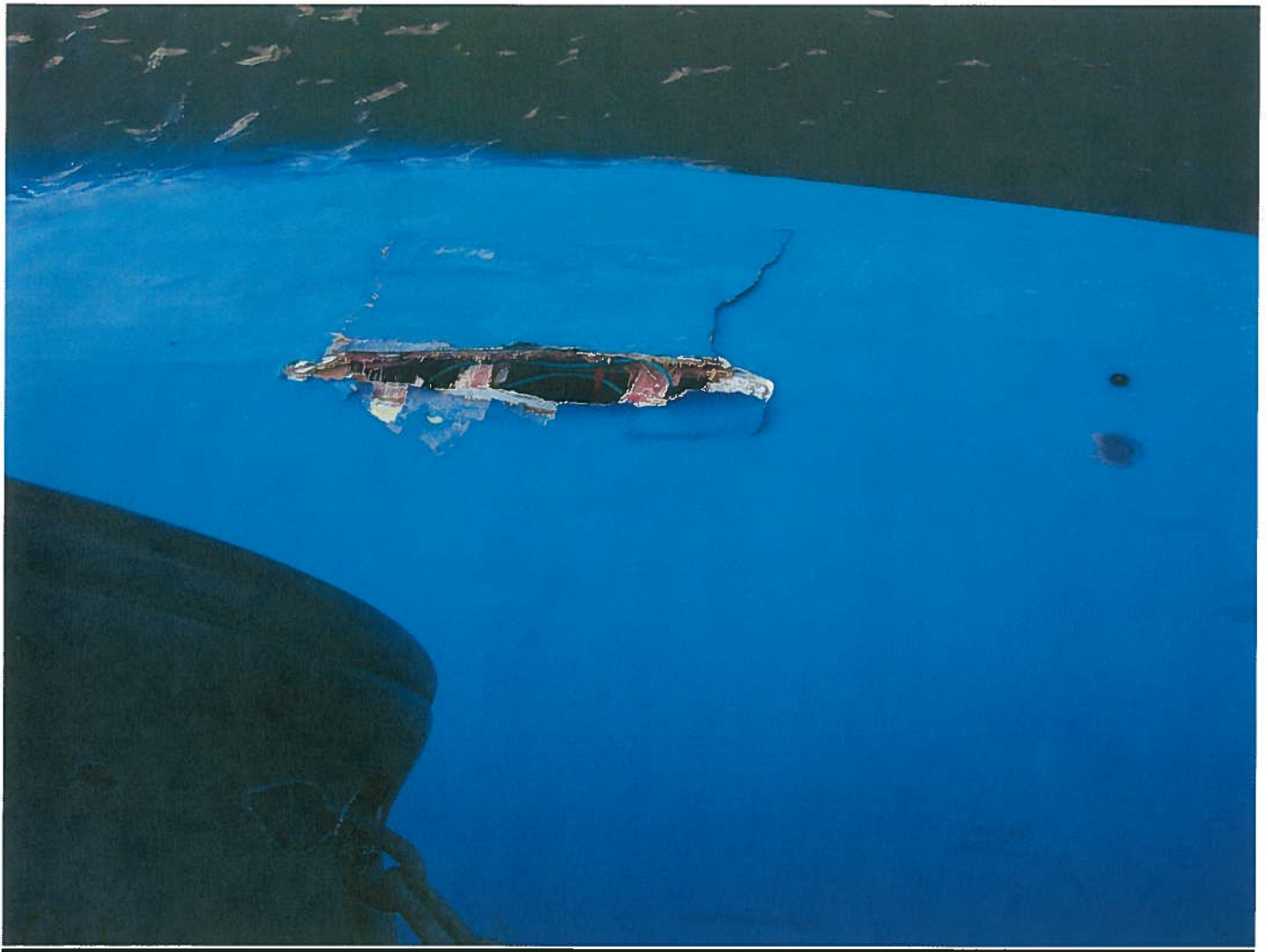


# Appendix E

## Dobroth Design, Inc. Science Report

# Science Report

*S/V Cynthia Woods*



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**The purpose of this Science Report is to examine why the keel-to-hull joint of the S/V *Cynthia Woods* failed catastrophically, thereby causing the keel to fall off the vessel during a race. The firm was retained by Texas A&M University at Galveston to determine the cause of the accident.**

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Nastran Finite Element Analysis-Complete Report	

## *Glossary Of Abbreviations And Acronyms*

ABS	American Bureau of Shipping
CW	<i>S/V Cynthia Woods</i>
FRP	Fiber Reinforced Plastic
h	Frame height
ISAF	International Sailing Federation
NOR	Notice Of Race
SM	Section Modulus, an indicator of strength
T1	Thickness of the side of the frame
T2	Thickness of the top of the frame
VCG	Vertical Center of Gravity = 40.85 inches measured from the top of keel
Wk	Weight of Keel =4870 lbs. stamped on keel (actual wt. greater)

## Executive Summary

On 6 June 2008, the location transponder on the yacht, *S/V Cynthia Woods*, a Cape Fear 38R, stopped moving during the XXI Regatta de Amigo. When the yacht was located, it was overturned, full of water, with a hole where the keel had been attached to the hull. The yacht's keel was missing. At approximately 2:00 a.m., Sunday, June 08, 2008, the U.S. Coast Guard located five of the six missing crew members: students Joe Savana, Steven Guy, Ross Busby, and Travis Wright, and safety officer Steven Conway. The U.S. Coast Guard later found the second Safety Officer, Roger Stone, who did not survive the accident.

The purpose of this report is to examine why the keel fell off the *S/V Cynthia Woods* and why the keel joint failed catastrophically.

The *S/V Cynthia Woods* is a production boat. The *American Bureau of Shipping Guide for Building and Classing Offshore Racing Yachts (1994)* ("ABS Guide") is used as the basis of this report because the yacht was required to pass its standards. The ABS Guide is required by the International Sailing Federation for all offshore sailboat races, including the Regatta de Amigo. The *Principles of Yacht Design*, by Larsson and Eliasson, is used as a reference in this report as another current reference on yacht design and structure. The Patran Finite Element Analysis (FEA) program, an industry standard for the examination of any material structures, is used as a reference in this report after a computer model was created for this study and report.

The *S/V Cynthia Woods* accident was caused by the keel ripping off the hull "in shear." The boat was not adequately designed and built. While the boat had many deficiencies, as detailed later in this report, the two primary deficiencies that caused the keel to fail were:

1. A direct result of a significantly inadequate amount of hull fiberglass laminate material at the keel joint when the sailboat was built. Material fatigue (material loss of strength as the material ages in service) likely played a significant role in the failure. This failure in construction was in direct violation of the requirements of the ABS Guide, the accepted standard of construction for all yachts in the race in question and for all offshore sailboat races in the United States, and most countries around the world. ABS Guide Rule 7.3.1 requires minimum bottom shell thickness to be at least the thickness of the diameter of the keel bolts. The bottom shell was as thin as  $\frac{1}{2}$  to  $\frac{9}{16}$ " and the keel bolts were  $1\frac{1}{2}$  inches. The minimum bottom shell thickness is  $1\frac{1}{2}$  inches. ABS Guide Rule 9.13.3a gives a bottom thickness of 3.11 inches mainly due to the narrow backing plates.

2. ABS Guide Rule 9.13.3a states that the allowable shear stress is 0.5 times the minimum ultimate shear stress of the material. The allowable shear stress is therefore  $0.5 * 14,000$  psi, which is 7000 psi. The average shear stress calculated is 9,178 psi, and the FEA has a peak shear stress of 21,785 psi on the middle backing plate, due to the torsion from the bulb on the keel. This would require a hull thickness of  $(21,785 \text{ psi} / 7,000 \text{ psi}) = 3.11$  inches. This number is even greater than the minimum hull thickness of 1.5 inches determined in number 1 above. Using the *as-built* hull thickness of 0.56 inches gives a safety factor of 0.32. A 0.32 factor of safety is inadequate for safety on the hull and caused the failure.

The March 2007 repair work by the students of TAMUG was performed on hairline cracks on three frame intersections on two frames. This was performed in a workmanlike manner. This work, which had been performed about one year before, is still intact on the boat and available for inspection. Moreover, the three cracks repaired by the students had absolutely no relationship to the inadequate laminate material thickness at the keel/hull joint where the failure occurred.

The following table shows a summary of the engineering conclusions which are supported through documents that follow:

## S/V Cynthia Woods Engineering Table

Three standard marine industry resources were used to analyze the design and construction of the S/V Cynthia Woods:

1. American Bureau of Shipping Guide for Building and Classing Offshore Racing Yachts (1994) ("ABS Guide")
2. *Principles of Yacht Design* (Larsson and Eliasson)
3. Patran Finite Element Analysis Program

1.	<u>ABS Guide</u>	<u>Result</u>
	Rule 6.1.3 Fiber-Reinforced Plastic (sides of framing)	FAIL
	Rule 6.3.1 Keel Bolts	PASS
	Rule 7.3.1 Single-Skin Laminate	FAIL-CAUSE OF FAILURE
	Rule 9.13.3 Structure – Transverse Load	FAIL
	Rule 9.13.3 Structure – Grounding Conditions	FAIL
	Rule 9.13.3 Structure – Shear Loading Vertical	PASS
	Rule 9.13.3 Structure – Shear Loading Heeling	FAIL-CAUSE OF FAILURE
2.	<u>Principles of Yacht Design</u>	<u>Result</u>
	Minimum Transverse Frame Sectional Modulus	FAIL
	Minimum Frame Size for Grounding	FAIL
	Required Area for Keel Bolts (forward 25% area)	FAIL
3.	<u>Patran Finite Element Analysis</u>	<u>Result</u>
	Model built and finite element analysis	FAIL

Framing Strength Analysis	<u>Result</u>
A. Required Section Modulus-ABS Guide	61.15
B. Required Section Modulus- <i>Principles of Yacht Design</i>	71.89
C. Section Modulus "As-Built" by manufacturer	<b>11.29</b>

Safety Factor Analysis	<u>Result</u>
A. Required by ABS Guide	2.0
B. Required by <i>Principles of Yacht Design</i>	4.0 – 6.0
C. "As-Built" Safety Factor used by manufacturer	<b>0.32</b>

*Important Note:* ABS Guide Rule 9.13.3 requires a hull safety factor of 2.0. However, most marine engineers use a safety factor of 4.0 or more for the hull because it is the most critical feature of a sailboat. This industry standard is consistent with the ABS Guide bolt requirements (Rule 6.3.1) which use a safety factor of 4.0.

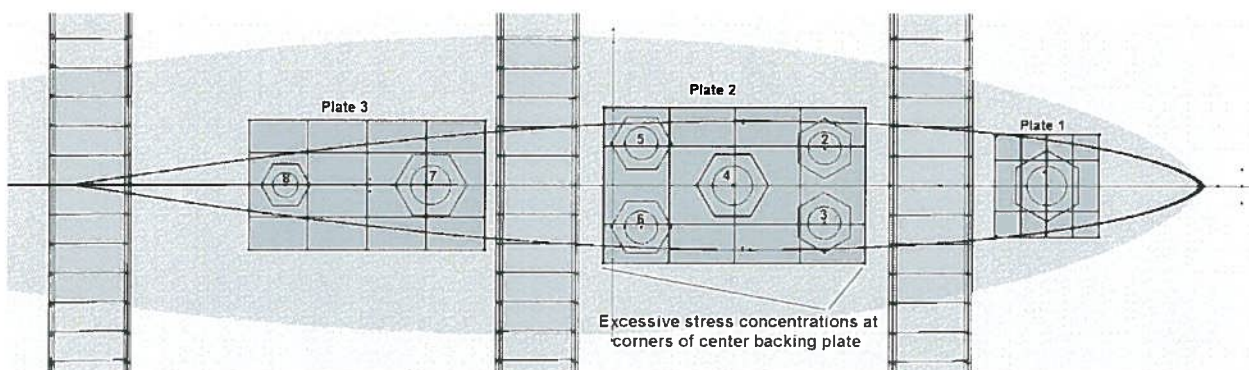


Sailboats, especially racing sailboats, run aground often. They are designed and built so that their keels do not fall off. The *S/V Cynthia Woods* had some well-documented grounding. After one grounding incident, there was some repair work done which is common in the industry. There are pictures in this report showing the *S/V Cynthia Woods'* keel after one such grounding. See page 21. One photograph shows common, non-structural damage to the trailing edge of the keel which is reduced to nearly zero thickness and has no attaching bolts. Lead is a soft material which deforms easily. The suggestion that had it been extensively inspected after grounding it would have been repaired differently is not only wrong, it runs counter to standard industry practice. No person inspecting the *S/V Cynthia Woods* during repair would have been able to conclude this boat was not properly designed and built without completely re-engineering the boat. Boatyards, and especially insurance companies, rarely, if ever, consult with the original design engineer. It is standard practice in the marine industry, adopted by boatyards, to accept that the yacht structure was engineered properly and built to the specifications of the naval architect. Boats are repaired by boatyards to be returned to "as-built" condition. The boatyard cannot and does not interpose its own opinion of engineering structural sufficiency for that of a more highly-qualified professional like a naval architect or marine engineer.

A boatyard did most of the keel repair work (removal and reattachment) and some Texas A&M students completed the internal repair work for some minor frame cracks. The keel frame sides as designed and initially built on the boat did not meet ABS Guide standards or standard engineering practice; *the students' repairs to the keel frame sides were done to industry standards, the material replaced was equivalent to the damage.* There is a section on grounding later in the report. See page 20.

*It is very important to note that the minor cracks repaired by the students are still intact in the boat. These repairs had nothing whatsoever to do with the keel failure.* See top photo at page 39.

The keel failure of the *S/V Cynthia Woods* was caused by a significantly insufficient lack of hull thickness through the keel attachment area. The hull where the keel was attached was built to thickness of about 0.54 to 0.58" with 1.5" bolts through the thin laminate. The bolts had unusually small backing plates. This design/build did not pass any of the critical standards used for offshore racing boats. The ABS Guide called for a minimum laminate thickness of 1.5 inches with large tapers in the laminate, which were also not present in the hull. The top of the keel had an unusual centerline split-bolt combination holding the keel to the hull of the yacht. Backing plate #2 (see diagram below) was too narrow—in one instance (bolt #6), the bolt washer actually extended beyond the edge of the plate next to one corner of the split bolt backing plate. See photo at page 19. Backing plate #2 had very high stress concentrations in the corners, which acted like an old style can opener, shearing right through the hull. The hull's fiberglass laminate under backing plate #2 was insufficient to hold the keel bolts. The bolts' sizes that were required by the ABS Guide were more than twice as strong as the shell of the hull. The highly overloaded backing plate fractured the boats' thin fiberglass hull laminate "in shear." A shearing load is like a pair of scissors (pair of shears). As all boats are used in service, the fiberglass laminate starts to fatigue and lose strength. Designers and manufacturers should account for this loss of strength. There is a section in this report on Fatigue and Safety Factors. See page 25.



There is an original keel drawing in this report. See page 28. The original Cape Fear 38 boats had about one (1) inch of hull laminate with one (1) inch keel bolts. This report does not address or comment upon the structure of the original Cape Fear 38 boats. The later boats, like the *S/V Cynthia Woods*, were built with a much thinner structural hull fiberglass laminate of just over ½ inch with much larger 1 ½ inch bolts accommodating the larger holes that needed to be drilled through thinner hull fiberglass laminate. The later boats also had a deeper keel which put much higher loads on the thinner hull structure around the keel. Furthermore, none of the attachment framing in the later Cape Fear 38 boats seems to have been changed, so the deeper, higher loaded, small footprint keel, which spanned less structural framing, created even more stress on the hull laminate.

**After some sailing time on any identical sister boat, whether or not the boat ever runs aground, the exact same failure will occur. This design/construction combination is not seaworthy.**



## Notice of Race, ISAF, ORC and ABS Guide Requirement

The Rules of the Regatta de Amigos Race specifically required **all** sailing yachts in the race to conform to the ABS Guide.

### XXI Regatta de Amigos **NOTICE OF RACE** **June 6<sup>th</sup>-14<sup>th</sup>, 2008**

Of particular significance in the Notice of Race is the requirement for the 2008 Category 1 International Sailing Federation Special Regulations:

#### **SECTION 1 – RULES:**

The regatta will be governed by The Racing Rules of Sailing (RRS) 2005-2008 including US SAILING Prescriptions, **the 2008 Category 1 International Sailing Federation Special Regulations, aka Offshore Racing Congress (ORC) Special Regulations**, PHRF of Galveston Bay and by this Notice of Race and the Sailing Instructions. LYC and GBCA reserve the right to amend this Notice of Race and Rules by the Sailing Instructions. The ORC Category 1 requirement for uncoated lifelines under section 3.14.6a is waived. Lifelines shall, in all respects, conform to Section 2.03.1 of the General Requirements.

Below is ISAF ORC Rule 3.03.1 showing the ABS Guide requirement for boats. This requirement is universal. It is used in every United States, European and Asian sailboat race. Very few boats have a CE mark, and every boat passes the ABS Guide rules. The ABS Guide statements or certificates are usually supplied with the boat owners' manual.

#### **ORC Section 3.03.1**

A yacht defined in the table above shall have been designed and built in accordance with either:

MoMu0,1,2

a) the EC Recreational Craft Directive for Category A (having obtained the CE mark), or

MoMu0,1,2

b) **the ABS Guide for Building and Classing Offshore**

**Yachts** in which case the yacht shall have on board either a certificate of plan approval issued by ABS, or written statements signed by the designer and builder which confirm that they have respectively designed and built the yacht in accordance with the ABS Guide,

MoMu0,1,2

c) **except that a race organizer or class rules may accept other evidence of suitability of design and build when that described in (a) or (b) above is not available, provided that the requirements of (a) or (b) have never been refused due to unsuitability of the boat.**

The **orange type** in the rule book designates a special rule. This subsection "C" refers exclusively to races like the Volvo Round the World Race, which has its own set of structural rules and it does not apply to boats entered in the Regatta de Amigos.

### Minimum Hull Thickness at Keel Bolt Holes - ABS Rule 7.3.1

**Failure to meet this requirement is the first primary cause of the keel failure on the S/V Cynthia Woods.**

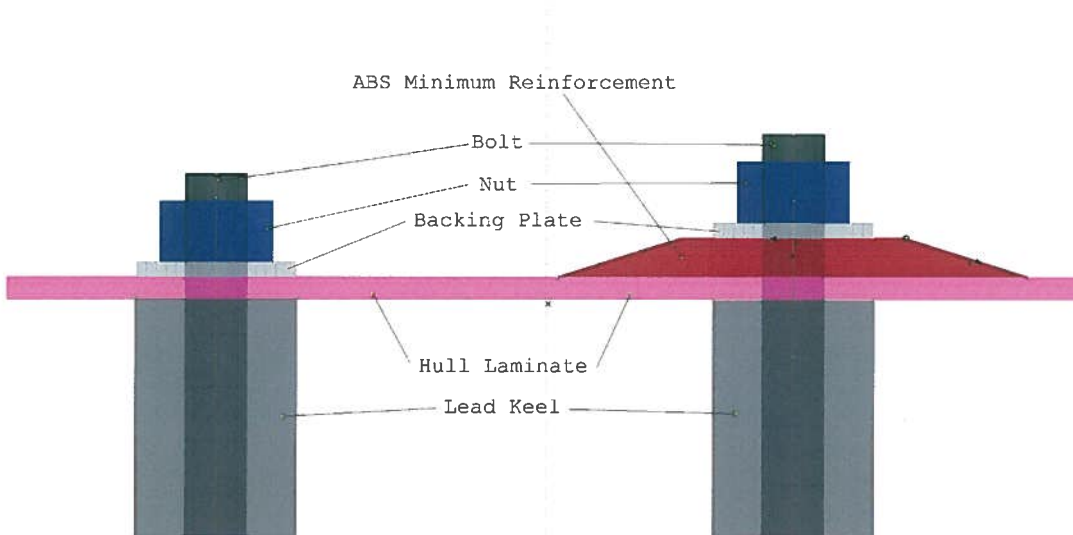
The ABS Guide establishes for every sailboat the minimum hull thickness at the keel joint. The “as-built” cross section for the S/V Cynthia Woods, shown on the left side of the diagram below, cannot possibly hold a keel on to boat. This would be the “**common sense**” rule, particularly in a structure as highly loaded and critical as in the hull to keel joint. If you are going to cut away a large area for a structural bolt, at least have a lot of material around it to hold it.

**ABS rule 7.3.1** *The bottom shell thickness is to be increased for the extent shown, and using the design heads given on Figures 7.1 and 7.2. In addition, the thickness of the bottom shell extending over the length of the keel attachment to points 50 mm (2 in) forward and aft of the forward and aft keel bolts, respectively, and 50mm (2 in) outboard of the bolts is not to be less than the diameter of the keel bolts. Bidirectional laminates are in general to be used, Bi-directional laminates are to be used also in way of local reinforcements for chain plate and other load-carrying fittings. Care is to be taken to provide a gradual transition in fiber reinforcement between hi-directional and uni-directional laminates to avoid abrupt changes in strength and stiffness.*

In addition ABS 5.3.2 b states:

*Transitions in laminate thickness are to be tapered over a length not less than three times the thickness of the thicker plate. A gradual transition in fiber reinforcement is to be provided between bi-directional and uni-directional laminates.*

**Diagram of forward keel bolt (backing plate #1)**

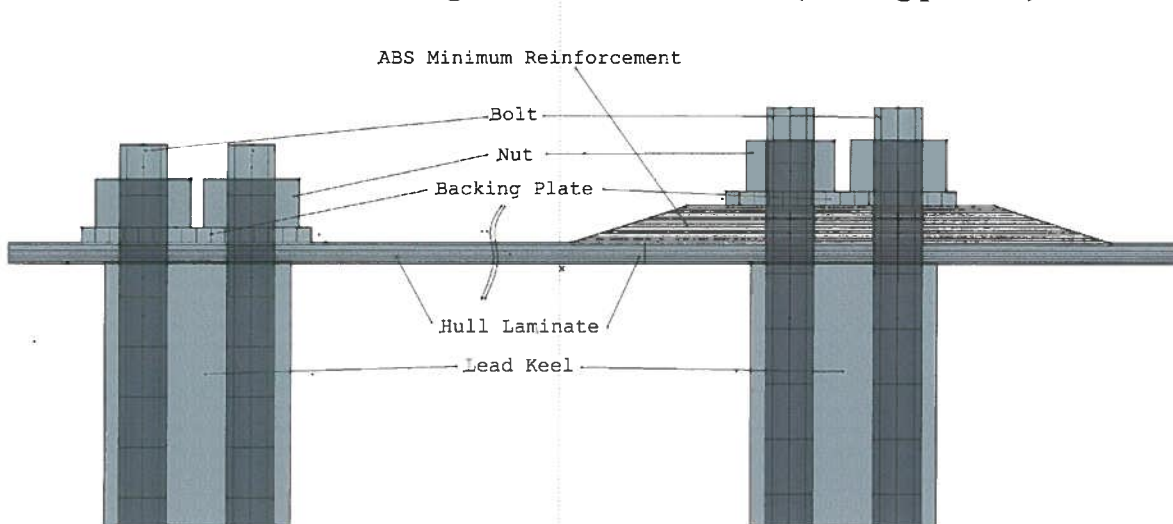


**As-Built Cynthia Woods**

**Absolute Minimum ABS Laminate**

Cross section on left shows the S/V Cynthia Woods as-built at the forward keel bolt. This shows a 1 ½ inch bolt though a thin (slightly greater than one-half (½) inch) layer of fiberglass hull laminate. On the right is a cross section showing the ABS Guide minimum of 1 ½ inches of reinforcement with the 1 ½ inch bolt. The 3 to 1 taper shown (ABS Guide Rule 5.3.2 b) is rarely used; most builders taper this laminate build-up over several feet.

### Diagram of center keel bolts (backing plate #2)



#### As-Built S/V Cynthia Woods

#### Absolute Minimum ABS Laminate

Cross section at a pair of split bolts (split from centerline) like those that were used at plate #2. The left shows the S/V *Cynthia Woods* as-built. It is at the edge of the backing plate that the keel laminate first failed. The diagram on the right above shows the minimum laminate that is required by the ABS Guide.



**Photo.** This photo is taken from the side of the keel. The picture shows a 1 ½" bolt through ½" to 9/16" of hull laminate. Backing plate is 3/8" thick for comparison. The pink colored material is the fiberglass laminate which is just a little thicker than the plate. The plate does not add strength, it is used to distribute load. The blue is the keel. You can see the sheared (clean, straight cut) fiberglass laminate.

### Allowable Stresses for Materials Used-ABS Rule 9.13.3

Base Laminate Properties			ABS Rule 9.13.3			
		ABS	CW	Max Allowable	Carbon	Carbon
Flexural Strength	F	25000	48500			
Flexural Modulus	Ef	1.1*10 <sup>6</sup>				
Tensile Strength	T	18000	35000	12250	55000	19250
Tensile Modulus	Et	1.0*10 <sup>6</sup>				
Compressive Strength	C	17000	33000	11550		
Compressive Modulus	Ec	1.0*10 <sup>6</sup>				
Shear Strength perpendicular Warp	Sppw	11000	14000	4900		
Shear Strength parallel Warp	Sphc	9000	14000	4900		
Shear Modulus parallel Warp	Es	0.45*10 <sup>6</sup>				
Interlaminar Shear Strength	Si	2500				

### **ABS rule 9.13.3 all keel component must use**

**0.35 ultimate shear stress and 0.35 ultimate primary stress for grounding**  
**0.50 for transverse loads**

Grade	Tensile Strength (MPa) min	Yield Strength 0.2% Proof (MPa) min	Elongation (% in 50mm) min	Hardness	
				Rockwell B (HR B) max	Brinell (HB) max
304	515	205	40	92	201
304L	485	170	40	92	201
304H	515	205	40	92	201

304H also has a requirement for a grain size of ASTM No 7 or coarser.

#### **1. Mechanical Properties at Room Temperature**

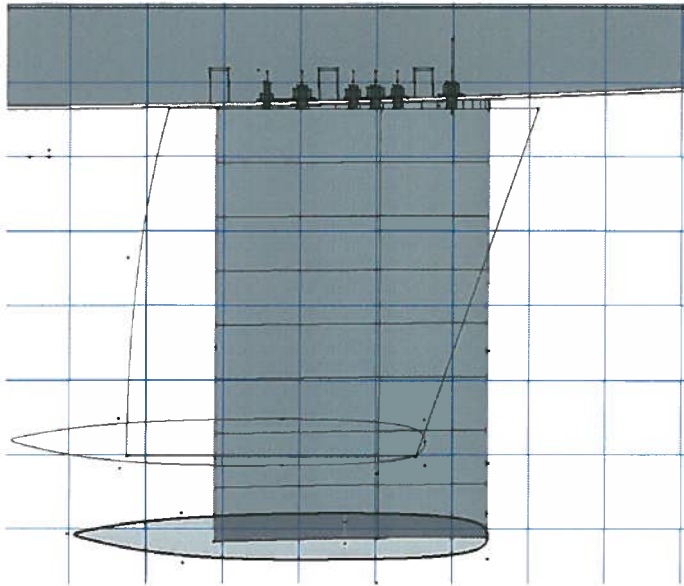
	304		304L	
	Typical	Minimum	Typical	Minimum
Tensile Strength, MPa	600	515	590	485
Proof Strength, (Offset 0.2 %), MPa	310	205	310	170
Elongation (Percent in 50mm)	60	40	60	40
Hardness (Brinell)	170	-	170	-
Endurance (fatigue) limit, MPa	240	-	240	-

**Principles of Yacht Design** establishes that the Section Modulus (indicator of strength) of the S/V *Cynthia Woods*' frames should be 71.89 for grounding and 27.44 for heeling forces. The actual calculated Section Modulus of the vessel's frames is 11.29 and 10.58, respectively. (See page 13).

<u>From Principles of Yacht Design</u> by Larsson and Eliasson			
FORCES FROM THE KEEL	YD-40 metric	YD-40 english	Cynthia Woods
(transverse heeling)			
CGdk	0.7 m	27.559 in	40.85 in
g	9.8 m/s <sup>2</sup>	32.2 ft/sec <sup>2</sup>	32.2 ft/sec <sup>2</sup>
Wblst	3253.353 kg	7172 lb	4870 lb
Mkt	22318 Nm	197663 in.-lb.	198940 in.-lb.
Ofbolt (average windward bolts)	0.275 m	10.82675 in	2.425 in
Pkt=Mkt/Ofbolt	81156.36 N	18256.87 lb	82037 lb.
Pkb=Pkt/Nkb	13526.06	3042.812 lb	13673 lb.
Nkb	6	6	6
$\sigma_y$	206 N/mm <sup>2</sup>	29870 psi	29870 psi
Dkb	22.39663 mm	0.882167 in.	1.870002 in.
Amin	13872.88 mm <sup>2</sup>	21.52298	96.71
Safety Factor Nkb	5	5	5
$\sigma_{uc}$	117 N/mm <sup>2</sup>	16965 psi	16965 psi
$\sigma_{ul}$	125 N/mm <sup>2</sup>	18125 psi	18125 psi
nfl	6	6	2
Mfl	18598.33 Nm	164718.8 in.-lb.	497349 in.-lb.
SMfl	148.7867 cm <sup>3</sup>	9.087934 in <sup>3</sup>	<b>27.44 in<sup>3</sup></b>
FORCES FROM GROUNDING	YD-40 metric	YD-40 english	CW
Fi=m*ar=m*Vs/ts	133493 N	29976 lb.	22941 lb.
ar=Vs/Ts	16.44 m/s <sup>2</sup>	53.92 ft/s <sup>2</sup>	53.92 ft/s <sup>2</sup>
Vb	8 knots	8 knots	8 knots
Vs	4.11 m/s	13.48 ft/s	13.48 ft/s
ts	0.25 s	0.25 s	0.25 s
H	1.5 m	59 in.	71 in.
m	8120 kg	17901 lbs.	13700 lbs.
Kr	1.6 m	63 in.	15 in.
Mkl	200239 Nm	1770261 in.-lbs.	1628819 in.-lbs.
Pr=Mkl/Kr	125150 N	28103 lbs.	108588 lbs.
$\sigma_{y25}$	181 N/mm <sup>2</sup>	26201 lb/in <sup>2</sup>	121599 lb/in <sup>2</sup>
Ab	346 mm <sup>2</sup>	0.536 in <sup>2</sup>	0.893 in <sup>2</sup>
nkb25	2	2	1
Lf	3 m	118 in.	48 in.
Mfl	93862 Nm	829810 in. lb.	1303056 in. lb.
SMfl	750.90 cm <sup>3</sup>	45.78 in. <sup>3</sup>	<b>71.89 in. <sup>3</sup></b>
Note, the YD-40 was the example in the book			



## Keel grounding and transverse loads (ABS 9.13.3)



### Load Aft

Yacht displacement	13700 lbs.
Crew and stores	2000 lbs.
Sailing weight	15700 lbs.
Sailing Waterline	37 ft.

Interpolation of grounding multiplier

$$= Fa (1.5 + (37-33)/(66-33) * 1.5$$

$$= 1.68 * Fa = 26,376 \text{ lbs.}$$

Load aft at tip of keel = 26,376 lbs.

Moment on keel root = 71 in. \* 26,376 lbs. = 1,872,696 in-lbs.

Stress Allowable = 35000 \* 0.35 = 12250 lb/in<sup>2</sup>

Sectional Modulus Required for frames

$$= Wl / (8 * \text{stress allowable}) = (1872696 / 15 * 48) / (8 * 12250)$$

Compensate for carbon

SMmin  
SMtop

61.15 in<sup>3</sup>  
42.81 in<sup>3</sup>

### Shear Load Upward

$$= 1.5 * F = 1.5 * 15700 = 23550$$

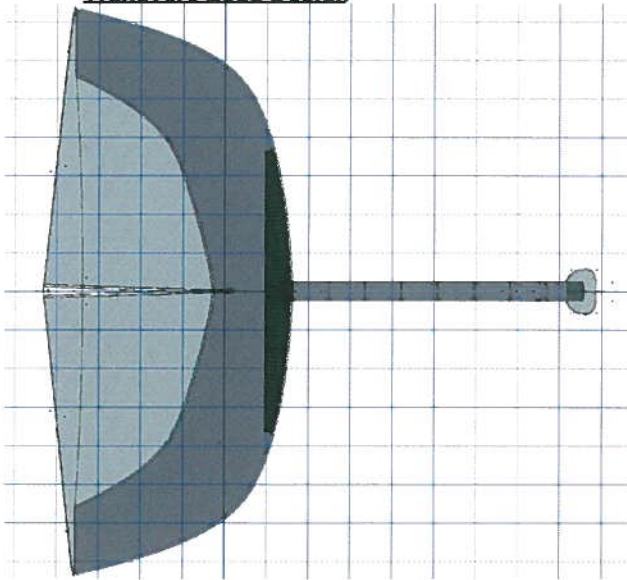
$$\text{Perimeter of keel} = 2 * 42 = 84 \text{ in.}$$

$$\text{Load} = 23550 / 84 * 0.54 = 519.18 \text{ Pass}$$

### Stress

Using fixed-fixed Stress =  $W l / 8Z$

### Transverse Load Design



### Minimum Floor Section Modulus Broach Load

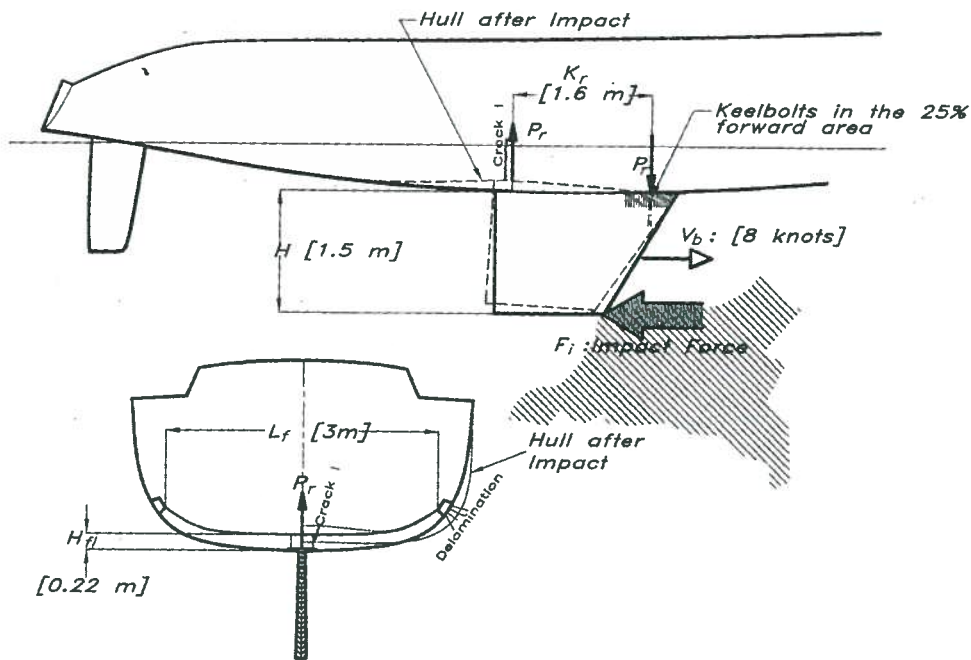
Keel Weight	4870
Keel CG	40.85
SF	1
Moment	198940
Stress Max	17500

SMmin	11.37
Smbuilt	11.29 and 10.58



## Principles of Yacht Design Fig 12.12 Loadings From Grounding/Heeling

### HULL CONSTRUCTION



Impact Force ( $F_i$ ) :

$$F_i = m \cdot a_r$$

$$a_r = V_s / t_s; \text{retardation } [16.44 \text{ m/s}^2]$$

$$V_b = \text{boatspeed } [8 \text{ knots}]$$

$$V_s = 0.514 \cdot V_b; \text{speed } [4.11 \text{ m/s}]$$

$$t_s = \text{time to full stop } [0.25 \text{ s}]$$

Impact Moment ( $M_{kl}$ ) :

$$M_{kl} = F_i \cdot H [200240 \text{ Nm}]$$

Reaction Force ( $P_r$ ) :

$$P_r = \frac{M_{kl}}{K_r} [125150 \text{ N}]$$

Required Tensile Strength for Keelbolts in the 25% Forward Keel Area ( $\sigma_{y25}$ )

$$\sigma_{y25} = \frac{P_r}{n_{kb25} \cdot A_b} [181 \text{ N/mm}^2]$$

$n_{kb25}$  = Number of Bolts in the 25% Area  
 $A_b$  = Cross Sectional Bolt Area

Floor Bending Moment ( $M_{fl}$ ) :

$$M_{fl} = \frac{P_r \cdot L_r}{4} [93863 \text{ Nm}]$$

Required Floor Section Modulus ( $SM_{fl}$ ) :

$$SM_{fl} = \frac{M_{fl}}{\sigma_{ut}} [750 \text{ cm}^3]$$

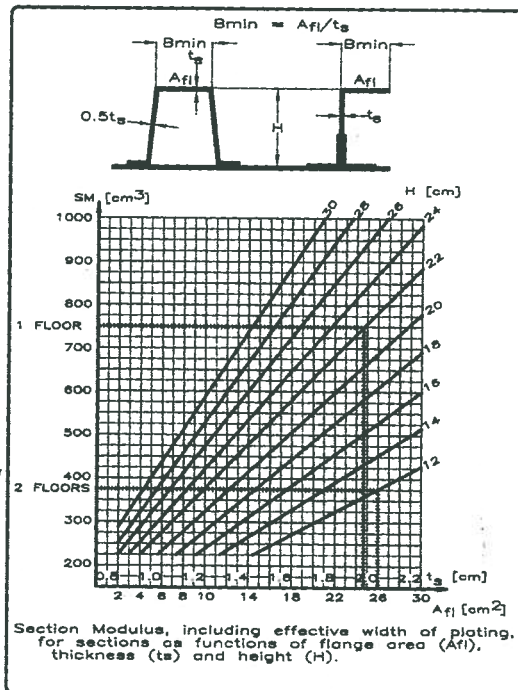
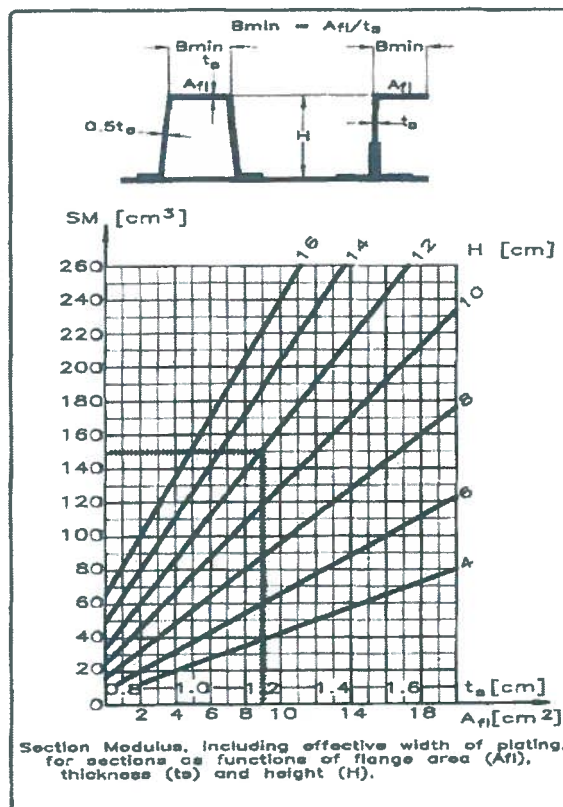
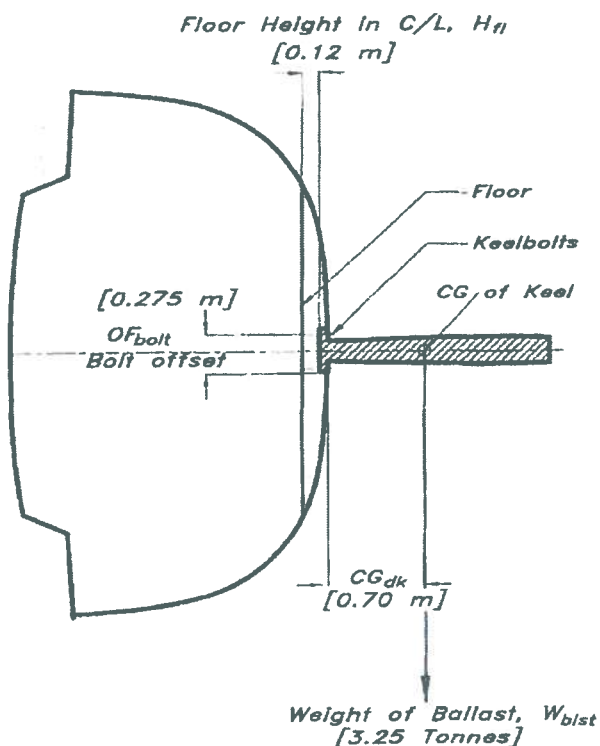


Fig 12.12 Loadings from grounding



Transverse Keel Moment ( $M_{kt}$ ) :  
 $M_{kt} = CG_{dk} \cdot W_{blst} \cdot g$  [ 22318 Nm ]

Total Keelbolt Load ( $P_{kt}$ ) :  
 $P_{kt} = \frac{M_{kt}}{OF_{bolt}}$  [ 81156 N ]

Required Keelbolt Diameter ( $d_{kb}$ ) :

$$d_{kb} = 2 \cdot \sqrt{\frac{P_{kt} \cdot \eta_{kb}}{\sigma_y \cdot \pi}}$$
 [ 21 mm ]

Minimum Keel/Hull-Area ( $A_{min}$ ) :  
 $A_{min} = \frac{P_{kt} \cdot \eta_{kb} \cdot \eta_{kb}}{0.25 \cdot \sigma_{uc}}$  [ 13873 mm² ]

Required Section Modulus for Floors ( $SM_{fl}$ ) :

$$SM_{fl} = \frac{M_{fl}}{\sigma_{ut}}$$
 [ 150 cm³ ]

Keelbolt Tension ( $P_{kb}$ ) :  
 $P_{kb} = \frac{P_{kt}}{\eta_{kb}}$  [ 13526 N ]

$\eta_{kb}$  = number of keelbolts [6]

$\eta_{kb}$  = factor of safety; 4-6 [5]

$\sigma_y$  = yield strength for keelbolts  
(206 N/mm² for AISI-316)

Floor Bending Moment ( $M_{fl}$ ) :

$$M_{fl} = \frac{M_{kt} \cdot \eta_{kb}}{\eta_{fl}}$$
 [ 18598 Nm ]

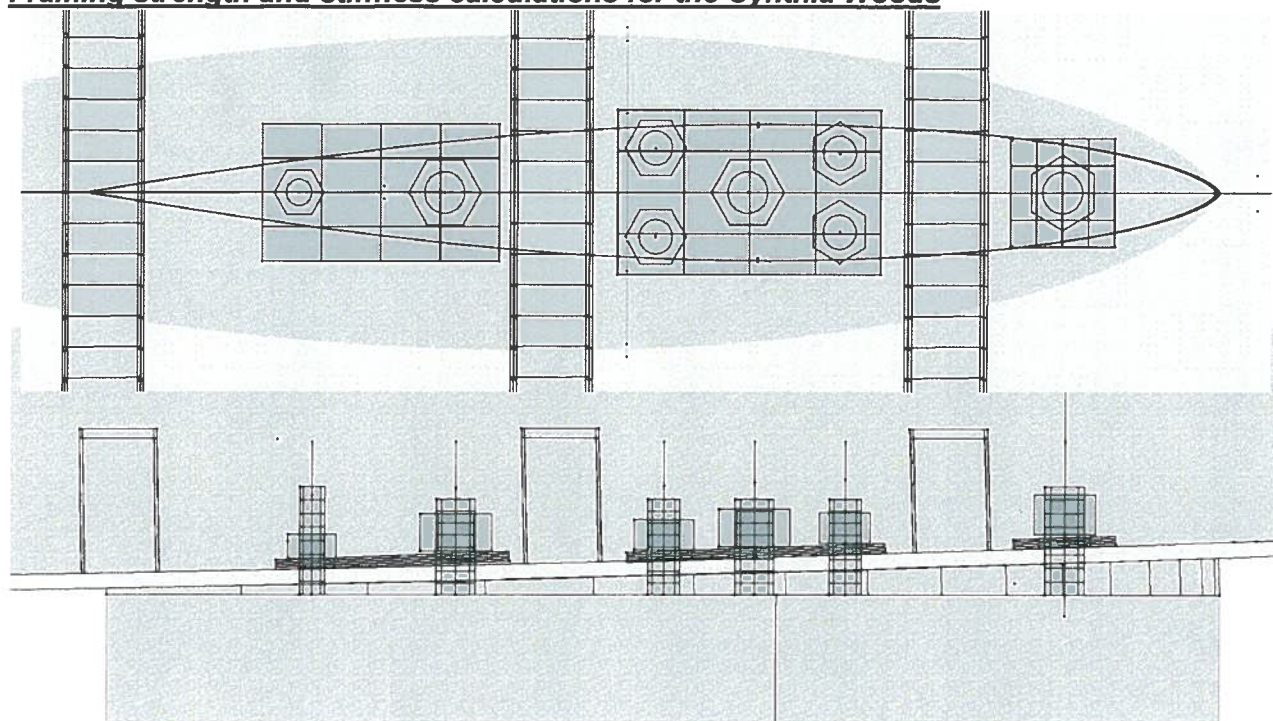
$\eta_{fl}$  = number of floors over keel [6]

$\sigma_{uc}$  = typical ultimate strength  
in compression for GRP  
( 117 N/mm² )

$\sigma_{ut}$  = typical ultimate strength  
in tension for GRP  
( 125 N/mm² )

Fig 12.11 Loadings from the keel

## Framing strength and stiffness calculations for the Cynthia Woods



Assumed neutral axis taken from outside hull

		CW	CW	YD-40	YD-40
		AFT frame	FWD frame	metric	English
hull thickness t	in.	0.54	0.54	3.35	1.34
side thickness t1	in.	0.13	0.13	1.00	<b>0.40</b>
Minimum ABS side thickness $t1_{min}=h/3$ in.		<b>0.19</b>	<b>0.18</b>	0.73	0.29
Maximum ABS frame height $h_{max}=30*t1$ in.		<b>3.75</b>	<b>3.75</b>	30	12.00
top hat thickness t2	in.	0.44	0.44	2.00	0.80
frame width top Wc	in.	3.00	3.00	12.00	<b>4.80</b>
frame width bottom b	in.	3.00	3.00	12.00	4.80
total frame height from floor h	in.	5.75	5.38	22.00	<b>8.80</b>
effective width of plating $w=18t+b$	in.	12.72	12.72	72.30	28.92
Area top hat ( $t2*Wc$ ) At	in.^2	1.32	1.32	24.00	3.84
Neutral axis top hat Nat	in.	6.07	5.70	24.35	9.74
Inertia Top Hat It	in.^4	0.02	0.02	8.00	0.20
Area frame sides ( $t2*Wc$ ) As	in.^2	1.33	1.23	40.00	6.40
Neutral axis frame side Nas	in.	3.20	3.01	13.35	5.34
Inertia frame side Is	in.^4	3.12	2.50	1333.33	34.13
Area effective hull ( $t2*Wc$ ) Ah	in.^2	6.87	6.87	242.21	38.75
Neutral axis effective hull Nah	in.	0.27	0.27	1.68	0.67
Inertia effective hull Ih	in.^4	0.17	0.17	226.51	5.80
Actual Neutral axis from outer hull NA	in.	2.04	1.95	4.45	2.27
Total Area A	in.^2	9.52	9.42	306.21	48.99
Moment of Inertia (@centerline) I	in.^4	48.01	41.96	16105.97	413.82
Sectional Modulus top SMt	in.^3	<b>11.29</b>	<b>10.58</b>	770.58	<b>52.55</b>
Sectional Modulus hull SMh	in.^3	<b>23.56</b>	<b>21.53</b>	3620.20	<b>182.65</b>
Stress max	lb/in^2	66341	70792	972.093	3219.61
Deflection @ load	in.	1.50	1.71	0.00446	0.03925

**Note: To get the book example Section Modulus you need a 1.34" bottom with 1" bolts  
The book also uses 0.4" side walls and the frame 8.8" high and 4.8" wide**

The ABS rule requires the frame height (h) not to exceed  $30 K t_1$  where  $K = \text{minimum } \sqrt{E/1.0 \times 10^6} \text{ or } \sqrt{17000/C}$

which gives 1 or 0.82.

**$t_1 \text{ as-built} = 0.13$  therefore the frames maximum height should not exceed 3.9 inches.**

The frames in the *S/V Cynthia Woods* were 5.7 inches and exceeded the height, and the sides of the frames would not support the shearing loads.

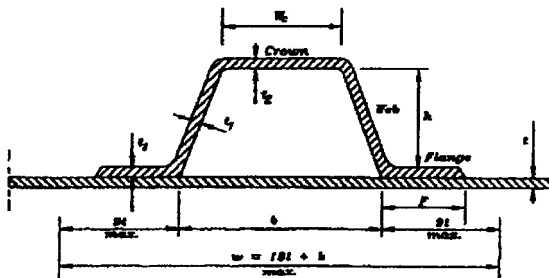
**The frames will fail in horizontal shear before the frame can take load.**

**Horizontal shear through beam**

**Horizontal Shear Stress =  $Vay'/Ib$ , the maximum shear stress occurs at the neutral axis of the beam.**

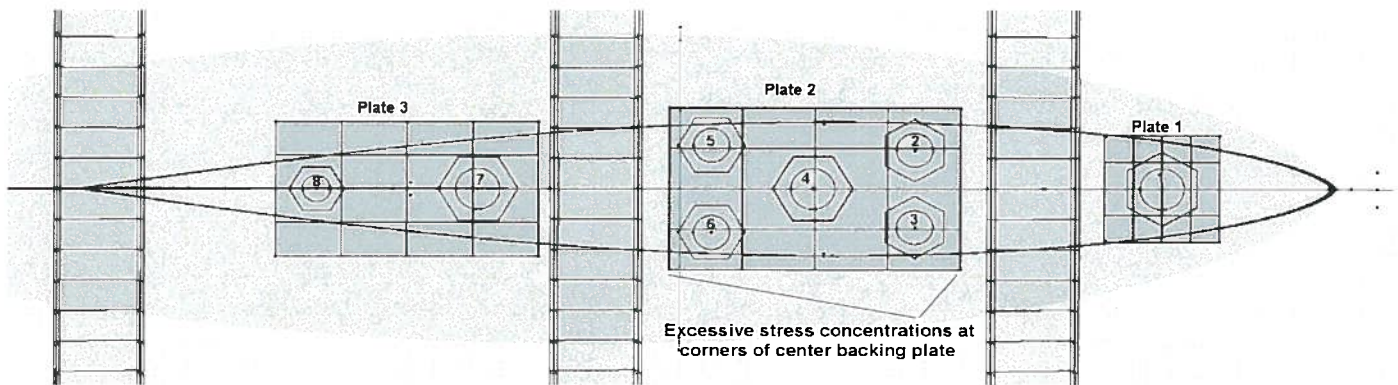
Shear Allowable in grounding is 4900 psi.

**FIGURE 3.1  
Effective Width of F.R.P. Plating and  
F.R.P. Stiffener Details**





## Hull Shear Tables and Load Calculations



The allowable load for the fiberglass floors and frames is 0.5 of ultimate material strength for the keel structure (ABS Rule 9.13.3a Structures). The allowable shear load for the fiberglass floors and frames is 0.5, or 0.4 of ultimate tensile strength (ABS Rule 9.13.3a Structures).

ABS method		Minimum hull thickness
Rule 7.3.1 Section 7I2		1.50 inches
Rule 9.13.3a Section 9I4		3.11 inches
	function	loads
Allowable shear load	$14,000 \times 0.5$	7000
Ultimate tensile strength	$35,000 \times 0.4$	7000
Max load	$21,785/7,000$	21785
Minimum Hull Thickness by ABS Method		3.11 inches

Note: The 3.11 inch thickness number is unusually high because of the very narrow backing plates used.

Note: The Safety Factor used for the ABS Keel Bolt sizing (Rule 6.3.1) is 4.0 on ultimate strength and 2.0 on yield strength.

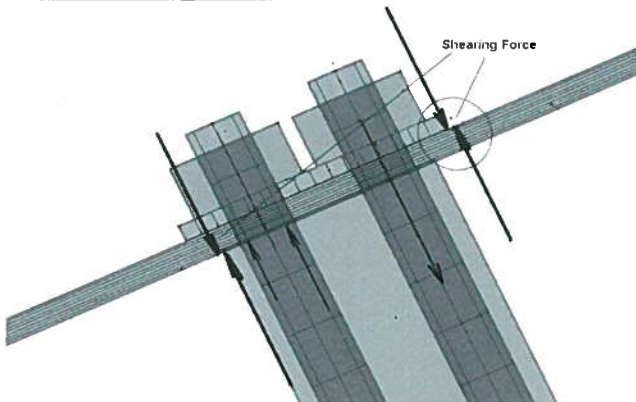
It would be engineeringly prudent to make the floors stronger than the bolts, a single bolt breakage would not be catastrophic. The hull floor safety factor is only half of the keel bolt safety factor, so a floor/backing plate combination is found to make the floors stronger than the keel bolts.

### S/V Cynthia Woods Failure

The S/V Cynthia Woods hull laminate thickness was only 0.56 inches, with its widest backing plate only 6 inches wide. The corners of Plate 2 acted like an old-fashioned can-opener (see diagram above)

### Shear Load

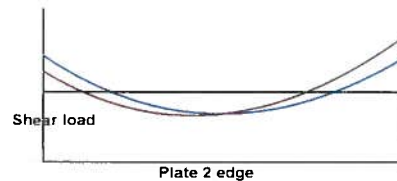
Cross-section @ split bolts



### Heeling Load

Load on 2 split bolts @ SS ult. strength, center plate	125020 lbs
Shear load center plate edge corners	12200 lbs
Factor of Safety	0.32

**Important Note.** The bolts are more than twice as strong as the shell of the hull



To think of a shear force, think of a pair of scissors, (shears).

On the right side of the picture, the edge of the backing plate is creating a large downward force.

As the edge of the backing plate pushes down on the laminate, the laminate pushes up to resist this force.

The top of the pair of scissors is the edge of the backing plate, the bottom of the scissors is the hull laminate.

## **Hull Shear Tables and Load Calculations 2**

<u>Vertical Loading (straight load on bolt for backing plate edge load)</u>						Bolt Load @ 35,000 psi lb.	Perimeter Load lb/in	Average Shear @ t=0.58" lb/in
	Length in.	Width in.	Area in^2	Perimeter in	Bolt Areas in^2			
Backing Plates								
Plate #1 forward	3.88	3.88	15.02	15.50	1.295	45325	2924	5042
Plate #2 mid	10.00	6.00	60.00	32.00	4.867	170345	5323	9178
Plate #3 aft	9.00	5.00	45.00	28.00	1.846	64610	2308	3978

<u>Vertical Loading (straight load on bolt for backing plate edge load) - continued</u>						Bolt Load @ 70,000 psi lb.	Perimeter Load lb/in	Average Shear @ t=0.58" lb/in
	Length in.	Width in.	Area in^2	Perimeter in	Bolt Areas in^2			
Backing Plates								
Plate #1 forward	3.88	3.88	15.02	15.50	1.295	90650	5848	10083
Plate #2 mid	10.00	6.00	60.00	32.00	4.867	340690	10647	18356
Plate #3 aft	9.00	5.00	45.00	28.00	1.846	129220	4615	7957

Note: small width of backing plate with washer hanging over backing plate



**Picture showing small backing plate with washer overhanging. 15 % of the hull area cut out under plate.**



## Groundings

The risk of grounding is an everyday hazard to those who use the water for trade and leisure. Ships, motor yachts, power boats, and sailboats run aground daily in seas, lakes and rivers. Thousands upon thousands of boats run aground every year. The adage that there are three kinds of skippers, those that have run aground, those that have yet to run aground, and those that are not honest about running aground, is very true.

All offshore races run in the United States (including Europe and most of the World) are run using ISAF's Offshore Racing Council (ORC) rules, including the race in which the *S/V Cynthia Woods* was competing.

The ORC rule *requires* compliance with the *ABS Guide*. The current ABS Rule is dated 1994. The most recent version of the ORC has included ABS or ISO.

The ISO regulations, which are currently being developed, had not completed its final draft of the hull/keel structure when the yacht *S/V Cynthia Woods* was built.

The ABS Guide is the de-facto standard for offshore racing yacht structures and all racing yachts must be designed and built to this standard.

*The S/V Cynthia Woods was built in 2005 and was required to be designed and built to the ABS Guide in order to enter any United States race. The S/V Cynthia Woods is a Cape Fear 38 and is designed and built as a Production boat.*

The ABS Guide has basically three criteria for the hull/keel joint structure: (1) hull thickness; (2) heeling loads; and (3) grounding conditions. These criteria establish the minimum hull thickness and overall framing sizes.

The *S/V Cynthia Woods* had several groundings, one of which was a well-documented grounding in which some keel damage had occurred. During this grounding incident, she was towed off the sand bar by a power boat. The yacht showed typical lead damage from the grounding on the yacht's trailing edge. See photos at page 21. The keel was removed, repaired, and reattached to the hull. The *S/V Cynthia Woods* received small hairline cracks in two (2) frames at the intersection of the hull/frame joint. It is documented that Texas A&M University at Galveston students repaired the small cracks and replaced the laminate to a similar thickness as that which had been originally built in the boat. The workmanship was more than sufficient.

*It is important to note that the students' repairs were still intact at the time of the keel failure and are still intact and available for inspection in the boat. The repairs by the students did not in any way contribute to the keel failure.*

This report in other sections shows that *S/V Cynthia Woods* failed to meet the ABS Guide hull thickness, heeling loads, and grounding load criteria. The hull thickness *and* the original built framing were inadequate for this type of yacht under the ABS guidelines.

This author is a naval architect and marine engineer with over 30 years of experience in designing and building fiberglass boats, especially offshore racing and cruise sailboats. Racing sailboats are expected to run aground because they have deep drafts and occasionally sand shifts into channels and they often enter shallow areas for tactical reasons during a race. It is a common saying in the yacht design profession that "you can do anything you want, but make sure you pass the ABS guidelines." The yachts designed by the author have run aground many times; at times so hard the bow of the boat went underwater. One of the boats slipped its mooring during Hurricane Gloria and was on solid rocks for more than a day, continuously banging in hurricane-size waves. When the boat was retrieved, nearly half of the lead keel had been beaten away, but the yacht's hull and structure suffered virtually no damage. Another yacht that had a keel replacement many years ago runs aground on a regular basis, resulting in no structural damage. All these yachts were built using the ABS Guide's design criteria.

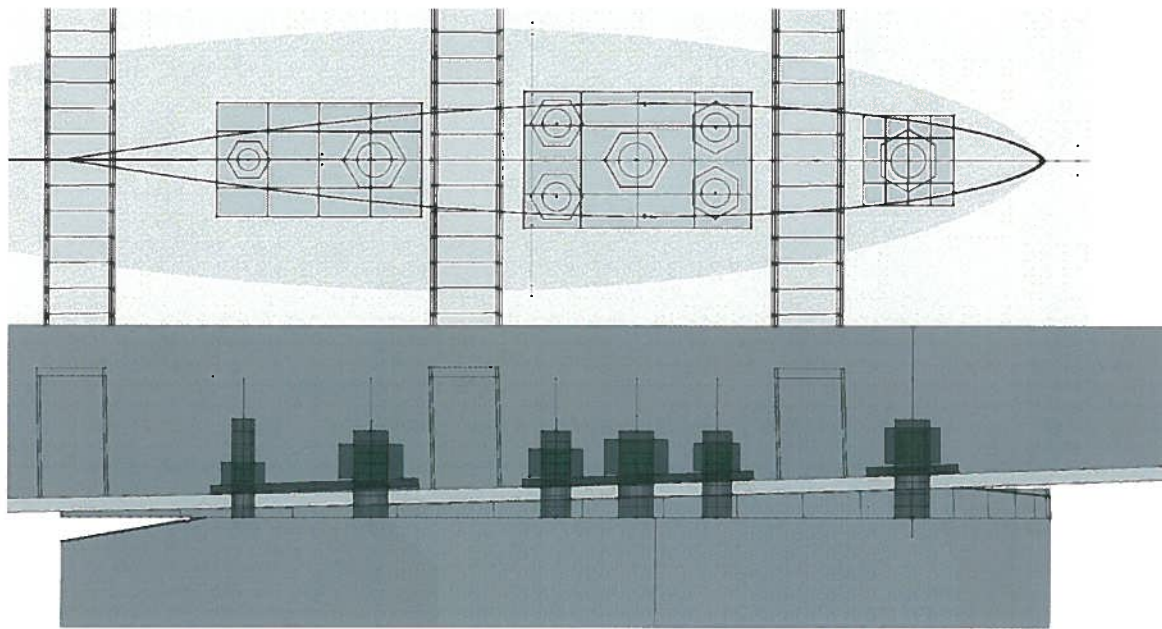
### Grounding Damage on the S/V Cynthia Woods



**Photo.** This is a photograph of the S/V *Cynthia Woods* after the grounding that was later repaired by the boatyard. The grounding damage in this photo is on the trailing edge of the keel. The thin, unsupported section (not attached to hull by bolts) is the trailing edge deforming lead material, which is a common occurrence in all groundings. The deformation stops at the furthest aft keel bolt. Shown above, the deformation below the hull is the fiberglass shim or spacer plate. This plate is used to “marry” the flat poured lead keel to the curved hull. Although this shim transmits load, it adds no structural strength.



**Photo.** This is a photograph taken at the same time, showing the separation of leading edge of the keel. This deformation of the unsupported lead material occurs forward of the location of the forward keel bolt. The *Yacht Design Principles* establishes a minimum area of keel bolts in the forward 25% of the keel. This area in the S/V *Cynthia Woods* was less than recommended.



**Diagram showing the damaged locations after grounding.**

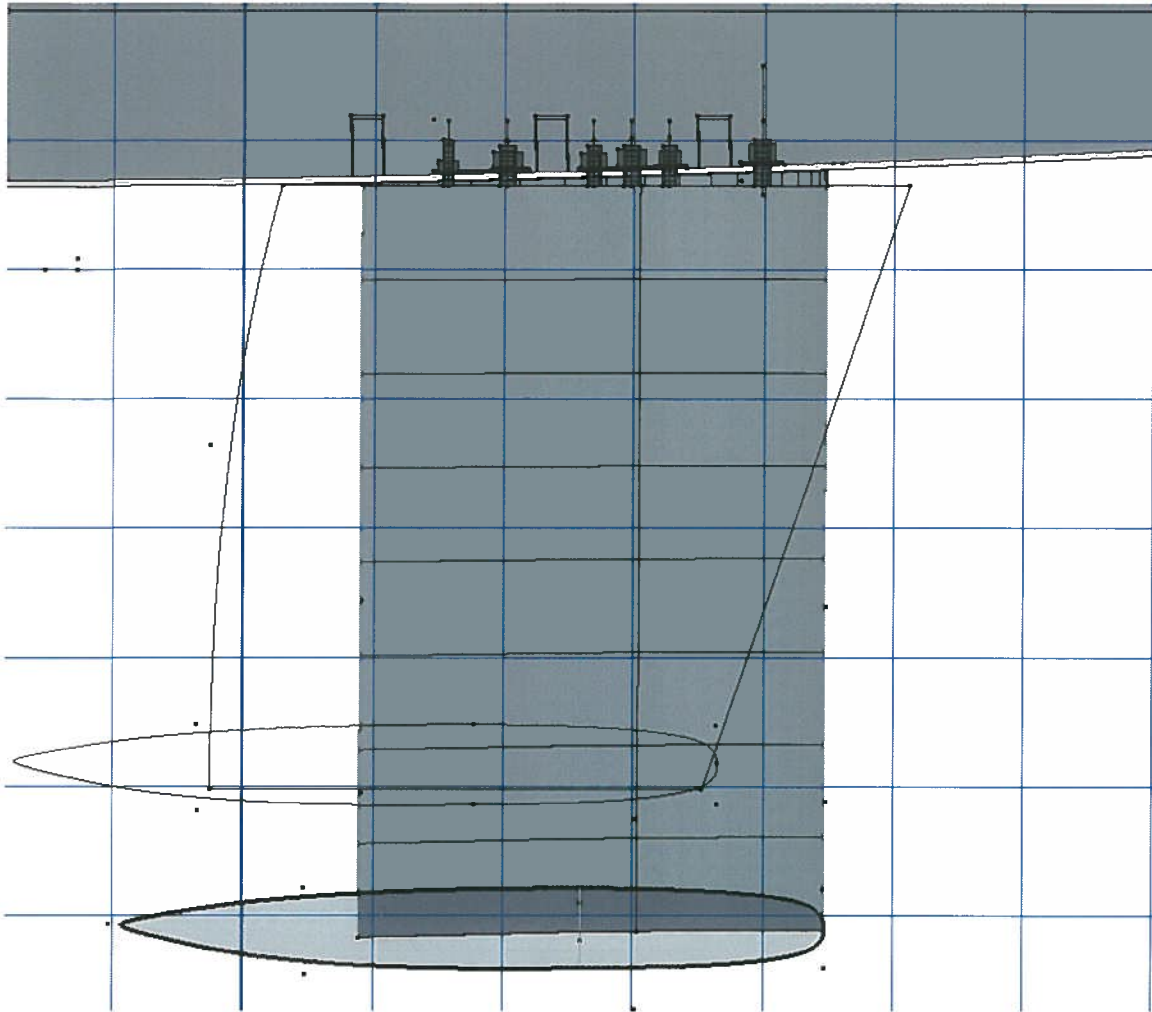
The damage to the lead is isolated to forward of the forward keel bolt and aft of the aft keel bolt. There is very little lead area aft of the last keel bolt and it is easily deformed. This type of damage is very common in groundings with a lead keel.



**Photo. The later keels like on the *S/V Cynthia Woods* produced significantly higher hull loads and stress.**



### Design Differences on the Cape Fear 38



**For comparison purposes, the white keel is on the original Cape Fear 38. The gray keel is on the later hulls, such as the hull installed on the *S/V Cynthia Woods*. The framing of both versions did not seem to change. The later deeper keels created much higher bending and grounding loads over a smaller hull area.**

For some inexplicable reason, the earlier production of Cape Fear 38 boats had a thicker fiberglass hull laminate around a shallow keel and the later production Cape Fear 38 boats (of which the *S/V Cynthia Woods* was one) had a thinner fiberglass hull laminate around a deeper keel. This design/construction is totally illogical.

The early shallow keels had 1 inch keel bolts with about 1 inch of hull fiberglass laminate. The later deeper higher loaded keels, as on the *S/V Cynthia Woods*, had 1 ½ inch bolts with just over ½ inch of hull fiberglass laminate.

### Towing Damage After Incident on the S/V Cynthia Woods

There were large external and internal cracks both left on and in the hull after towing.



**Photo.** There was major damage to the *S/V Cynthia Woods* when it was towed in from the sea. There are large cracks through the hull from below the waterline to the sheer line (top of hull). When the tow vessel approached the hull, it was floating only about one foot above the water. In the overturned condition and being full of water, it weighed over 70,000 lbs. At this weight, it was easily damaged. You can see at each crack an impact from the tow vessel.

### ABS Keel Bolt Diameter and Safety Factor

The ABS Guide establishes the minimum keel bolt sizes for every sailboat.

#### ABS Guide Rule 6.3.1 Keel Bolts

The diameter,  $dk$ , at the bottom of the thread of each keel bolt, is not to be less than obtained by the following equation.

$$dk = \sqrt{2.55W_k Y_k / \sigma_y \sum l_i}$$

$W_k$  = total weight of the keel = 4870 lbs.

$Y_k$  = vertical distance in in. from the center of gravity of the keel to the bearing surface at the bolt connection = 40.85 in. This was measured directly from the *S/V Cynthia Wood* keel.

$\sigma_y$  = minimum yield strength at 2% = 35,000 lbs./in<sup>2</sup> for 304 Stainless Steel. ABS states that the yield strength shall not be taken as more than half the ultimate strength

$\sigma_{ult}$  = ultimate strength (breaking) = 75,000 lbs./in<sup>2</sup> for 304 Stainless Steel

$\sum li$  = summation of transverse distances at each bolt from the center of the bolt on one side of the keel to the edge of the keel on the other side in inches = 1.18+1.84+4.72+2.52+4.86+1.79=16.91 inches

Using the equation,

$$dk = \sqrt{2.55WkYk / \sigma_y \sum li}$$

Dk=minimum bolt size at root = 0.857 in.

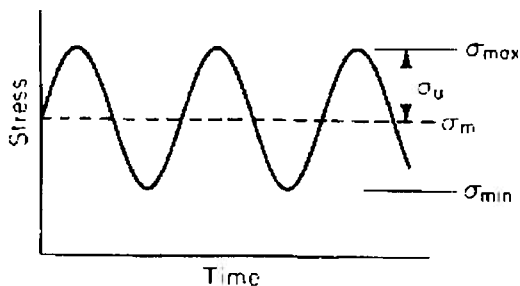
Bolt and Bolt Root Diameters		
BOLT DIA.	ROOT DIA.in. <i>dk</i>	AREA <sub>root</sub>
0 7/8	0.731	0.419
1	0.838	0.551
1 1/8	0.939	0.694
1 1/4	1.064	0.893
1 3/8	1.158	1.057
1 1/2	1.283	1.295
1 5/8	1.389	1.515

The aft bolt of the *S/V Cynthia Woods* has a slightly smaller root area (0.838), but 7 of the 8 bolts would pass ABS Guide requirements.

Note: Root diameter is the diameter of the bolt minus the thread on the bolt.

### Fatigue and Safety Factors

We are all familiar with bending back and forth a metal coat hanger. If we bend it back and forth long enough, it will eventually break. The graph below represents bending it back and forth over time, showing the stress going up and down as it bends back and forth.

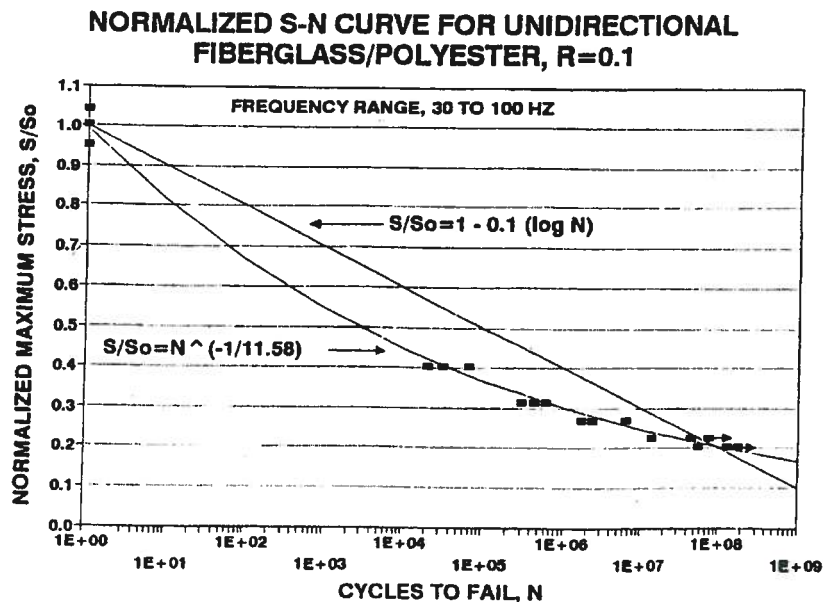


**Figure 1.6** Terminology for alternating stress.



Of course, you can take a stronger structure, like a steel pipe, and bend it back and forth, and it probably would never break. But even a pipe in a large structure (like holding a water tower in a windy area) could flex thousands of times daily, a million times over its life, and it will weaken.

As the material bends back and forth, it gets weaker; this is called “fatigue.” Just about all materials fatigue. As materials age and flex, they weaken. Below is a graph of the fiberglass material used to build the *S/V Cynthia Woods*. As with all such material, it is getting weaker over time. The graph begins on the left edge at 0 time and 100% strength; as it cycles (starts flexing back and forth) over time, the graph moves to the right showing a loss in strength. Design engineers must first determine how long the structure will be in service, then pick the appropriate strength number to design to. For example, most commercial aircraft are 30 years old and the design engineer picked a very low design fatigue limit of around 0.2, functionally over-building the material by design, so that the aircraft would be in service for a longer time. They used only 20% of the new materials strength as their design strength.



If you were designing a front axle for a car, for example, you would need to plan on the fatigue of the axle material, so the front axle did not break as the car got older.

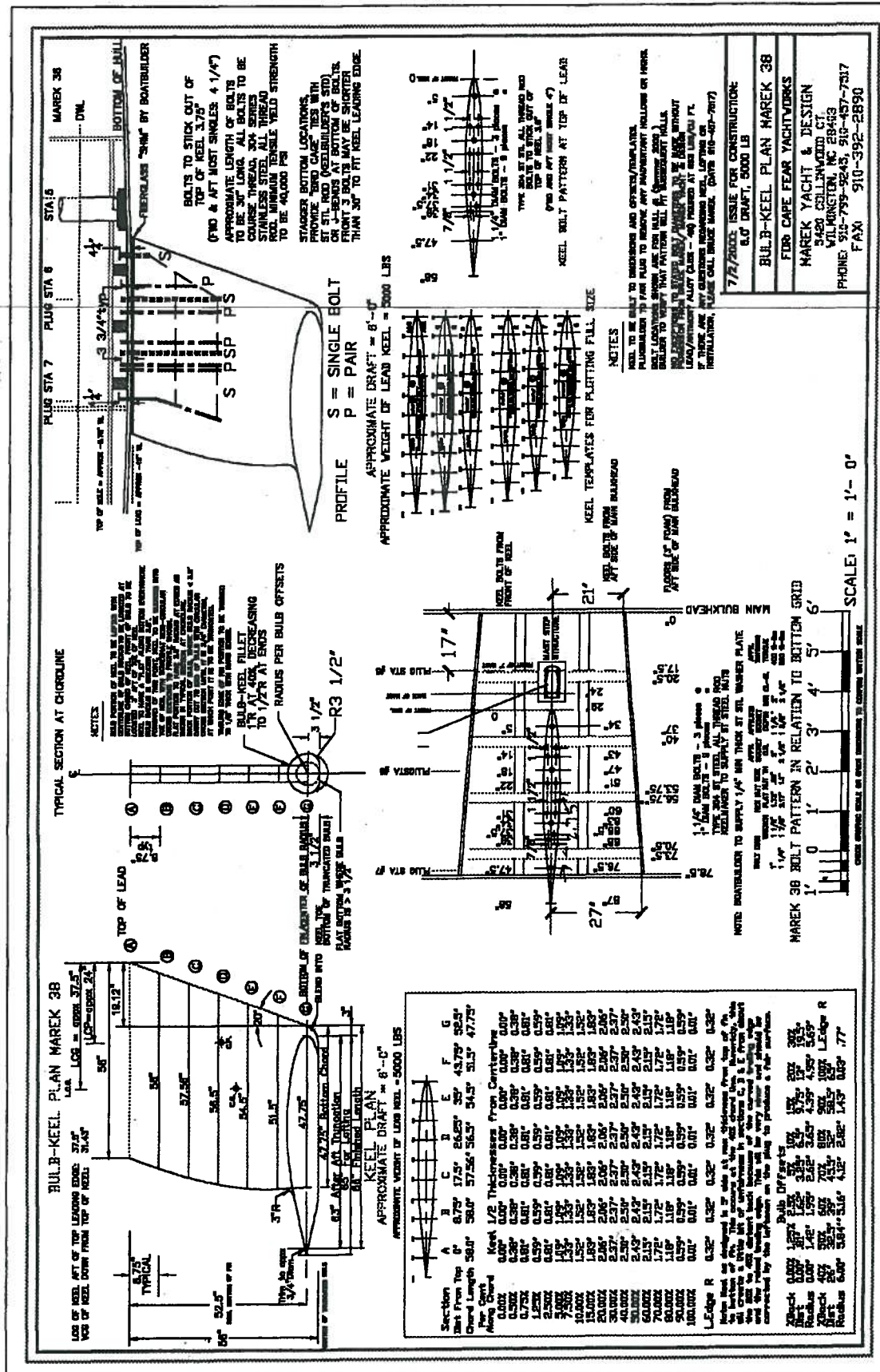
The application of a Safety Factor is common in engineering. The factor is generally applied as a multiplier of minimum fatigue load you picked to increase the design strength of a structure.

In the front axle of the car example, the design engineer would want the front axle of the car much stronger than the tire of the car. The engineer would want the tire to fail before the front axle. Breaking the front axle could be catastrophic driving down a highway. If the tire fails and the car falls to its rim, it can be driven off the road to safety. If the axle failed, there would be a seriously unsafe result. Safety factors usually start at around 2 and go as high as 10.

In the same way, the floor structure in a sailboat should be stronger than the attaching keel bolts. A single keel bolt breakage can become a manageable condition. A complete floor failure would lead to serious problems.

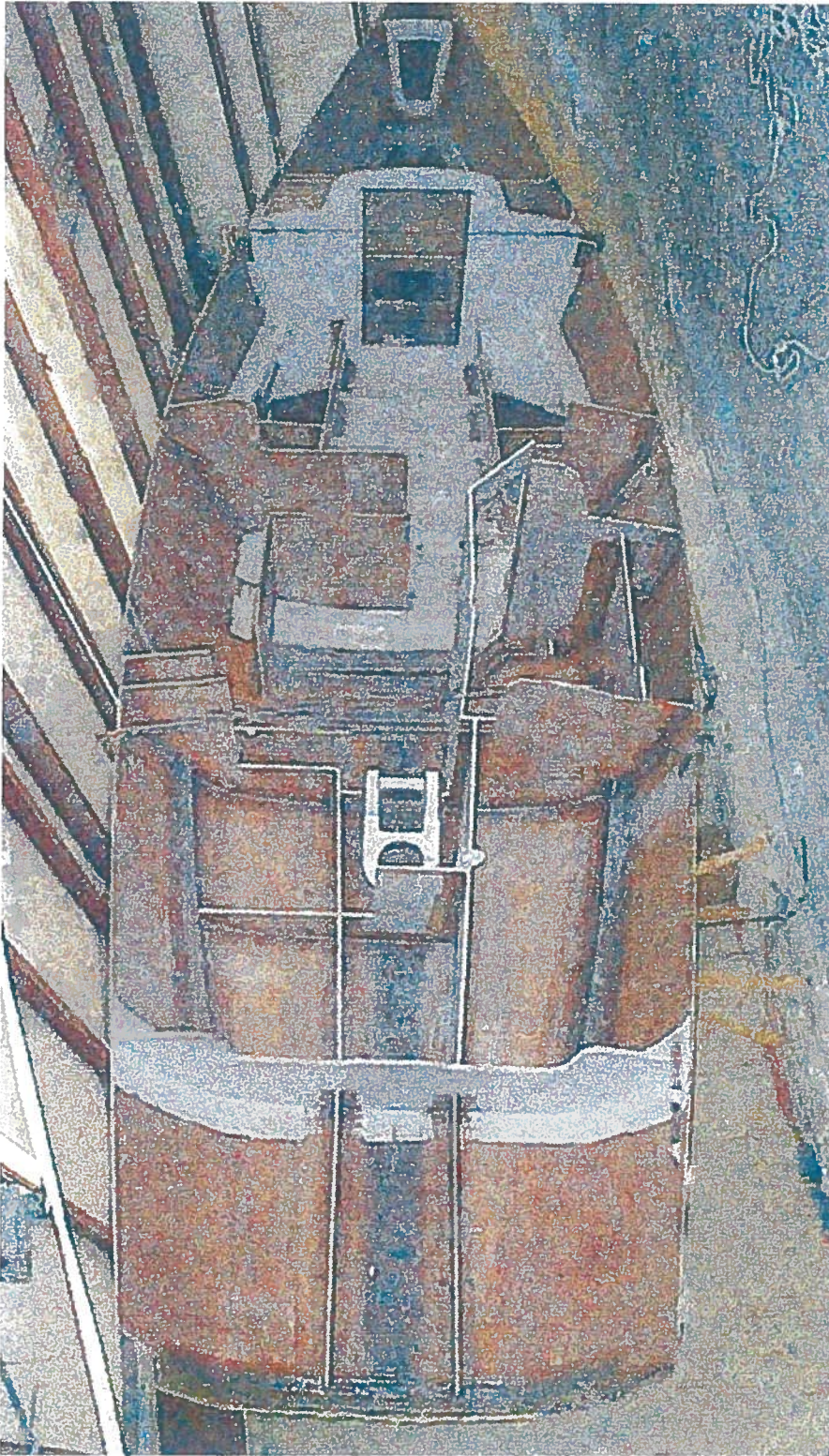
The ABS Guide uses 0.35 (grounding) and 0.50 (transverse) as a fatigue value for fiberglass in the keel area. It then uses a safety factor of 2.0 for the hull, and 4.0 for its ultimate load on the keel bolts. So, when a boat is properly designed and manufactured according to ABS Guide standards, it has a safety factor two times stronger built in to the design of the boat. This anticipates the material fatigue it will experience during its lifetime, reducing the material to a point of the initial safety factor. The *S/V Cynthia Woods*, as-built, used a safety factor of 0.32. **This serious design flaw is the second primary cause of the keel failure on the *S/V Cynthia Woods*.**

If a structure such as a boat fiberglass laminate is built without safety factors and fatigue limits, it will fail at an early age, just like the *S/V Cynthia Woods*. So, it should be properly engineered and manufactured with the safety factor and fatigue designed in so that, even after material fatigue, it does not break.





Picture of Hull Number One with One Inch of Fiberglass Laminate



**Photo.** This is an overhead picture of hull number one. The dark strip down the centerline of the yacht is where the core has been removed and has been replaced with solid fiberglass. The *S/V Cynthia Woods* had no core, and was solid. Peter Ross, the builder of the first hull, said the solid down the centerline was one inch thick where the keel was attached.

### **Designer and Builders**

#### **Cape Fear Yachts**

Cape Fear Yacht Works  
111 Bryan Road  
Wilmington, NC 28412  
Phone: (910) 395-0189

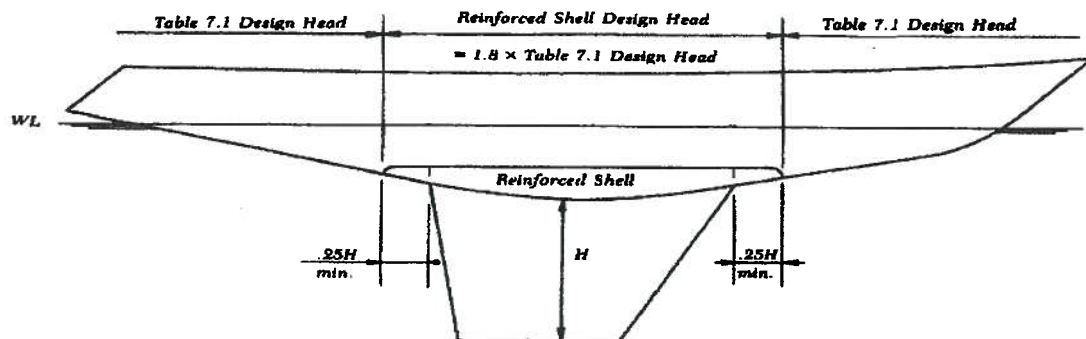
#### **Yacht Designer of Record: Bruce Marek (Cape Fear 38 Yacht Designer)**

Marek Yacht & Design  
5489 Eastwind Rd,  
Wilmington, NC 28403-3445  
Phone: (910) 799-9245  
SIC:Engineering Services

#### **Builder of molds and first boat**

Peter Ross  
Contract  
50 Seacrest Drive  
Kingston, RI 02879  
Phone: 401-207 9326

## ABS Guide Diagrams for Keel Reinforcements



**ABS Guide Figure 7.1 Profile at Centerline**

$H=71"$  for *S/V Cynthia Woods* (CW)  
 $0.25 H=18"$

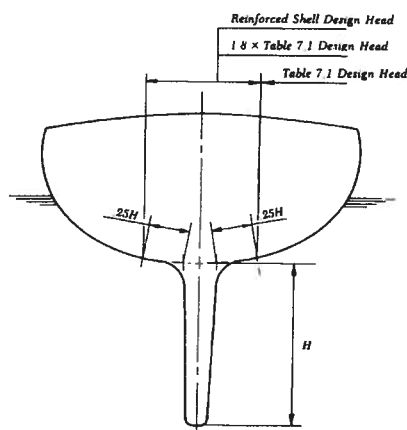
Total width of Keel Floor Reinforcements =  $0.5 H + 5"=41.5"$   
Total length of Keel Floor Reinforcements =  $0.5 H + 43"=78.5"$

The CW had a structural bottom thickness in way of the keel bolts of an average of 0.54 to 0.58 or 9/16" thick. The largest keel bolt on the CW was 1 1/2 ".

The 43" x 5" keel on the CW would require a minimum of 53" x 10" tapered laminate reinforcement of 1 1/2" minimum thickness in way of the keel. The thickness of the keel floor in the CW was only around 1/3 of the minimum laminate specified by ABS.

This rule requirement is simply that if you drill a structural hole in the laminate, you need to reinforce it.

The additional ABS Guide reinforcing laminate was not present in the *S/V Cynthia Woods*.



**ABS Figure 7.2 Transverse Section**



## **American Bureau of Shipping (ABS)**

The mission of ABS is to serve the public interest, as well as the needs of clients, by promoting the security of life, property, and the natural environment; primarily through the development and verification of standards for the design, construction, and operational maintenance of marine-related facilities.

ABS is the third largest classification society in the world with a rich history of providing the maritime industry with excellence in standards, surveying, engineering, and research and development.

ABS' core service is the provision of classification services through the development of standards called ABS Rules. These rules form the basis for assessing the design and construction of new vessels and the integrity of existing vessels and marine structures.

### **ABS Surveyors Worldwide**

ABS surveyors, located in all major ports throughout the world, routinely 'attend' vessels to conduct periodic surveys and reviews, verifying that a vessel remains in compliance with ABS Rules. ABS engineers, located in ABS engineering offices in Houston, Genoa, Busan, Singapore, Yokohama, Piraeus, London, Rio de Janeiro, Shanghai and Manila, regularly liaise with ship owners and shipyards to provide guidance on the safety and the acceptability of proposed designs and/or repairs, all guidance being based on ABS Rules. The sound judgment and professional experience of ABS engineers and surveyors are among ABS' chief strengths.

### **ABS Rules**

The ABS Rules themselves are developed and approved through a technical committee structure. The result is that Rules are developed in collaboration with industry, ensuring the independence of the conclusions. Currently, ABS has over 30 committees ranging from regional technical committees to specifically-themed committees for subjects such as mechanical equipment and propulsion systems.

### **Backing Plates and the Point Where the S/V Cynthia Woods Hull Started to Fail**

Wide backing plates distribute load through the hull more evenly. The S/V *Cynthia Woods*' backing plates were too narrow to adequately distribute the heavy load of the bulb keel. The failure location is on the backing plate to hull laminate.



**Photo.** Picture of multiple bolts through hull laminate. Notice the 3/8" thick backing plates are of similar width to keel fiberglass laminate width. For the backing plates to be effective, they should have been much wider than the keel. Backing plates the same width as the keel structure is bad practice; this design choice produces high stress concentrations at that point. Even the ABS Guide requires the minimum laminate to go 2" past the edge of the keel.

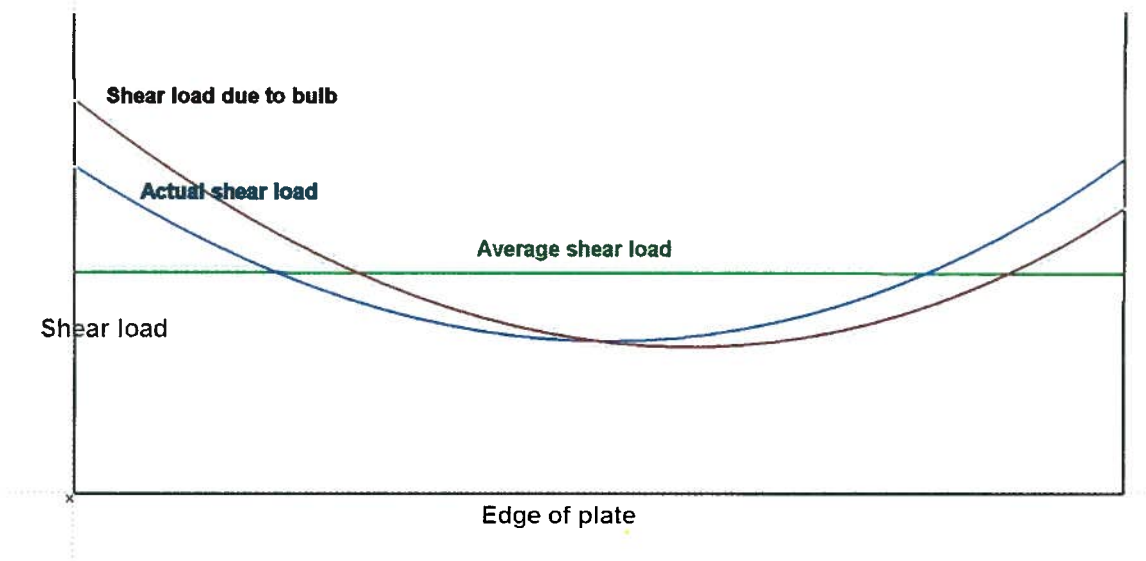
#### **Where this failure occurred:**

The keel failed in shear.

The center plate (plate #2) was very highly loaded due to the less than specified minimum hull thickness. The failure would start in a corner of those plates because the forward corner would have a higher load due to the bulb.

The failure was on the port (left) side due to the boat being on port tack.

Shear failures start clean and then disintegrate—much like cutting through thick cardboard with scissors; it starts cleanly and then will not cut vertically, and starts to tear.



**Shear load diagram on edge of plate with picture of plate #2 directly above it for comparison purposes.**

Note the top right keel bolt has a washer overhanging the backing plate.





**Photo.** This is a photo at the point of the start of shear failure. Look right under the corner of the backing plate on the right side of the picture; it has a straight vertical side with no delamination.

What should be noted about this point of failure is it is a clean shear break.

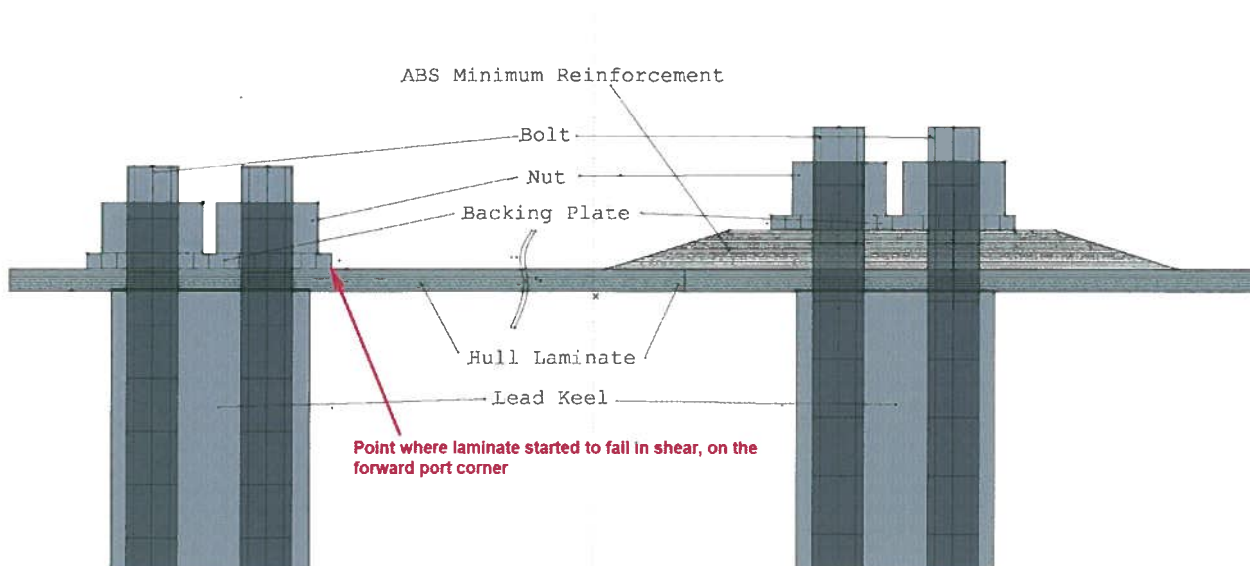
It is between the two frames that hold the keel on. The loads, when grounding, rotate around this “middle” zone and have very low stress. The stresses from any grounding are on the front and back of the keel, not in the middle of the keel where this plate is located. The weight of the bulb, because of its aft location, causes the front of the plate to “dig-in” the more the boat heels.

This area was not one the areas repaired by the TAMUG students.





**Photo.** Another view of the port side of backing plate #2. Notice the vertical face through the laminate forward, before the failure of the keel goes catastrophic and starts to rip out of the boat. You can also see that because of the proximity of the backing plate edge so close to the keel bolts, that the tearing passes through the hole drilled for the bolt.



**This diagram shows another view of where keel failure started.**

### Minor Repairs by Texas A&M Students



**Photo.** As a result of the grounding in March 2007, there were some cracks at the junction of the frame face and the hull where the glass turns 90 degrees. The replacement patch was two layers of 24 oz/yd.<sup>2</sup> woven roving. This and the following pictures show the repairs as a yellow, translucent color with some red and white underneath. This yellow color is an epoxy resin which is stronger than the red vinylester resin used for the hull.

The repairs were covering the small frame cracking, and are done to industry standard.

The important part is that all these repairs done by the TAMUG students are still intact, and that they had nothing to do with the keel's ultimate failure.









**Photo.** Inside the hull at the point where failure started. This area was not repaired by TAMUG students.

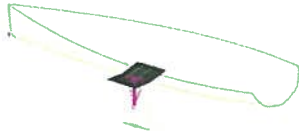




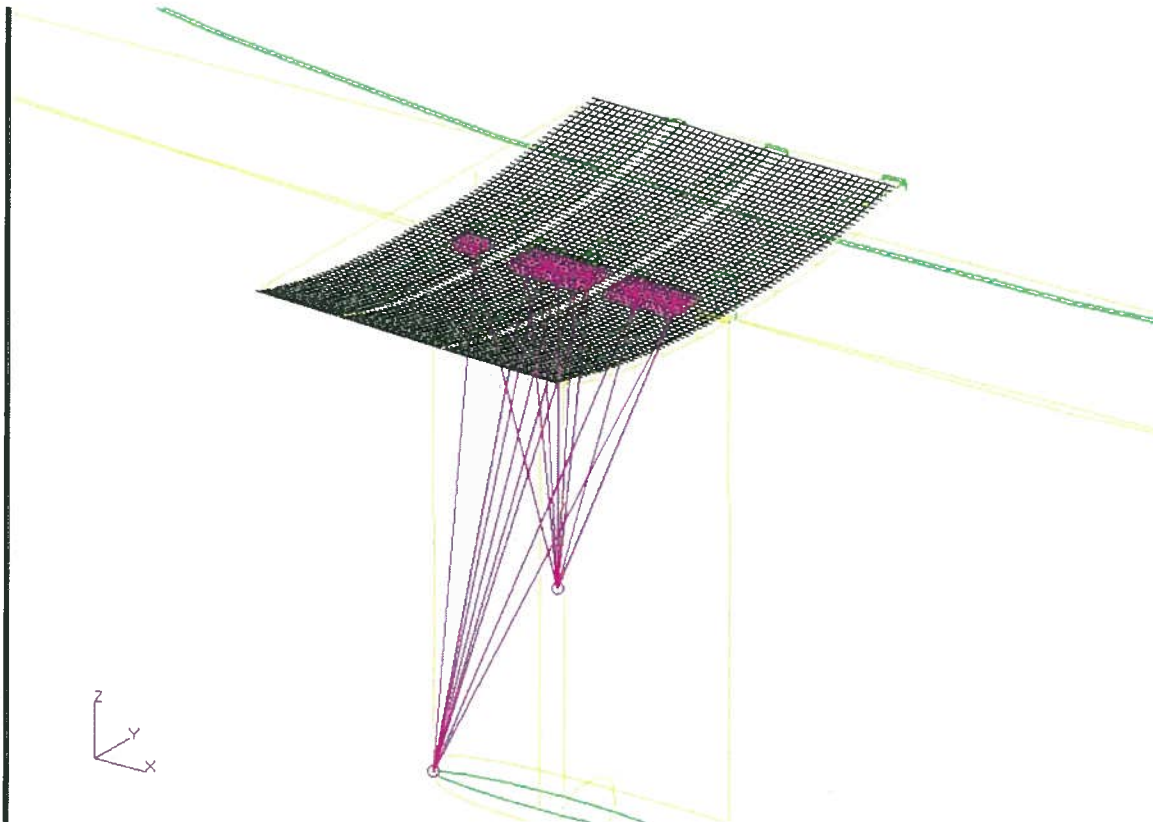
### **Nastran Finite Element Analysis-Summary**

A computer model was built for the *S/V Cynthia Woods* in its as-built configuration where the keel attaches to the hull. The model was run in Nastran finite element software. This software is the industry structural standard for NASA, Sikorsky Helicopter, the Air Force, and nearly all other major industry structural builders.

In the case of the *S/V Cynthia Woods*, a 50 x 72 inch grid was located on a section of the hull where the keel is attached to the hull. The grid is made up of a point at every one-inch interval. This grid contains 3,628 points. Each point is related or tied to the points next to it. As one point is loaded, or moves, the point right next to that point are loaded and moves in relationship to it.

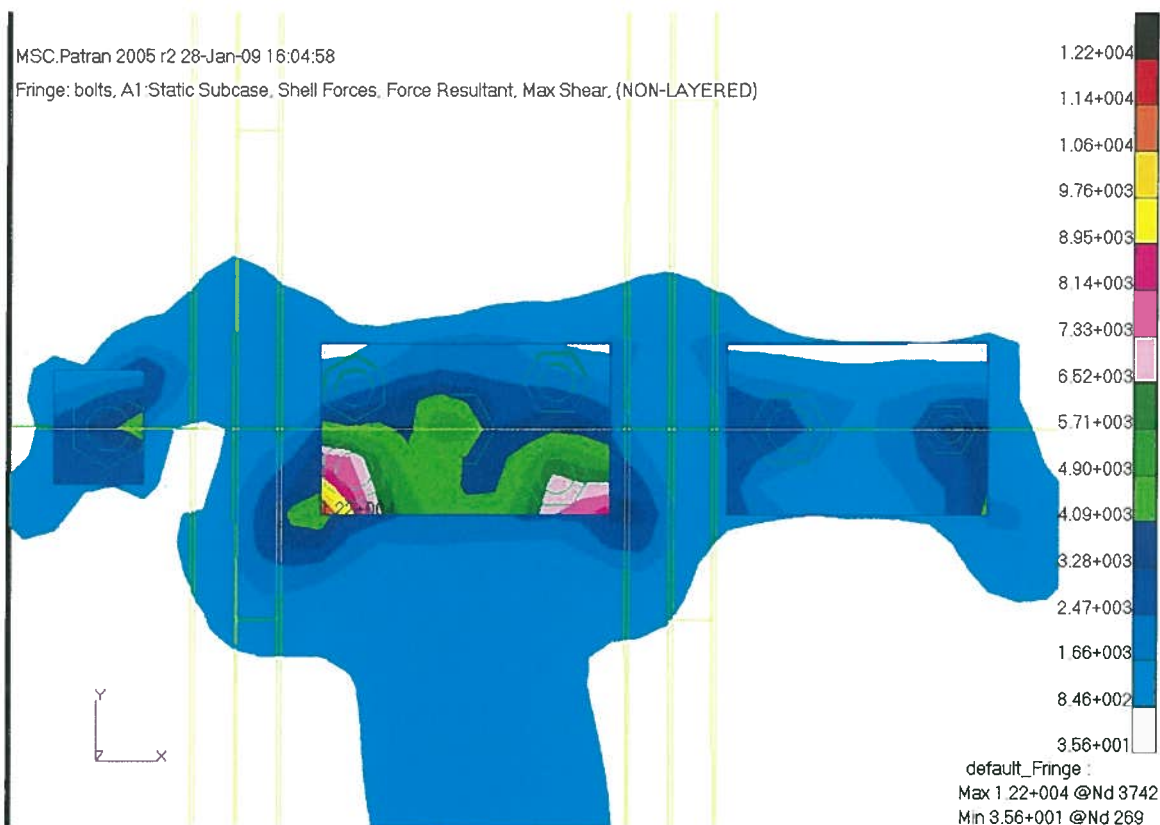


**Showing grid location in hull**



**Close up of grid placement on the hull structure**

While all the plots on the Nastran finite element analysis show the hull is significantly under built, the one on page 16 (reproduced below) is the most significant, since it shows the mode of hull failure. The maximum load the ABS Guide allows is 50% of the materials' maximum shear strength. That number is 14,000 psi x 50% = 7,000 psi. The ABS Guide requires a safety factor of 4.0 for ultimate and 2.0 yield for keel bolts. The plot below has yellow showing and orange, red, and black on the forward tip of the middle backing plate. The backing plates for the keel are seen on the plot as the three rectangles. Reading from the scale on the right of the diagram shows that the black equates to  $1.22 \times 10^4 = 12,200$  lbs. on a broach load, or 90 degrees of heel. This 12,200 lbs. of load equates to 21,785 psi ( $12,200 \text{ lb./0.56 in.}^2$ ) of shear load is more than 3 times the boat's hull allowable design stress of 7,000 psi. The backing plate acted like an old-style can-opener (a shearing device), tearing through the hull on the port side, starting at the middle backing plate forward corner. The peak shearing load equates to an ABS hull thickness of 3.11 inches. The excessive thickness of the hull fiberglass is due to the use of very narrow backing plates. The thickness of the fiberglass could be reduced with the use of wider backing plates.



**Shear force diagram on the hull. This diagram shows the failure mode for the *S/V Cynthia Woods*. The failure started on the left front corner of the middle backing plate.**

### Flanged Keels

Flanged keels distribute the load over the hull to reduce stress on the laminate.



**Photo.** The keel in this photo shows the keel framing system for a 30 foot boat with a 1500 lb keel vs. the *S/V Cynthia Woods*' 5000 lb keel.

### Keel Grounding Frames and Systems



In this center photograph, this design has a 7-inch wide grounding frame on a 34-foot boat. The keel weighs only 1,500 pounds.





### Cape Fear 38 Particulars

#### Yacht Dimensions- from Brochure

LOA	38'
LWL	34'
Draft	6'
Beam	11'
Displacement	11,800 lbs.
I	48.5'
J	14'
P	48'
E	17'
Mast Height	58.5'
Displacement as Weighed	13,700 lbs.
Sailing Displacement	15,700 lbs.
LWL measured	36.3'
Keel Weight stamped	4870 lbs
Keel CG measured	40.85 in (no shim)

## cape fear 38

### A Production Boat Built To Your Specifications.

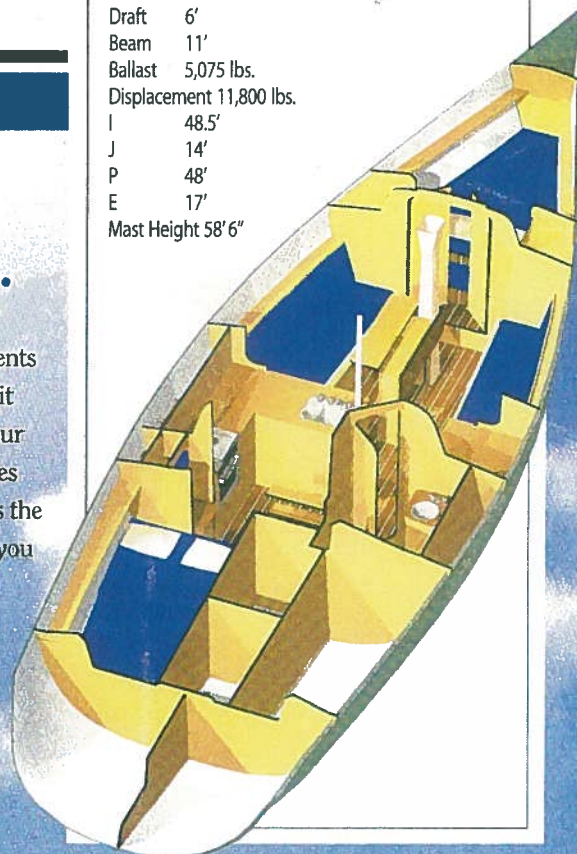
While Cape Fear Yacht Works is a production company, we're small enough to service our clients beyond simply delivering a quality boat. We'll sit and talk with you, sailor-to-sailor, and go over our extensive list of options to determine the features which are right for you. If the Cape Fear 38 fills the bill, plus or minus this or that, we'll work with you to create the boat that meets your expectations.

The point is, we want you to be as excited about the Cape Fear 38 as we are.

Factory Direct - Brokers Protected  
Specifications Subject To Change Without Notice

#### SPECIFICATIONS

LOA	38'
LWL	34'
Draft	6'
Beam	11'
Ballast	5,075 lbs.
Displacement	11,800 lbs.
I	48.5'
J	14'
P	48'
E	17'
Mast Height	58' 6"



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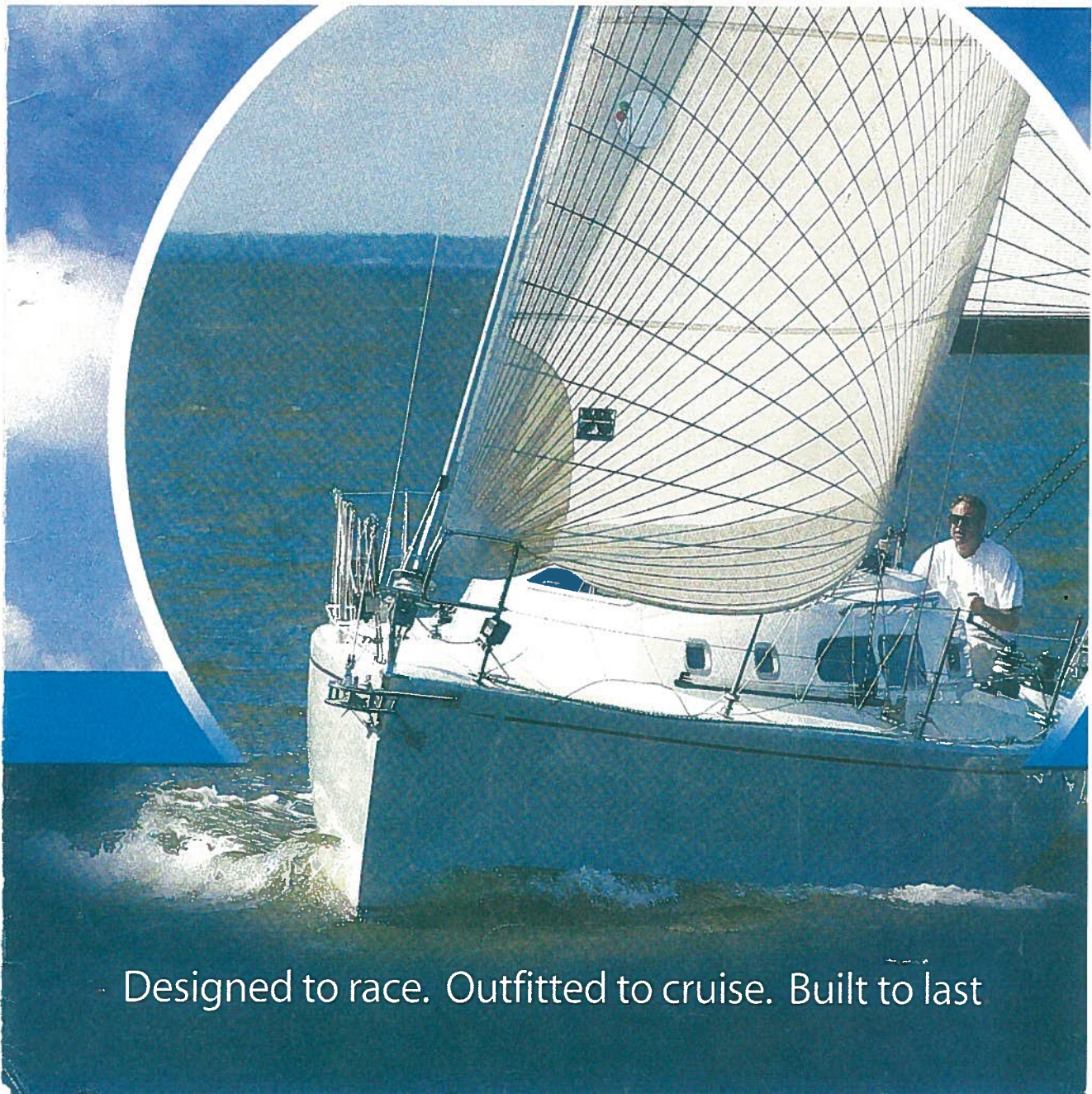
  
**CAPE FEAR**  
YACHT WORKS



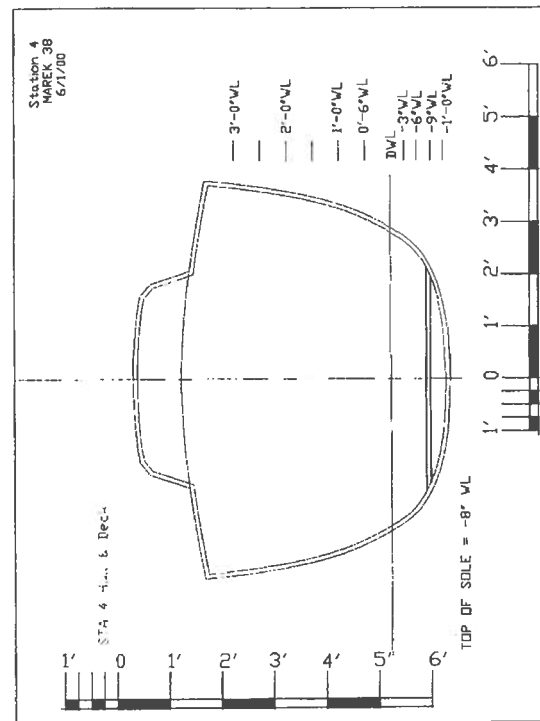
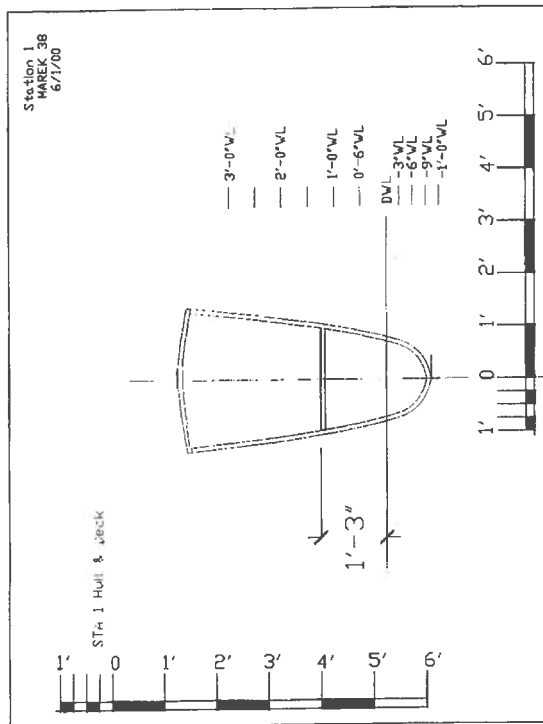
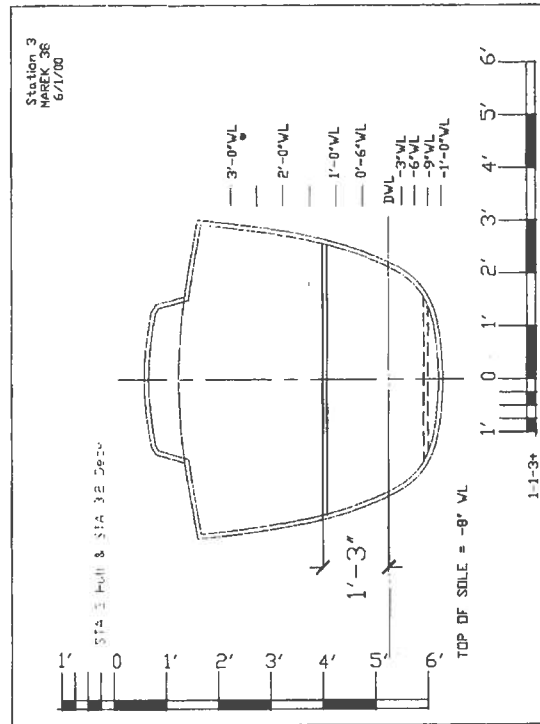
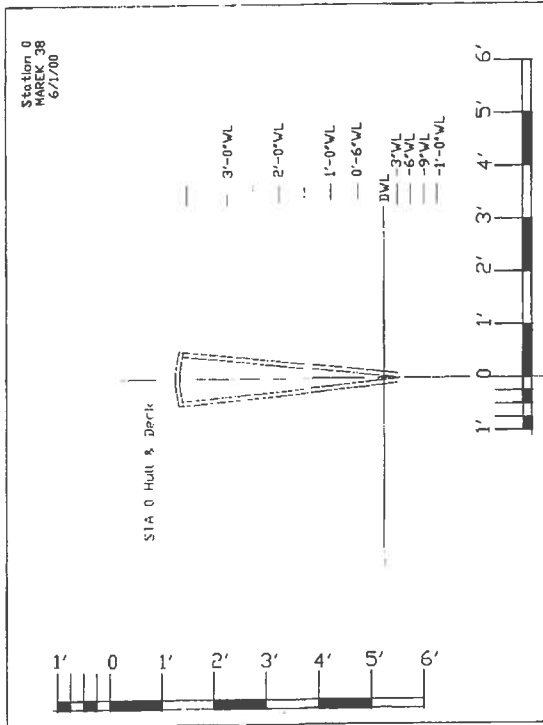
**CAPE FEAR**  
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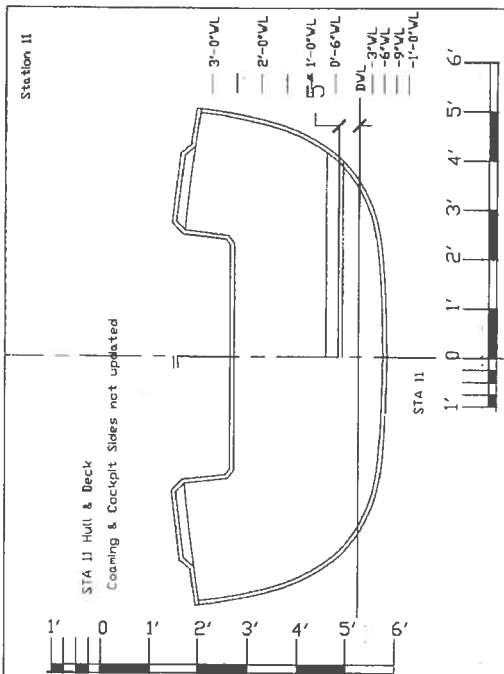
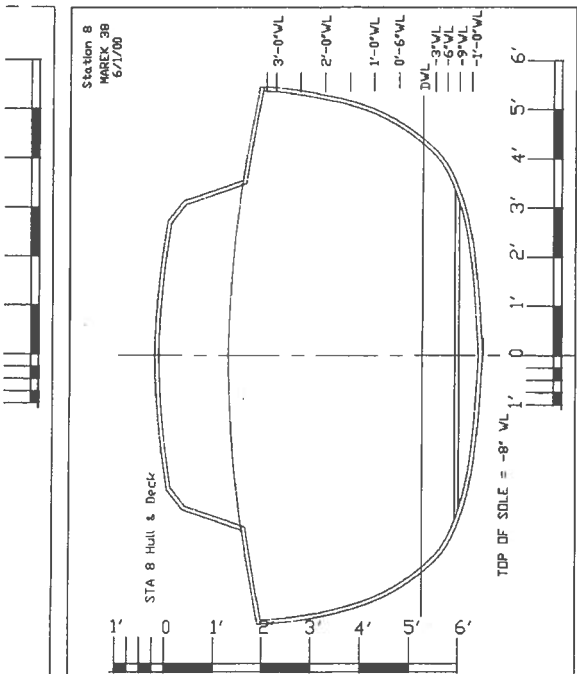
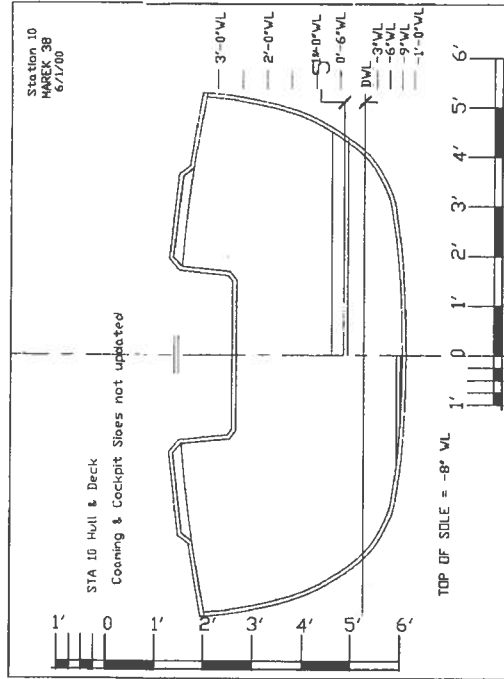
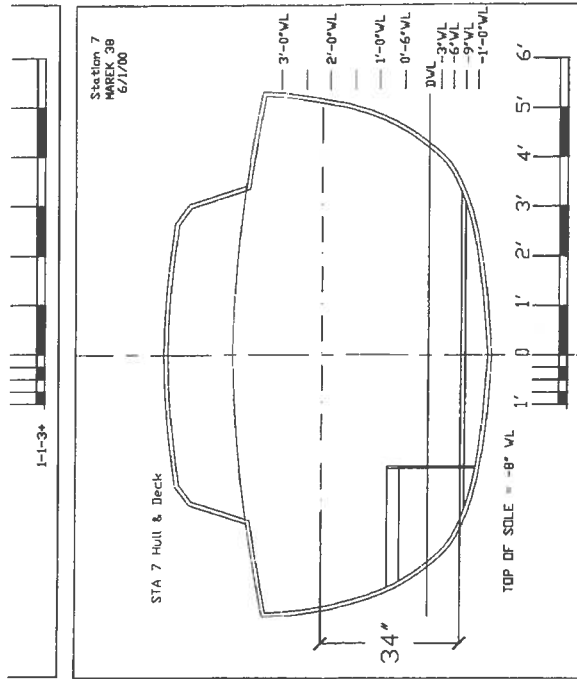
cape fear 38

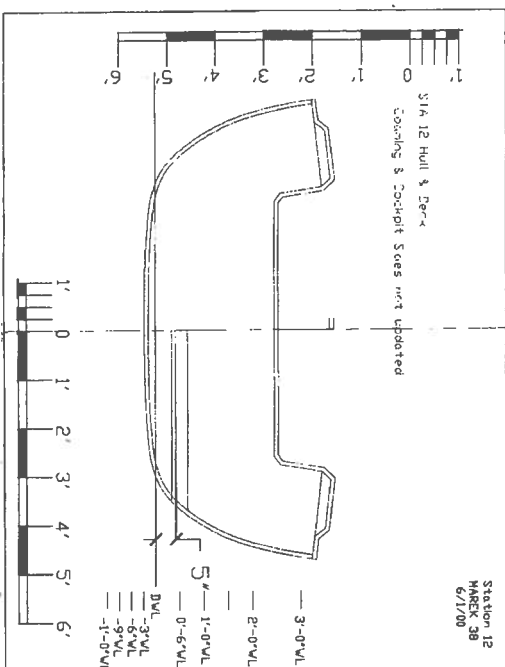
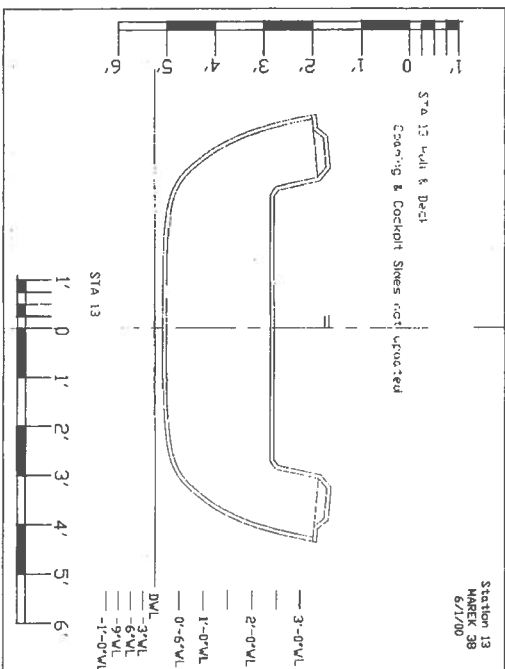
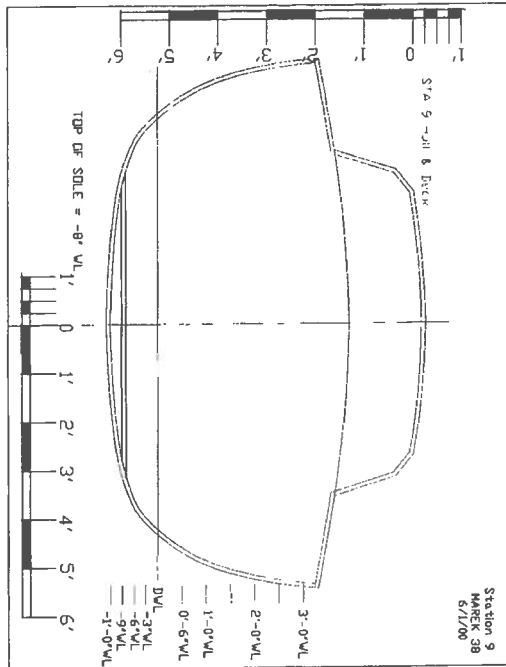
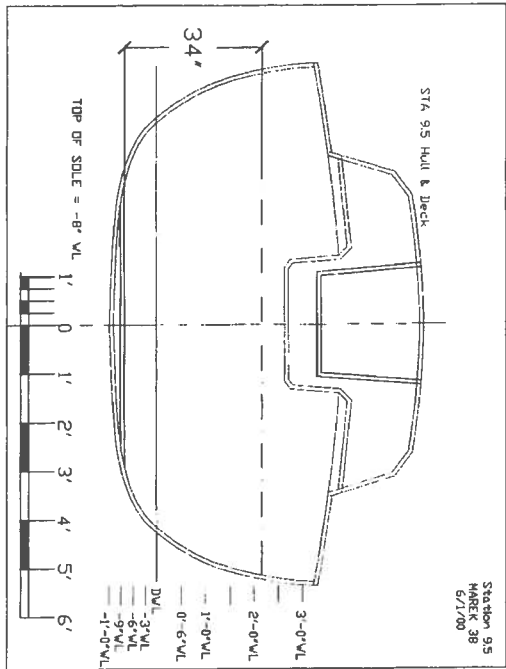


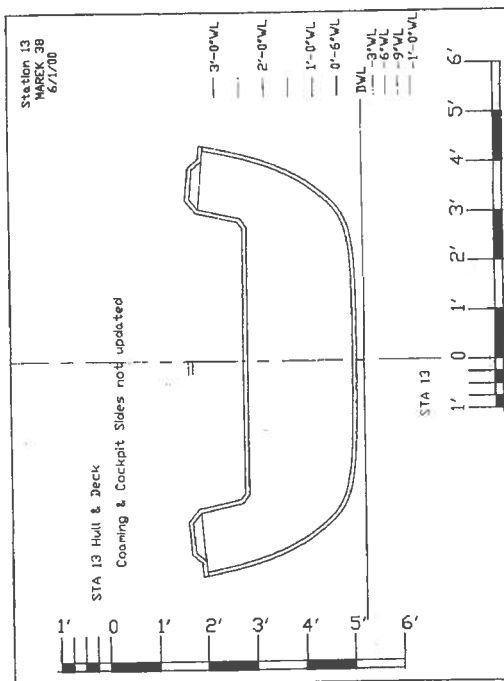
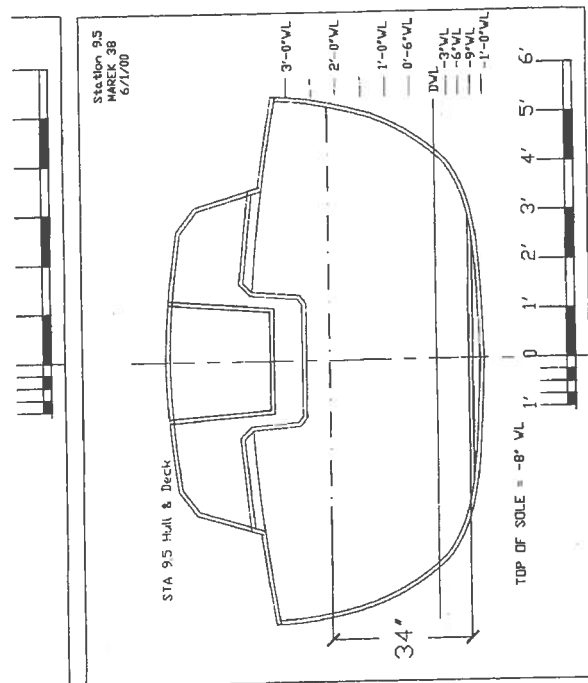
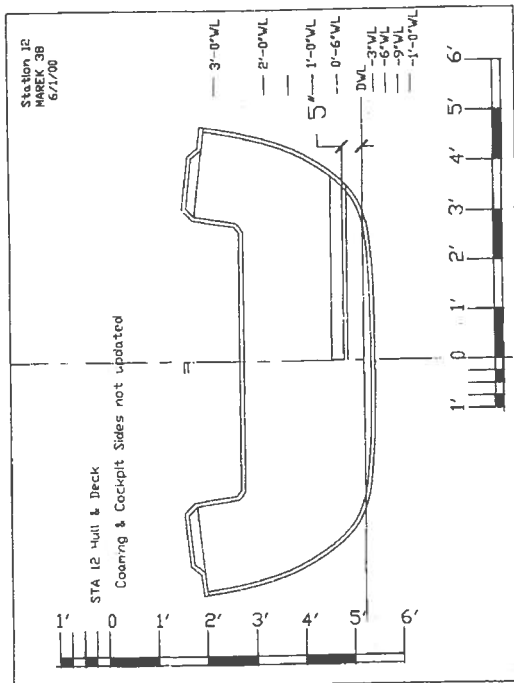
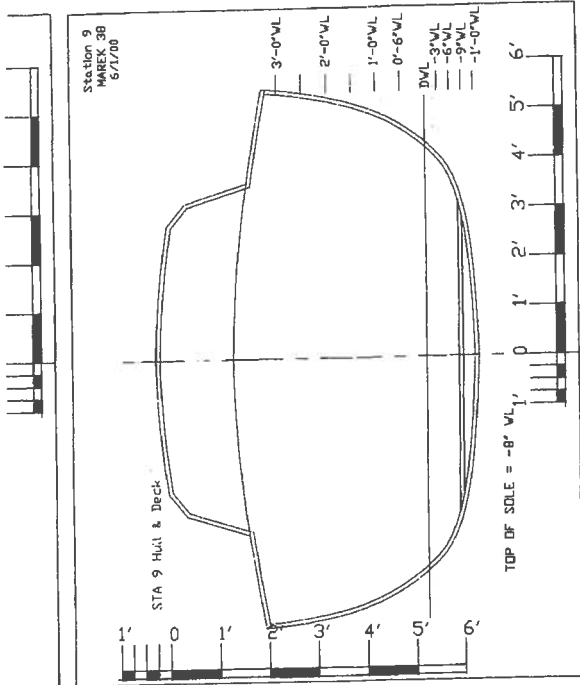
Designed to race. Outfitted to cruise. Built to last

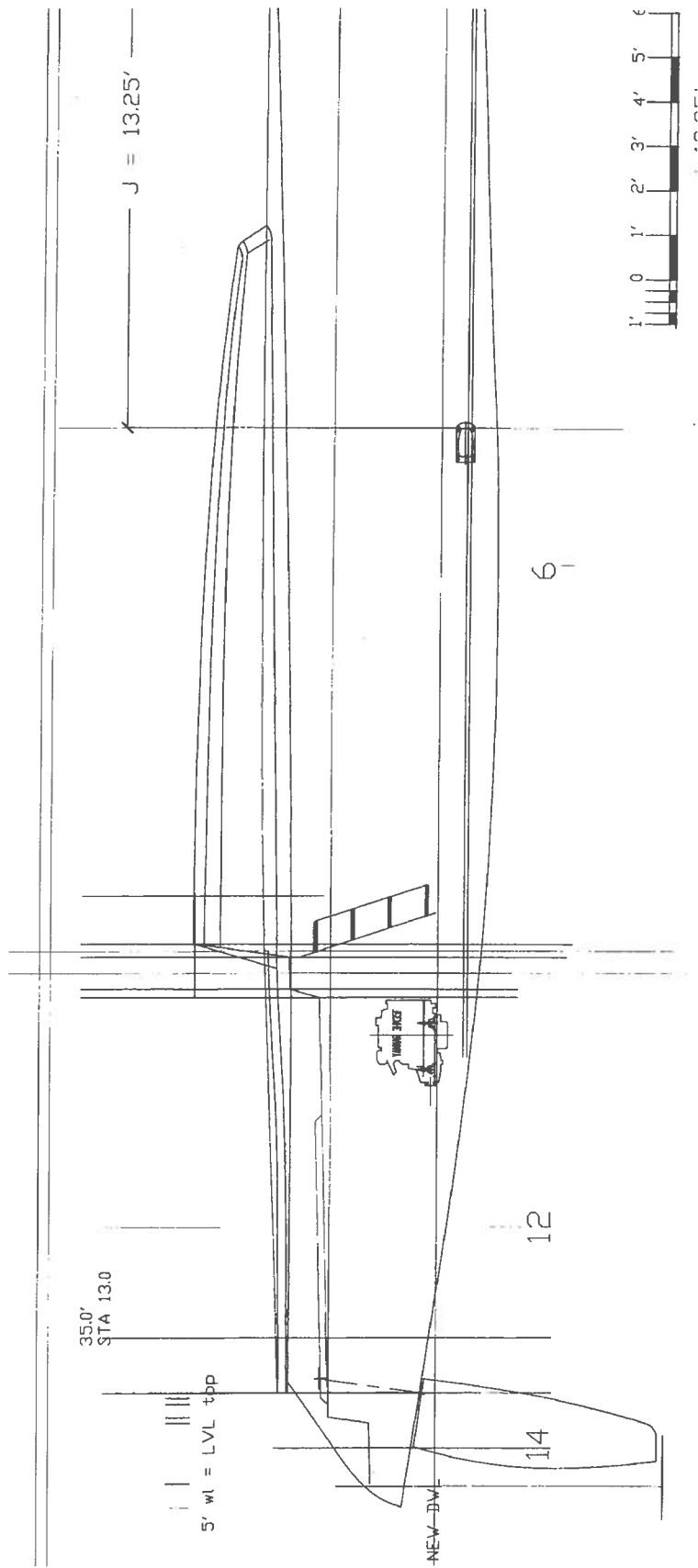




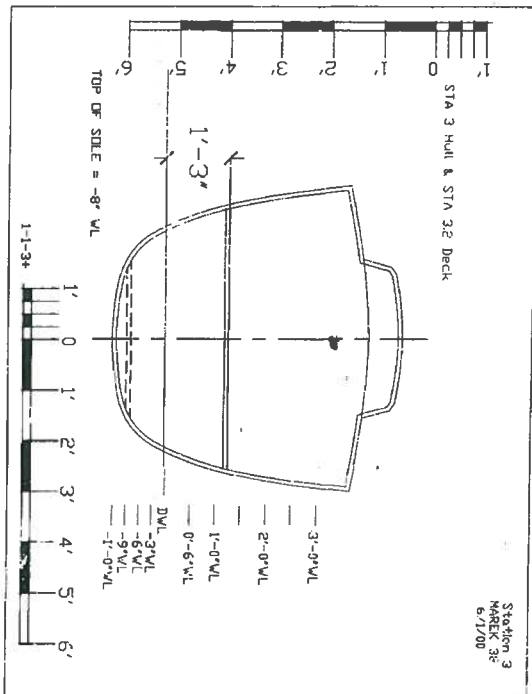
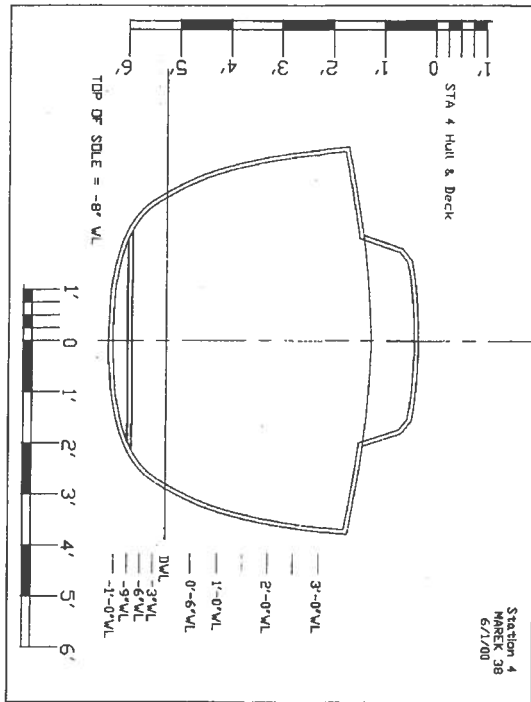
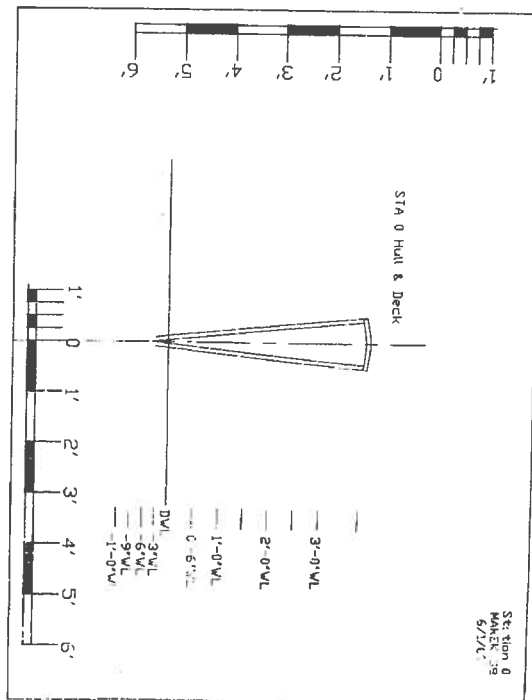
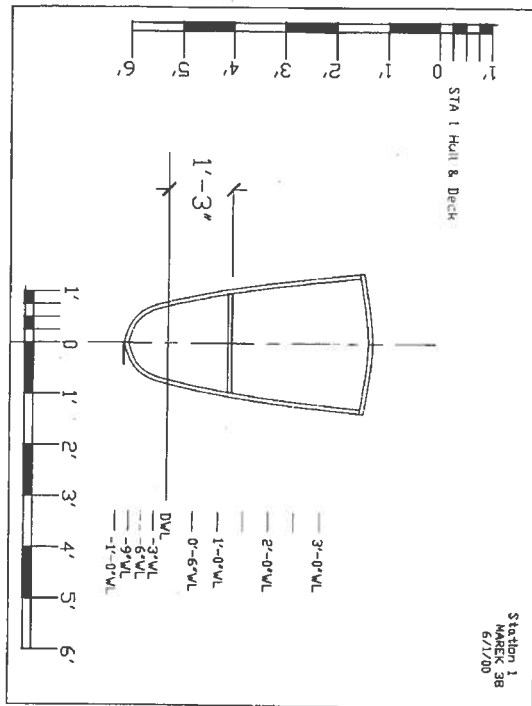


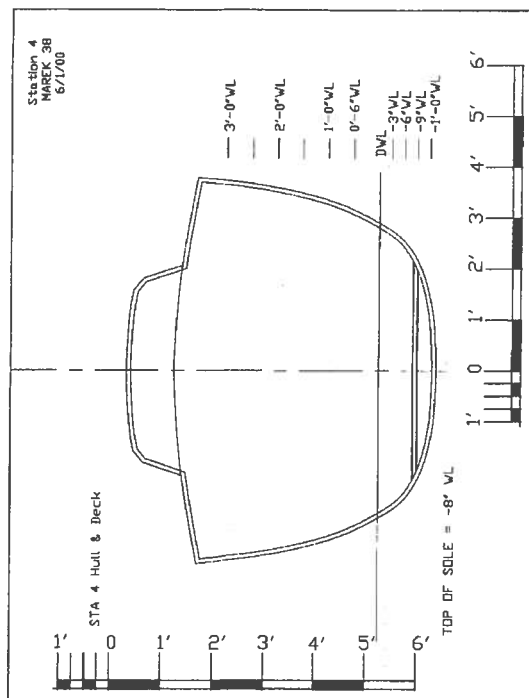
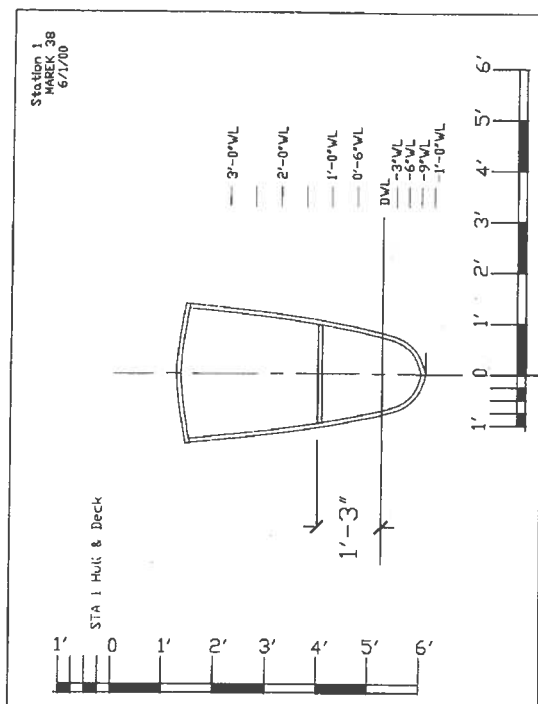
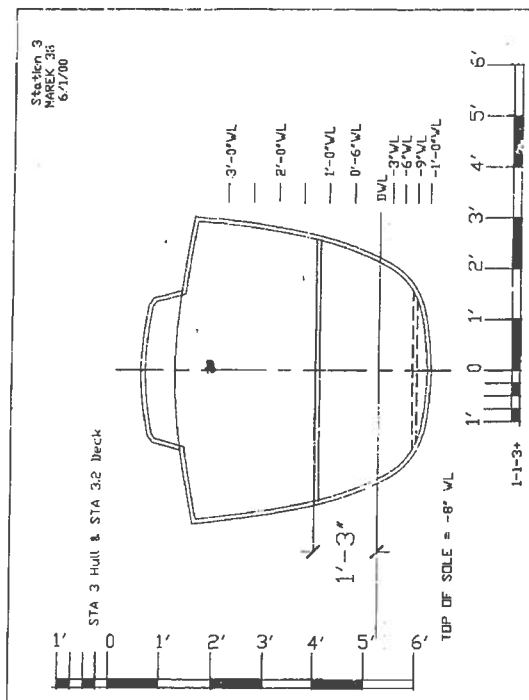
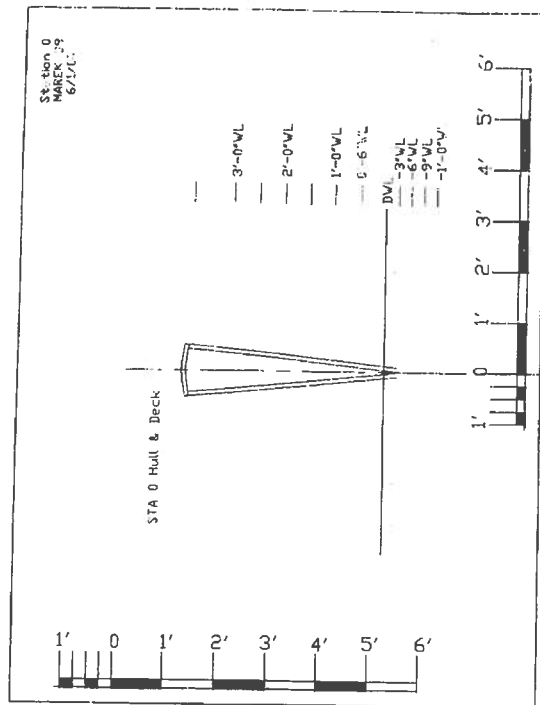




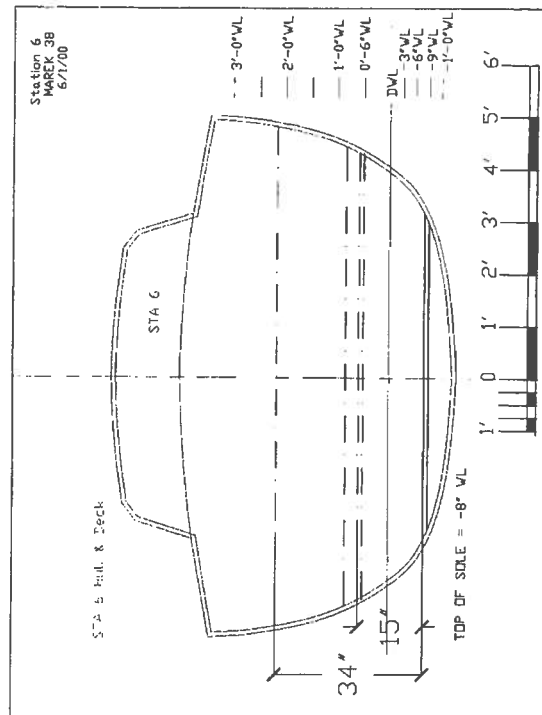
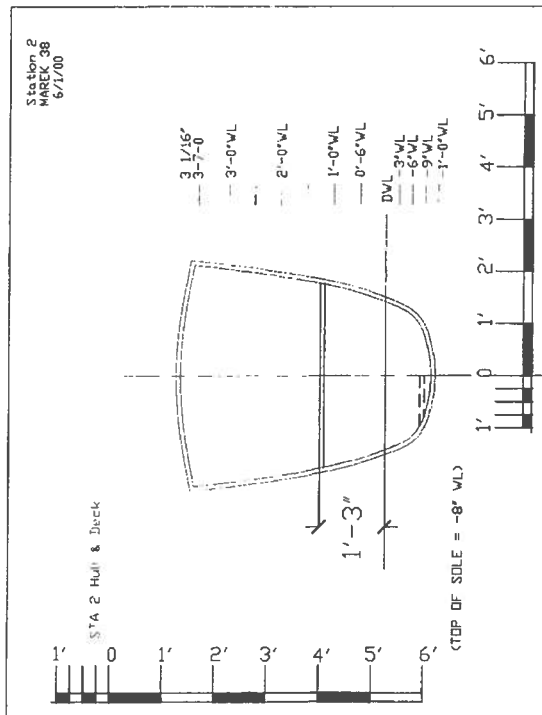
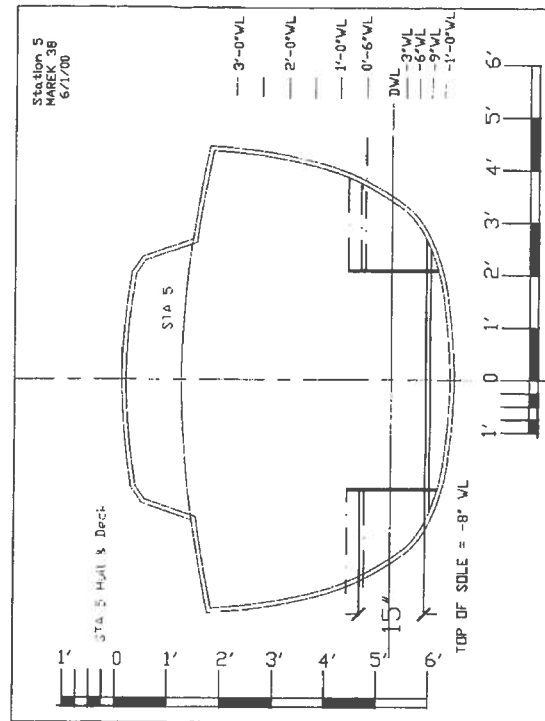
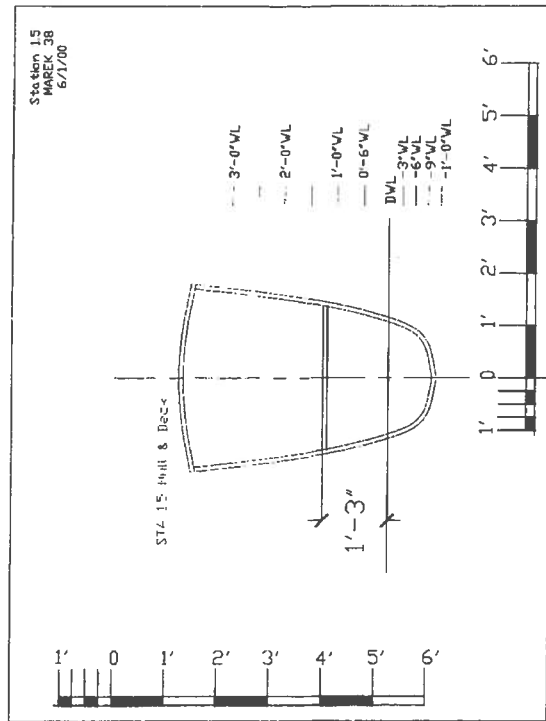




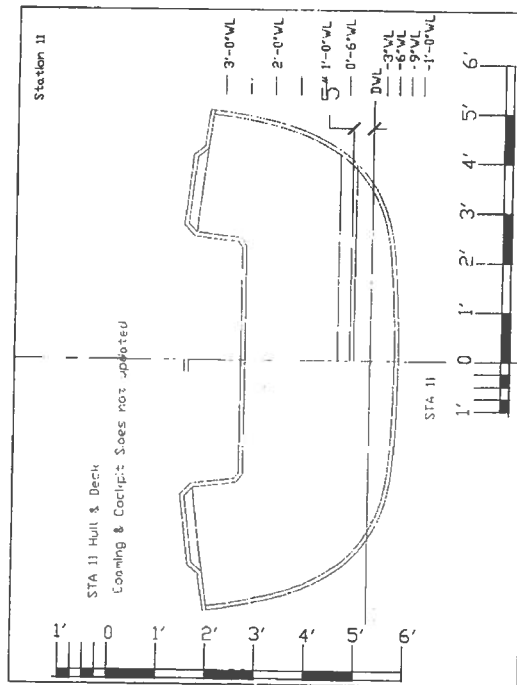
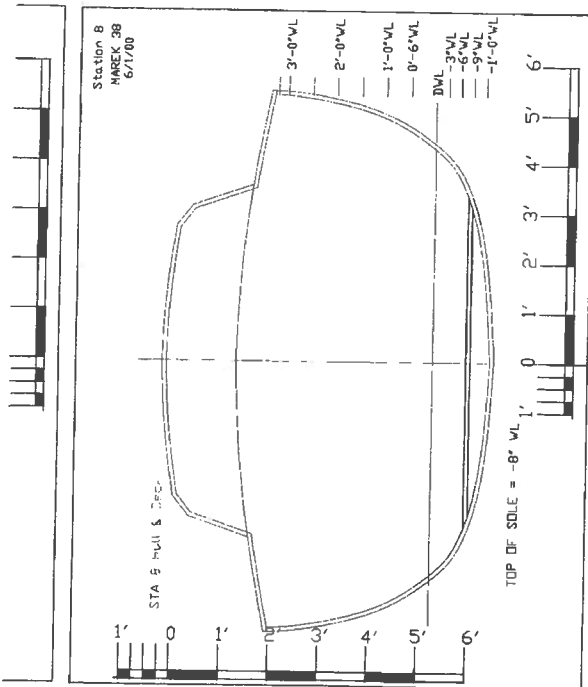
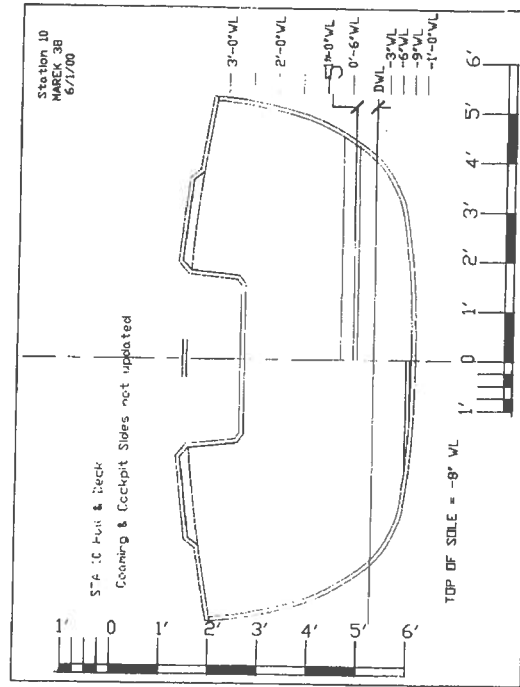
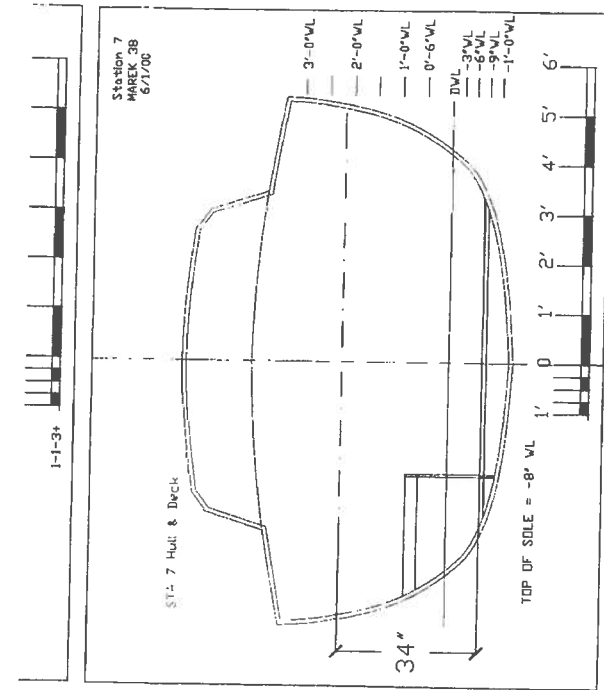




Section 0









# OC® FABRICS OC® BIAxIAL FABRICS (0°/90°)

## PHYSICAL PROPERTIES / AVAILABLE PRODUCTS

FABRIC STYLE	TOTAL WEIGHT (OZ/YD²)	0°	90°	+45°	-45°	MAT	DRY THICKNESS (INCHES)
CD120	12.7	5.8	6.0	0	0	0	0.023
CDM1208	20.3	5.8	6.0	0	0	7.6	0.036
CDM1608G	23.8	10.4	5.5	0	0	7.6	0.045
CD180	21.5	10.3	10.6	0	0	0	0.034
CDM1808	29.2	10.3	10.6	0	0	7.6	0.049
CDM1815	35.1	10.3	10.6	0	0	13.5	0.067
CD240	26.0	13.9	11.9	0	0	0	0.042
CDM2408	34.1	13.8	12.1	0	0	7.6	0.059
CDM2415G	39.6	13.9	11.9	0	0	13.5	0.065
CDM3205G	40.4	15.7	17.7	0	0	6.8	0.059
CDM3208G	41.2	15.7	17.7	0	0	7.6	0.056
CDM3610G	44.6	17.4	17.4	0	0	9.0	0.065

## SAMPLE MECHANICAL PROPERTIES

Sample Mechanical Properties of Laminate based on  
CDM1808 (50% glass content by weight).

	ENGLISH UNITS	SI UNITS
<b>Tensile (ASTM D 638)</b>		
Strength	37.2 ksi	256 MPa
Modulus	2.10 msi	14.5 GPa
<b>Compression (ASTM D 695)</b>		
Strength	30.2 ksi	208 MPa
Modulus	1.83 msi	12.6 GPa
<b>Flexural (ASTM D 790)</b>		
Strength	61.0 ksi	420 MPa
Modulus	2.30 msi	15.8 GPa

Sample Mechanical Properties of Laminate based on  
CDM2415 (50% glass content by weight).

	ENGLISH UNITS	SI UNITS
<b>Tensile (ASTM D 638)</b>		
Strength	35.2 ksi	243 MPa
Modulus	2.06 msi	14.2 GPa
<b>Compression (ASTM D 695)</b>		
Strength	31.3 ksi	216 MPa
Modulus	1.97 msi	13.6 GPa
<b>Flexural (ASTM D 790)</b>		
Strength	58.6 ksi	404 MPa
Modulus	1.95 msi	13.4 GPa



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## Conclusions and Recommendations

### S/V Cynthia Woods

The vessel was a Cape Fear 38R production sail boat owned by Texas A&M University at Galveston. The boat was used for various functions by the university's student sailing team, including offshore races. On the 6 June 2008, the boat was taking part in a race to Mexico when the keel fell off of the yacht, resulting in the loss of one life. The vessel was commissioned in 2005.

The vessel had a few groundings during its time commissioned as a sailing yacht. The yacht spent most of its time sailing in Galveston Bay which is shallow compared to other popular coastal areas for sailing. This use in this type of area is similar to that of thousands upon thousands of boats every year. Groundings of sailing vessels are very common and they do not result in their keels falling off.

There was nothing unusual or spectacular about any of the groundings. In March 2007, there was a grounding requiring the assistance of a powerboat to free the yacht by towing it across a sandbar/oyster bank. While the crew could have elected to be pulled in the opposite direction, the decision was not material to causing the keel to fail. The bottom of the keel showed nothing unusual about typical grounding accidents—some scrapes, maybe a small indentation. The physical condition of the keel does not suggest anything unusual or different from the many thousands of boats that go aground worldwide in the course of their usage.

Texas A&M University at Galveston followed best practices by taking the yacht to a professional boat yard to be repaired. This is an accepted course of action as tens of thousands of boats undergo repairs for grounds every year. This is comparable to car owners taking their vehicles to mechanics for repairs.

The damage from grounding was nothing unusual. The lead aft of the last keel bolt had compressed. The familiar v-shaped crunch was present where the lead is thin and there are no supporting structural bolts. The front of the keel had a small gap because the forward keel bolt was further back than the standard connection design. There were some small foot-long cracks along the intersection between the sides of two of the frames and hull. The bottom of the keel had no unusual damage due to the grounding.

The keel had some leaks in the joint of the hull and keel and the keel was removed by the boatyard and re-bedded with new caulking. The caulking is a thin rubbery/glue-like substance that prevents water from leaking between the hull and the keel of the boat where they are attached. The fact that the keel was leaking was due to the keel being deep (long), and having a small footprint on the hull. A footprint, like a footprint in the sand, is the amount of area that the top of the keel has where it attaches to the hull. Typically, small footprint keels use a flange on the top to distribute the load from the top of the keel to the hull.

When the keel is removed, a boatyard will normally sound tap and inspect the hull to look for any delamination that might have occurred and any other flaws, and inspect the area before putting the keel back on the boat. It is hard not to inspect the area since all the old caulk must be removed before reattachment of the keel.

The keel was reattached with new caulk and the small cracks were repaired with two layers of 24 oz/yd<sup>2</sup> fiberglass woven roving material and epoxy resin. This was similar to the underlying material. The ABS Guide calls for 2.5 inch overlaps, and these were well exceeded in the repair of the cracks. The internal fiberglass frame repair work was done by TAMUG students and done in an acceptable manner. The boat should have been, at this point, sufficiently sound for its intended use because it was repaired to the as-built specifications.



The process used by the university happens on a day-to-day basis for boat owners and boatyards around the world. Boats are damaged and they are brought to boatyards for repair. At times, the owner does some minor repairs. This is standard procedure in the industry. There are no engineers, designers, original builders, thermal imagers, statisticians, philosophers, painters, or any others brought in to investigate. This is simply a production boat being repaired for a common problem. While the March 2007 grounding and resulting damage might have been an unusual event for the TAMUG sailing team, it was a very common event for any boat that is used as the team used the boat. A boat ran aground and it was brought to a boatyard for repair. It is always a reasonable assumption to presume the boat was initially properly engineered.

The boat was repaired and went on to perform its function without incident for more than a year. The internal repairs made by the TAMUG students were to minor framing cracks and the repairs done are still structurally intact. It is not reasonable to expect an owner or a shipyard to know the vessel's hull-to-keel joint did not pass the ABS Guide standards. When the boat was built, meeting the design and construction criteria of the ABS Guide was, and still is, a requirement for recreational and offshore racing yachts prior to leaving the builder's factory—just as the purchaser of a car or truck can reasonably assume the manufacturer properly designed and built his vehicle.

Two of the most basic requirements of the ABS Guide were violated: (1) the hull was not minimally as thick as the diameter of the bolts; and (2) a seriously deficient safety factor was utilized, causing insufficient sheer load capacity. When the 1 1/2 inch diameter holes were drilled into the 1/2 inch laminate, there was not enough structure there to securely hold the keel in place. These deficiencies, coupled with the very narrow backing plates sized to the width of the keel, produced high internal stresses in the hull. The initial joint was experiencing fatigue (a loss of strength) as do all materials. This eventually produced enough stress to tear the hull apart, separating the keel. Once the tear started next to the forward port keel bolt of the second backing plate, it tore through the hull in just a very few seconds, causing the boat to capsize.

#### *S/V George Phydias*

The *S/V George Phydias*, a sister ship to the *S/V Cynthia Woods* that is owned by Texas A&M University, was very prudently taken out of service.

If this yacht would continue to sail, it would eventually experience the same failure as the *S/V Cynthia Woods*. The keel would fail in the forward split bolt area in the second backing plate between the main two keel frames.

If this boat will be continued in service, I recommend a new flanged keel for the *S/V George Phydias* with a new internal structure with properly placed framing to accept the keel.

#### Other Cape Fear 38s not owned by TAMU or TAMUG

Knowing the framing structure of the boats owned by TAMU and TAMUG, it is my opinion that a marine engineer should critically inspect these boats to determine if design and construction modifications should be made to the vessels.

#### **END OF DOBROTH SCIENCE REPORT**

## **APPENDIX – NASTRAN FINITE ELEMENT ANALYSIS**

## **APPENDIX – NASTRAN FINITE ELEMENT ANALYSIS**



**Cynthia Woods**  
**90 Degree Load (Keel Bending Moment), Grounding Load,**  
**Keel Bolt & Hull Shell Analysis**  
January 30, 2009

**1.0 INTRODUCTION**

This structural analysis of the keel bolts & keel mounting structure (including the keel bolt backing plates) & keel floors, was started after the Cynthia Woods, a Cape Fear Yacht Works 38' model, lost its fin/bulb keel during an overnight yacht race in the Gulf of Mexico this past summer on June 6, 2008. The wind & wave conditions at the time of this incident (indicative of the loads on the keel & hull) & additional details of this incident are summarized in the United States Coast Guard investigation into the sinking of the Cynthia Woods. The wind was averaging 20 knots, gusting to 30 knots, & the report states that the loss of the keel was not 'because of bad weather or normal racing loads'.

Rev #	Revision Description	Date	By
1	Initial Release	1/19/2009	W. Dickerson
2	Final Release	1/30/2009	W. Dickerson

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## **2.0 REFERENCES**

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2. Re: United States Coast Guard investigation into the sinking of the Cynthia Woods,  
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Claudia Feldman & Mike Tolson  
12/2/2008
4. Lost at Sea – The tragedy of the Cynthia Woods.  
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11/29/2008
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6. Lost at Sea – Crew of sunken sailboat rescued.  
Claudia Feldman  
12/1/2008
7. Lost at Sea – Stone family's fears come true.  
Claudia Feldman  
12/2/2008
8. E.F. Bruhn, Analysis and Design of Flight Vehicle Structures, 2<sup>nd</sup> edition
9. MMPDS-01, Metallic Materials Properties Development and Standardization 2003

### 3.0 SCANTLINGS

The structural portion of the laminate for the hull shell was approximately 9/16" thick Owens Corning 1808 combination roving & mat. Experience has shown that actual hand layup in a boat shop for an air cure generally achieves 85% of the published properties for this material, which gives the following laminate properties used in this analysis. The hull shell was modeled as CQUAD shell elements for this model.

Property	Symbol	85% Value	Comment
Thickness	t	0.049 in./ply	Actual
Longitudinal Modulus	E11	1790000. psi.	
Transverse Modulus	E22	1790000 psi.	
Shear Modulus	G66	250600. psi	
Poissons Ratio	V12	0.14	
Thermal Expansion	Alf1	5.6E-7	Longitudinal
Thermal Expansion	Alf2	5.6E-7	Transverse
Longitudinal Tension	F1t	31600. psi.	
Longitudinal Compression	F1c	25700. psi	
Transverse Tension	F2t	31600. psi.	
Transverse Compression	F2c	25700. psi.	
Shear	F12	9500. psi.	
Interlaminar Shear	Fils	4000. psi.	
Interlaminar Tension	Filt	3000. psi.	
Bearing	Fbu	50000. psi.	Ultimate
Bearing	FbrO	15000. psi.	Open Hole
Compressive Strain	eOHC	0.006 in./in.	Open Hole
Tensile Strain	eOHT	0.006 in./in.	Open Hole

Note: eOHC = Open Hole Compressive Strain Allowable.  
eOHT = Open Hole Tensile Strain Allowable. Both strain allowables for laminate without holes would be 0.010 in./in.

**Table 3.1 – Laminate Properties**

For the stainless steel backing plates, a Young's Modulus of 28.5E6 was used (Reference #9). Neither the keel bolts or the backing plates failed. Thus, no strength properties were required for the bolts & the backing plates for this model. The overall dimensions for the backing plates were:

Backing Plate	Length	Width	Thickness
	inches	inches	inches
Forward – Bolt #1	3-7/8	3-7/8	3/8
Middle – Bolts #2 - #6	10	6	3/8
Aft – Bolts #7 & #8	9	5	3/8

**Table 3.2 – Keel Bolt Backing Plate Dimensions**



To examine the loads at the outboard edges of the backing plates bearing on the hull, constraints (MPC's) were located at nodes along the edges of the backing plates along the right hand side outboard edge. In addition, rigid body elements (RBE3's) attaching the backing plates to the hull shell are located at each of the nodes of the backing plates to examine these local loads.

The transverse keel floors were modeled as CBEAM elements for this model. This model was not intended to examine specifically the strength of the transverse floors, since they were modeled to correctly distribute the keel loads (bolt loads) to the hull shell. Constraints (six SPC's for the three floors) were located at the outboard ends of the floors to correctly distribute the load out away from the keel to the berth fronts. The dimensions & properties of these three (3) floors were modeled correctly from the information given as follows:

Keel Floor Property	Forward Floor	Middle Floor	Aft Floor
Thickness – Floor Side inches	0.13	0.13	0.13
Thickness – Floor Top inches	0.44	0.44	0.44
Height - inches	5-3/8	5-3/8	6
Top Width - inches	3	3	3
Area – square feet	0.0192	0.0192	0.0203
Moment of Inertia X-X Axis – ft.^3	3.27E-4	3.27E-4	5.4E-4
Moment of Inertia Y-Y Axis – ft.^3	4.82E-5	4.82E-5	4.82E-5

**Table 3.3 – Properties of the Keel Floors**

Even though the keel floors were not examined in detail for this analysis, it should be noted that the Nastran results, especially for the grounding loadcase, show that the 0.13" thick vertical sides of the floors are not sufficiently thick to support the 0.44" thick floor caps & will fail in shear.

#### **4.0 MARGIN OF SAFETY SUMMARY**

The summary information available from the Nastran runs was reduced to maximum principal, minimum principal, maximum shear, max. & min. element X direction, max. & min. element Y direction & maximum XY shear loads for the most critical hull shell elements. All margins are written for limit loads (no factor of safety) with respect to ultimate strength. Further details for the reduced set of critical element loads can be found in Section 5.0 Loads of this report. Margins of safety greater than or equal to 2.00 are reported as ample.

##### **Analyses of 90 Degree Bolt Load (Loadcase #1)**

<b>ID</b>	<b>Description</b>	<b>Critical Loading</b>	<b>Element No.</b>	<b>Failure Mode</b>	<b>MS</b>	<b>Page</b>
1	Bolt #3 Element - LHS	Min Principal Force	3730	eOHC	-0.70	22
2	Bolt #4 Element - Centerline	Minimum Nx X Force	3714	eOHC	-0.51	23
3	Bolt #6 Element - LHS	Maximum Mxy Shear Moment	2630	eOHC	-0.76	24

##### **Analyses of 90 Degree Bolt Load (Loadcase #2)**

<b>ID</b>	<b>Description</b>	<b>Critical Loading</b>	<b>Element No.</b>	<b>Failure Mode</b>	<b>MS</b>	<b>Page</b>
4	Bolt #1 Element - Centerline	Maximum Nxy Shear Force	3675	eOHC	-0.63	32
5	Bolt #2 Element - RHS	Maximum Ny Y Force	3691	eOHT	-0.48	33
6	Bolt #3 Element - LHS	Max Principal Moment	2261	eOHC	-0.80	34
7	Bolt #6 Element - LHS	Minimum Nxy Shear Force	3728	eOHT	-0.58	35

**Analyses of Grounding Condition (Loadcase #3)**

<b>ID</b>	<b>Description</b>	<b>Critical Loading</b>	<b>Element No.</b>	<b>Failure Mode</b>	<b>MS</b>	<b>Page</b>
8	Bolt #2 Element - RHS	Min Principal Force	3690	eOHC	-0.96	43
9	Bolt #3 Element - LHS	Min Principal Moment	3720	eOHC	-0.95	44
10	Bolt #5 Element - RHS	Maximum Mx X Moment	3698	eOHT	-0.96	45
11	Bolt #6 Element - LHS	Max Principal Force	3738	eOHC	-0.96	46

Note: eOHC = Open Hole Compressive Strain Allowable.  
eOHT = Open Hole Tensile Strain Allowable. Both strain allowables for laminate without holes would be 0.010 in./in.

## **5.0 LOADS**

### **5.1 Loadcase #1**

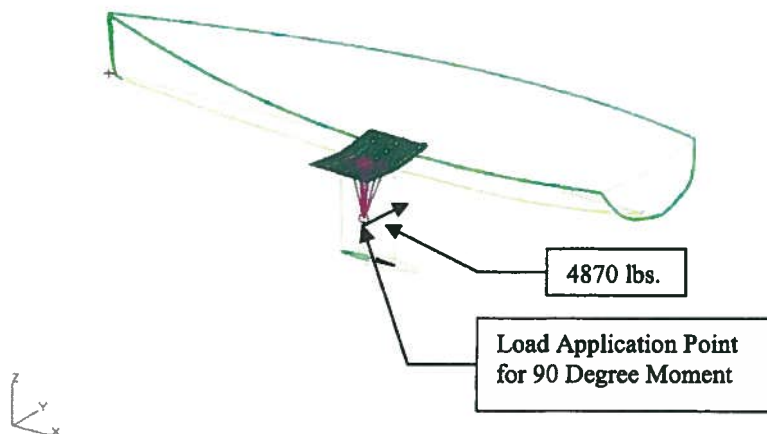
Three loadcases were run to evaluate the strength of the keel mounting structure system. The first loadcase was to calculate the maximum keel bolt loads, without consideration of the deflection of the hull shell & the keel floors, in other words, an infinitely rigid mounting structure. This calculation was done for two (2) subcases, one with the keel moment distributed to all the bolts & the second with the keel moment just distributed to the five (5) bolts through the center backing plate, since this is the stiffest load path between the two (2) keel floors & the aft keel floor is located well off the aft end of the keel & would not be as effective. Based on engineering judgement, the results of these two (2) subcases were averaged for the middle five (5) bolts. The applied moment is the weight of the keel times the moment arm:

$$\text{Keel Moment} = 40.85' (4870 \text{ lbs.}) = 198930 \text{ in. lbs.} = 16578 \text{ ft. lbs.}$$

Then the calculated bolt loads were applied to the Patran model at the keel bolt locations.

### **5.2 Loadcase #2**

The second loadcase was to apply the 90 degree heel keel weight at the CG of the keel & beam this load to the bolt locations in the keel mounting structure Patran model. An illustration of this is shown in Figure 4.2.1.



**Figure 5.2.1 – Patran Model**

This method of load application will result in reduced bolt loads & a different bolt load distribution than above, based on the stiffness of the hull shell, backing plates & keel floors & the widths of the backing plates. It will not result in the maximum bolt loads, but will give a truer representation of the bolt load distribution.



### 5.3 Loadcase #3

Loadcase #3 is the grounding loadcase. An illustration of this case is shown in Figure 4.3.1.

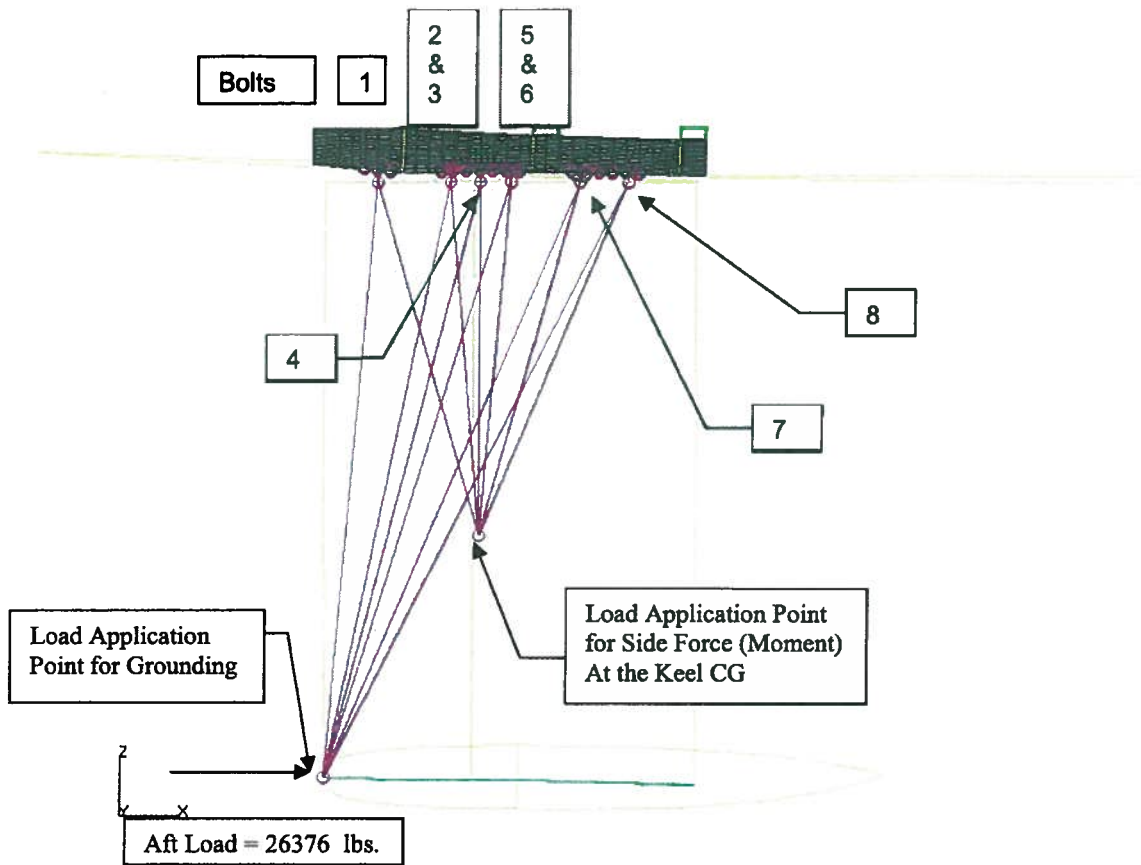


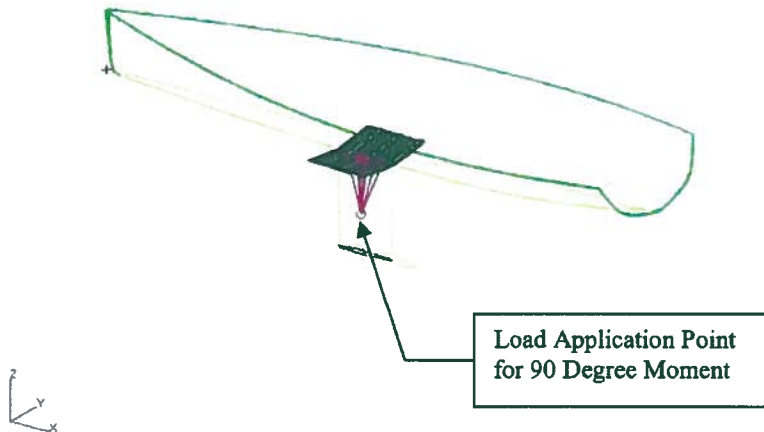
Figure 5.3.1 – Load Application Point for Grounding

## **6.0 PATRAN MODEL**

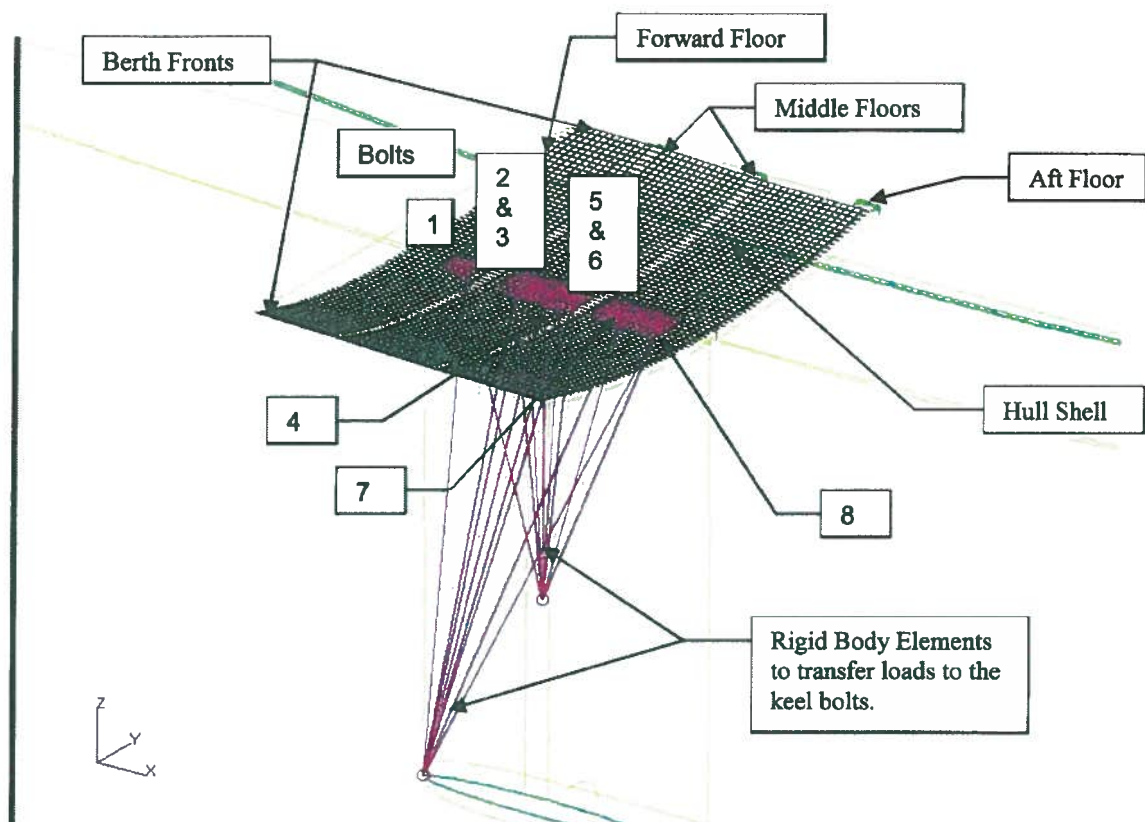
As shown in Figure 5.0.1, a structural finite element model (FEM) of the keel mounting structure was made using Patran, which included the hull shell, the three (3) backing plates & the four (4) keel floors. The actual keel bolts were modeled as multipoint constraints at each bolt location. The fiberglass hull shell was modeled as a layered composite shell element, using a Young's Modulus of 1.4E6 psi for the laminate & 85% of the Owens Corning published properties to account for an actual wet, sailboat shop environment layup. In general, published strength properties are not achieved with actual shop laminates.

The stainless steel backing plates are modeled as duplicate shell elements that use rigid body elements (RBE3's) at each node to attach each backing plate element to the hull shell. Constraints are located along the right hand side of the backing plates to simulate the backing plates bearing on the hull shell for the 90 degree moment loading. From these rigid body elements (RBE3's), the vertical shear loads along the edges of the backing plates can be extracted. Beam elements with the properties of the keel floors are used to simulate these floors. The overall model is constrained (spc's) as being simply supported at the outboard ends of each of the floors (along the berth fronts), which keeps the model from rotating in space & gives the closest to reality representation of the keel mounting structure.

This Patran model is translated into Nastran, a finite element solver, (both programs are aircraft industry standards) to calculate the displacements, internal element forces, moments, strains & stresses to analyze. Then, an aircraft industry standard laminate strength program, CLAM, is used to calculate the layered ply stresses & strains for the hull shell laminate to determine the margin of safety (factor of safety minus 1.0) from the strength allowables.



**Figure 6.0.1 – Patran Model**



**Figure 6.0.2 – Floor Structure & Keel Bolt Locations**

## **7.0 STRUCTURAL ANALYSIS**

### **7.1 BOLT LOADS**

The calculated keel bolt loads for the two (2) subcases are as follows:

Subcase #1 considers only the five (5) keel bolts through the middle backing plate. The centerline keel bolts #1, #4, #7 & #8 are 1-1/2" diameter (root area = 1.295 in.<sup>2</sup>) & the split bolts #2, #3, #5 & #6 are 1-1/4" diameter (root area = 0.694 in.<sup>2</sup>). The Young's Modulus for the stainless steel bolts is 28.5E6 & the length of the backing plate for bearing area is 10" with a Young's Modulus of 28.5E6. The load factor calculated by this analysis, based on the keel root geometry, bolt geometry, Young's modulus of the keel bolts & lead keel (keel root bearing area estimate), is multiplied times the moment to give the bolt load. The bolt loads are as follows:

Keel Bolt No.	Load Factor	Bolt Load	Location
		Lbs.	
2	0.1014	20171	Weather Side Tension
3	-0.0066	-1303	Leeward Side Compression
4	0.0942	18740	Centerline
5	0.1014	20171	Weather Side Tension
6	-0.0066	-1303	Leeward Side Compression

**Table 7.1.1 – Keel Bolt Loads for Subcase #1**

Subcase #2 considers all eight (8) of the keel bolts with the keel moment distributed evenly, regardless of the back-up structure stiffness. The other difference from subcase #1 being that the bearing length being considered is the length of the keel root of 42.42" & the Young's Modulus of the Lead-Antimony of 2.0E6 (Reference #9) to give an estimate of the effective root bearing area.. The bolt loads are as follows:

Keel Bolt No.	Load Factor	Bolt Load	Location
		Lbs.	
1	0.0505	10053	Forward Centerline
2	0.0747	14863	Weather Side Tension
3	-0.0205	-4088	Leeward Side Compression
4	0.0505	10053	Centerline
5	0.0747	14863	Weather Side Tension
6	-0.0205	-4088	Leeward Side Compression
7	0.0505	10046	Aft Centerline
8	0.0505	10046	Most Aft Centerline

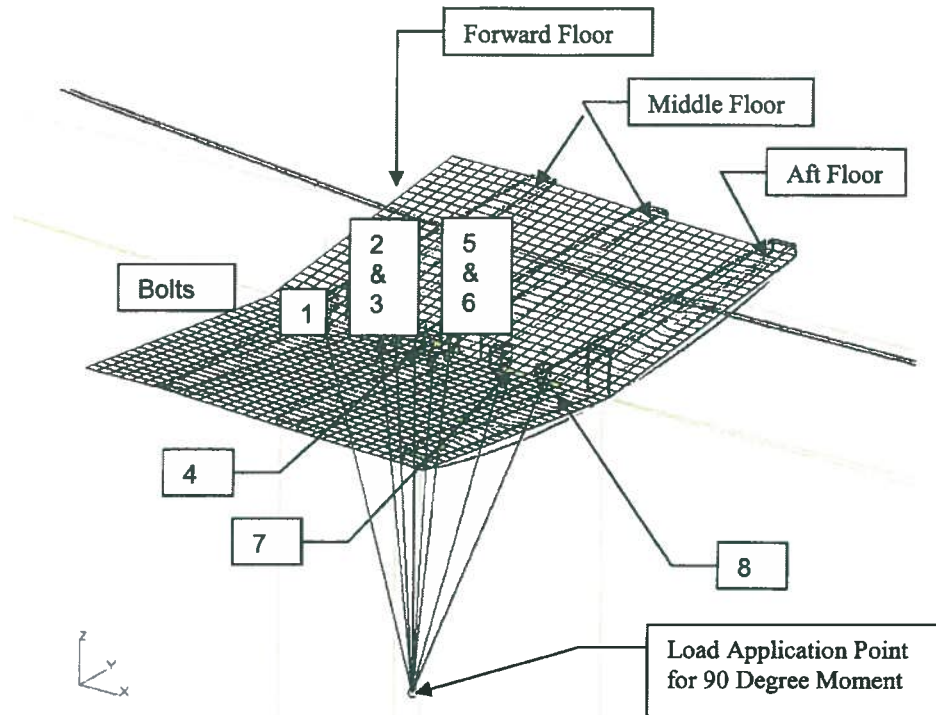
**Table 7.1.2 – Keel Bolt Loads for Subcase #2**

My assumption is to average the two (2) subcases giving the following estimated bolt loads:

Keel Bolt No.	Load Factor	Bolt Load	Location
		Lbs.	
1	0.0505	10053	Forward Centerline
2	0.0845	16802	Weather Side Tension
3	-0.0135	-2696	Leeward Side Compression
4	0.0724	14397	Centerline
5	0.0845	16802	Weather Side Tension
6	-0.0135	-2696	Leeward Side Compression
7	0.0505	10046	Aft Centerline
8	0.0505	10046	Most Aft Centerline

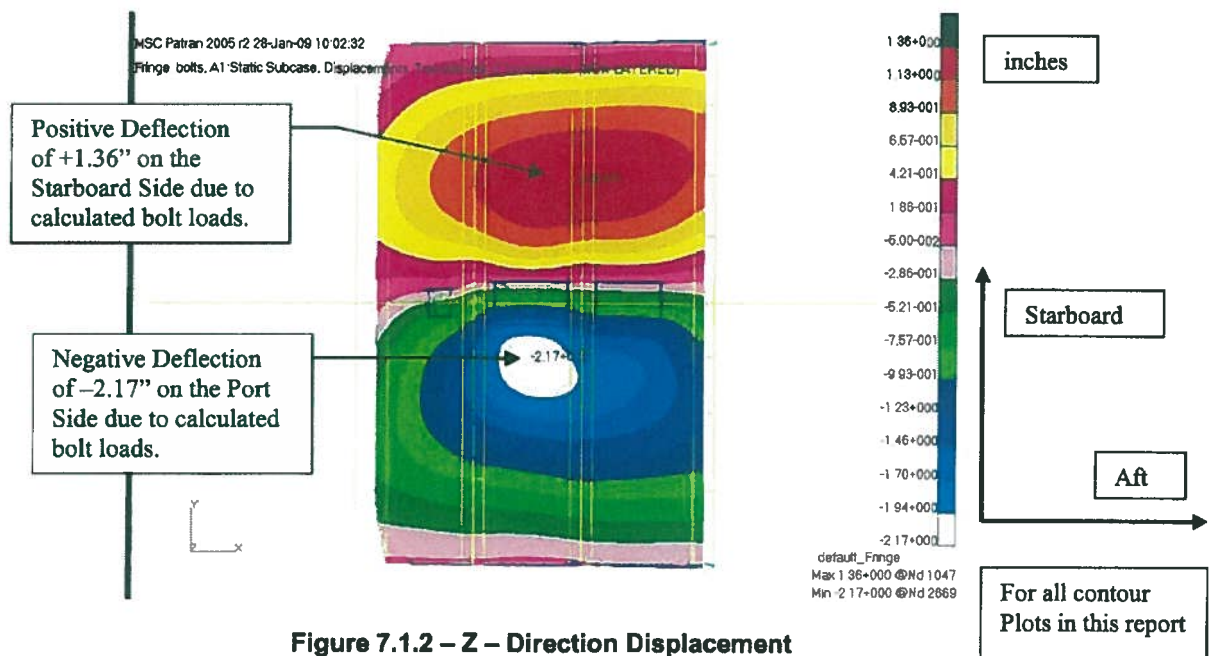
**Table 7.1.3 – Average Keel Bolt Loads**



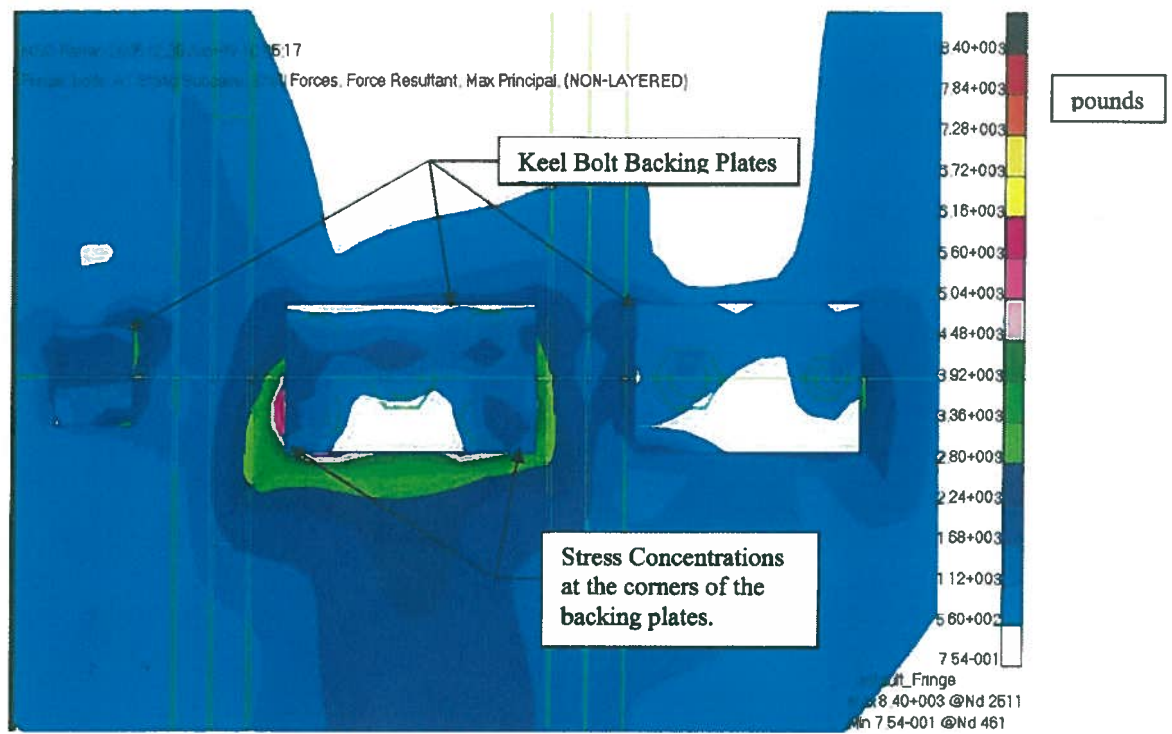


**Figure 7.1.1 – Floor Structure**

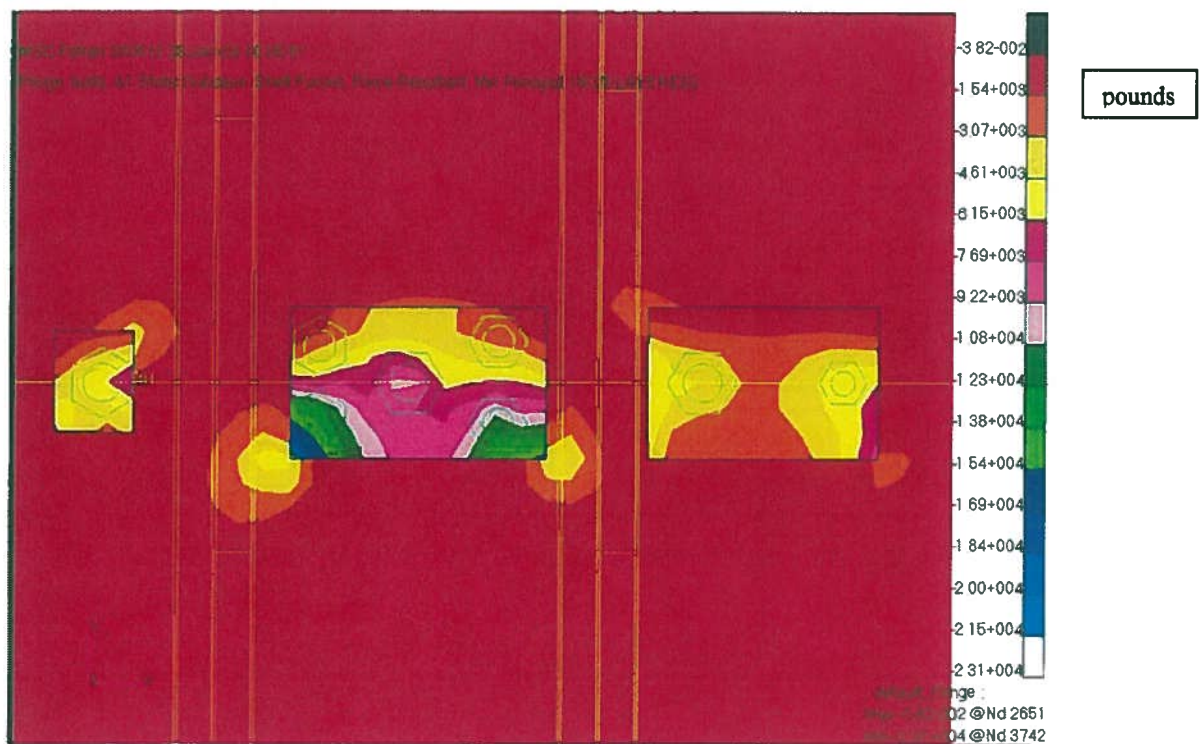
For Loadcase #1, these keel bolt loads were applied directly at the keel bolt locations in the proper direction (tension pulling down on the bolt – weather side), giving the following results.



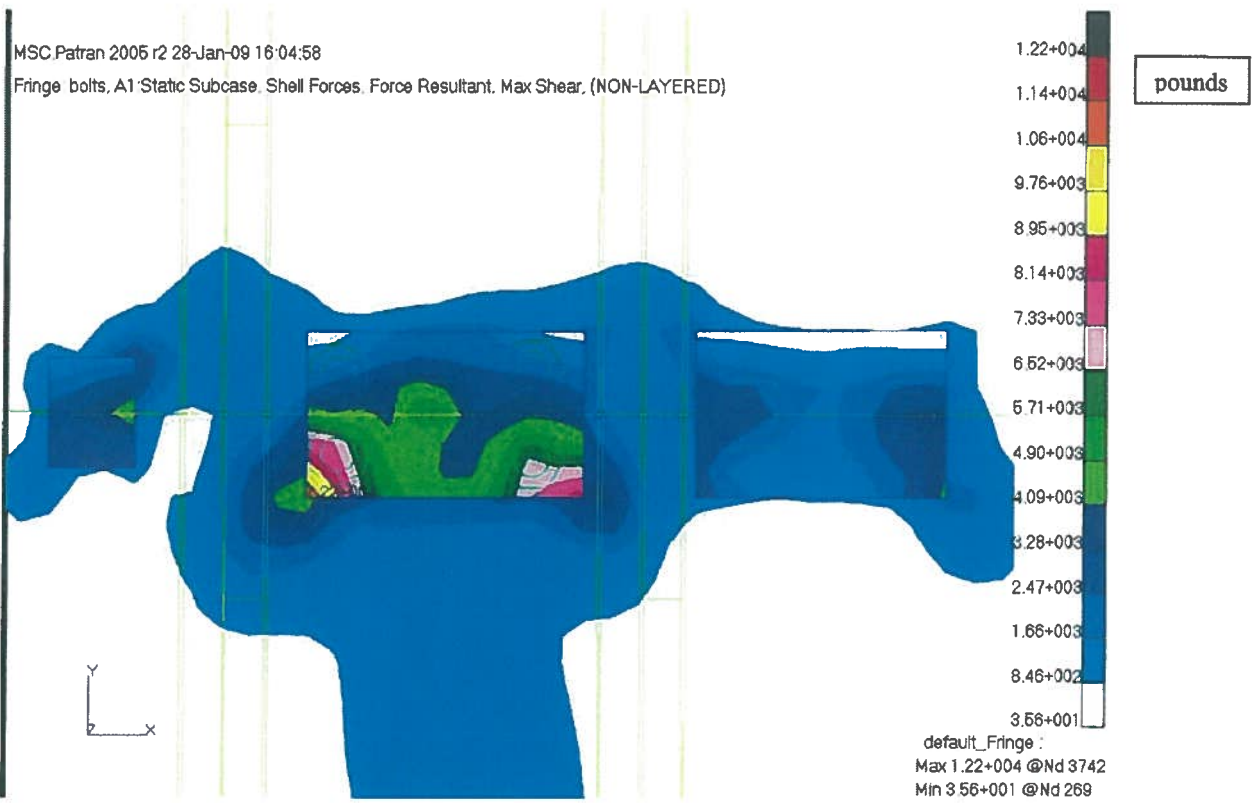
**Figure 7.1.2 – Z – Direction Displacement**



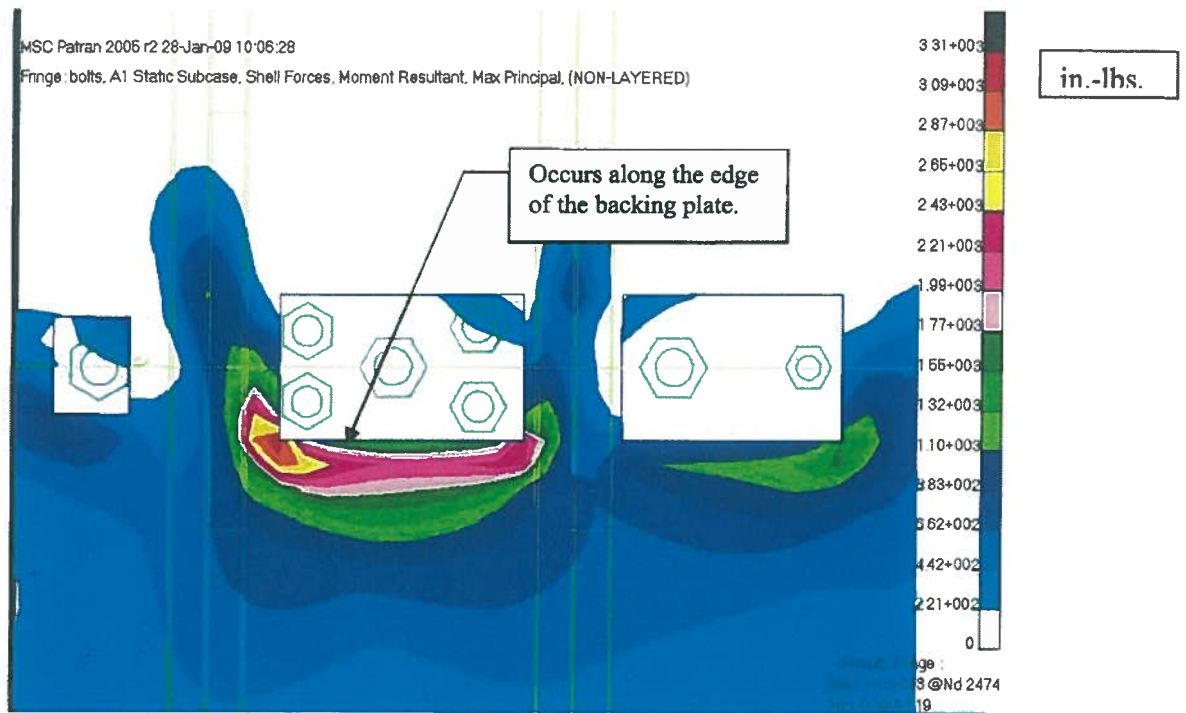
**Figure 7.1.3 – Maximum Principal Force**



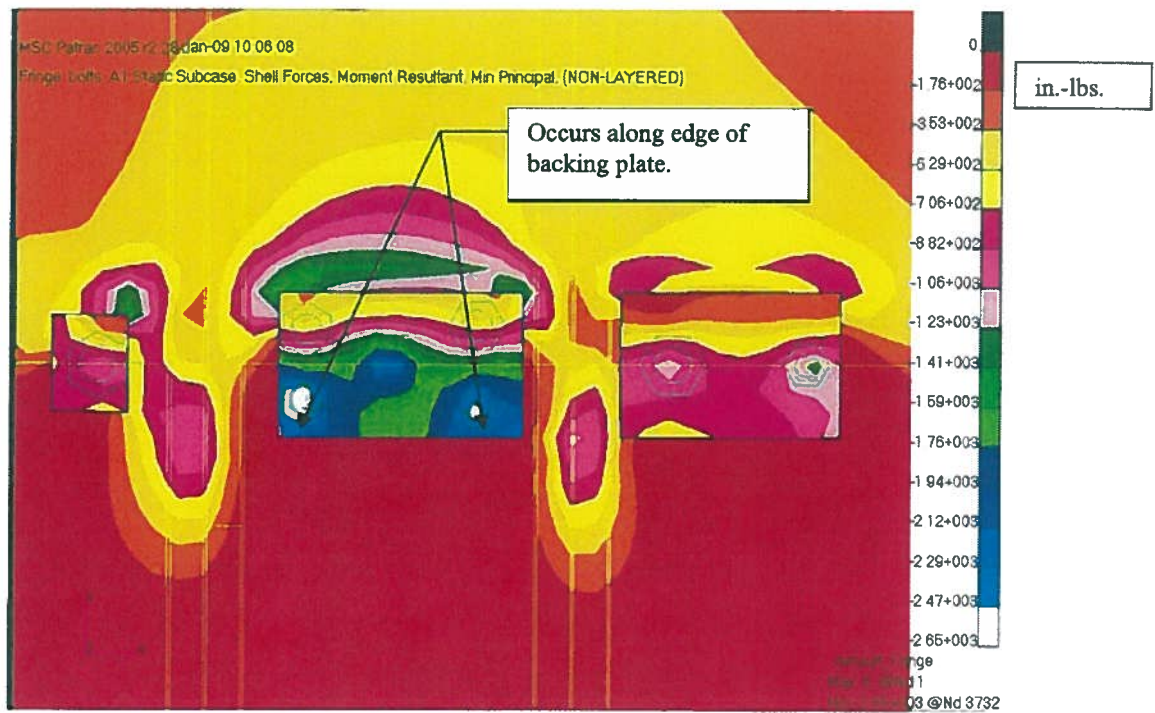
**Figure 7.1.4 – Minimum Principal Force**



**Figure 7.1.5 – Maximum Shear Force**



**Figure 7.1.6 – Maximum Principal Moment**

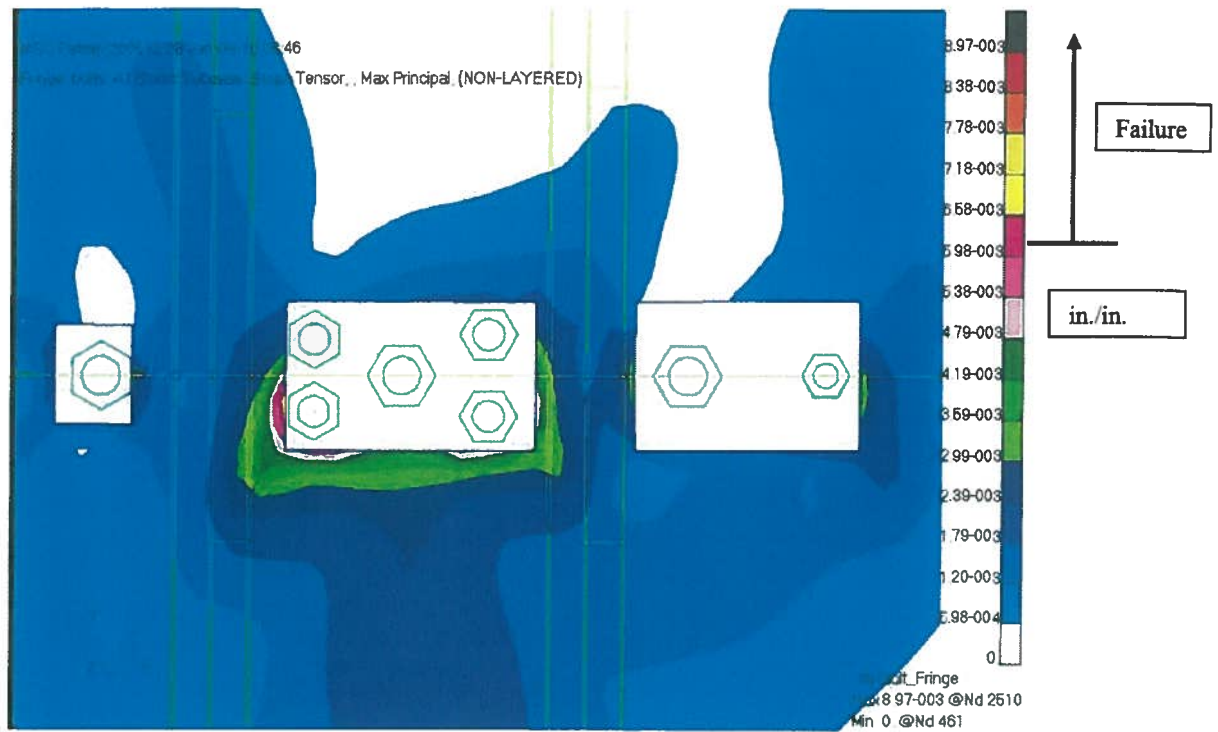


**Figure 7.1.7 – Minimum Principal Moment**

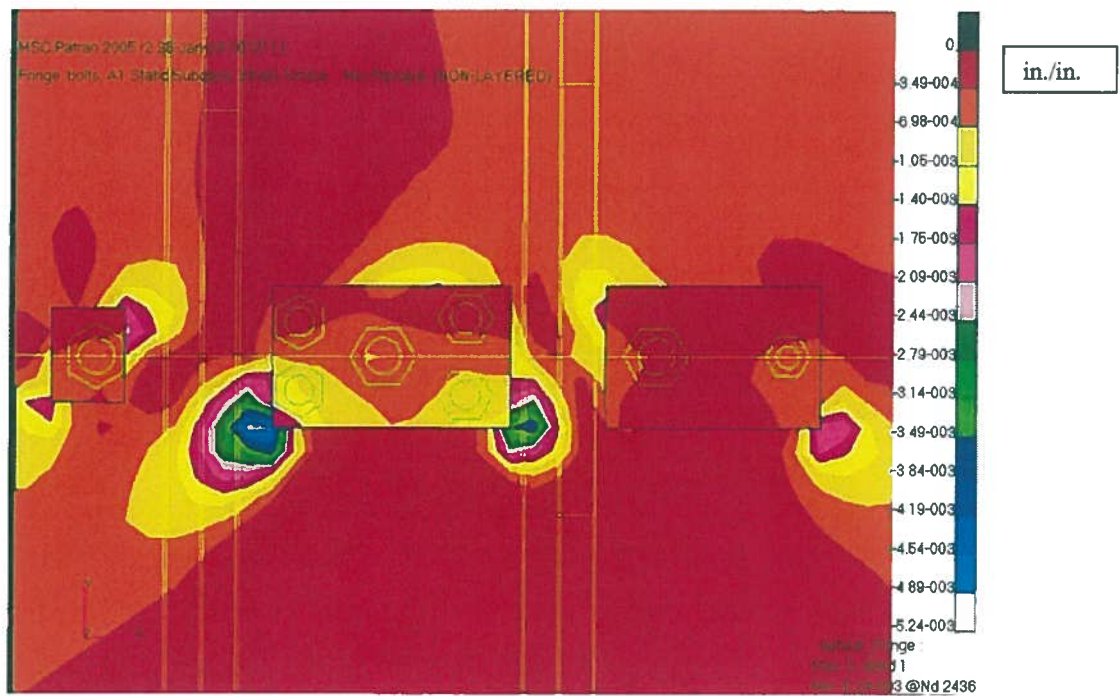








**Figure 7.1.9 – Maximum Principal Strain**



**Figure 7.1.10 – Minimum Principal Strain**



Margin of Safety (M.S.) calculations using CLAM for most critical hull shell elements adjacent to the keel bolts for limit loads, showing that the hull shell & the hull shell plus the stainless steel backing plates are significantly under designed (negative margins of safety). The results of these margin of safety calculations follow:

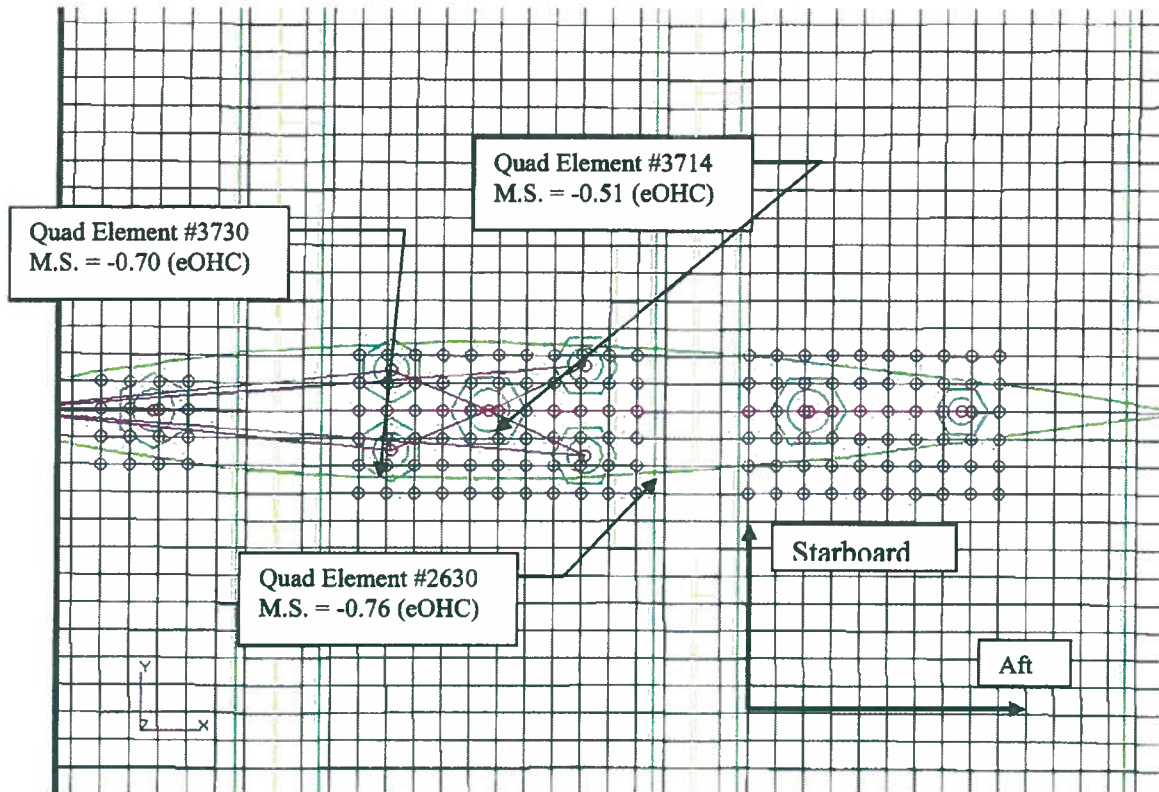


Figure 7.1.9 – Locations of Most Critical Elements

### LHS Hull Shell at Bolt #3 Margin of Safety

Cynthia Woods - Loadcase: Bolt Loads - Bolt #3 - 1/28/2009  
 Laminate Strength - t = 0.637" + 0.375" ss - Element #3730

DTLAM Version 13.35 Laminate Strength Analysis

#### Laminate Boundary Conditions

Nx (lb/in)	= -10893.00	ex (in/in)	= -0.003008
Ny (lb/in)	= -9662.00	ey (in/in)	= -0.002834
Nxy (lb/in)	= +6275.00	rxxy (in/in)	= +0.005920
Mx (in-lb/in)	= -1455.0000	kx (rad/in)	= -0.008360
My (in-lb/in)	= -1768.0000	ky (rad/in)	= -0.008228
Mxy (in-lb/in)	= +536.0000	kxy (rad/in)	= +0.016146

Delta Temperature (deg F) = +0

#### Laminate Principle Strains (in/in):

Surface 1:	emax = -0.000072		
	emin = -0.014164	eOHC = -0.004310	MS = -0.70
Surface 2:	emax = +0.002402	eOHT = +0.004310	MS = +0.79
	emin = +0.000149		

#### Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	-0.000068	-0.013762	+0.000237	+0.04
0.0490	+0.0	owens corning 1	-0.006624	-0.006393	+0.012903	+1.17
0.0490	+45.0	owens corning 1	-0.000046	-0.012158	+0.000224	+0.18
0.0490	+0.0	owens corning 1	-0.005804	-0.005587	+0.011320	+1.47
0.0490	+45.0	owens corning 1	-0.000024	-0.010554	+0.000211	+0.36
0.0490	+0.0	owens corning 1	-0.004985	-0.004780	+0.009738	+1.88
0.0490	+45.0	owens corning 1	-0.000003	-0.008950	+0.000199	+0.60
0.0490	+0.0	owens corning 1	-0.004166	-0.003974	+0.008156	+2.45
0.0490	+45.0	owens corning 1	+0.000019	-0.007346	+0.000186	+0.95
0.0490	+0.0	owens corning 1	-0.003347	-0.003167	+0.006574	+3.29
0.0490	+45.0	owens corning 1	+0.000041	-0.005742	+0.000173	+1.50
0.0490	+0.0	owens corning 1	-0.002527	-0.002361	+0.004991	+4.68
0.0490	+45.0	owens corning 1	+0.000062	-0.004138	+0.000160	+2.47
0.3750	+0.0	STEEL (125 HT)	-0.000346	-0.000213	+0.000777	+8.36

Total Thickness = 1.0120 in

### Centerline Hull Shell at Bolt #4 Margin of Safety

Cynthia Woods - Loadcase: Bolt Loads - Bolt #4 - 1/28/2009  
 Laminate Strength - t = 0.637" + 0.375" - Element #3714

DTLAM Version 13.35 Laminate Strength Analysis

#### Laminate Boundary Conditions

Nx (lb/in) = -9785.00	ex (in/in) = -0.003585
Ny (lb/in) = -6059.00	ey (in/in) = -0.001963
Nxy (lb/in) = +366.00	rxxy (in/in) = +0.000136
Mx (in-lb/in) = -2300.0000	kx (rad/in) = -0.010403
My (in-lb/in) = -2207.0000	ky (rad/in) = -0.006131
Mxy (in-lb/in) = -75.0000	kxy (rad/in) = +0.000193

Delta Temperature (deg F) = +0

#### Laminate Principle Strains (in/in):

Surface 1:	emax = -0.005061	emin = -0.008853	eOHC = -0.004310	MS = -0.51
Surface 2:	emax = +0.001679	emin = +0.001139	eOHT = +0.004310	MS = +1.57

#### Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	-0.006640	-0.006869	+0.003680	+1.09
0.0490	+0.0	owens corning 1	-0.008085	-0.004614	+0.000219	+0.78
0.0490	+45.0	owens corning 1	-0.005840	-0.006049	+0.003261	+1.37
0.0490	+0.0	owens corning 1	-0.007065	-0.004014	+0.000200	+1.03
0.0490	+45.0	owens corning 1	-0.005039	-0.005230	+0.002842	+1.75
0.0490	+0.0	owens corning 1	-0.006046	-0.003413	+0.000181	+1.37
0.0490	+45.0	owens corning 1	-0.004238	-0.004410	+0.002424	+2.26
0.0490	+0.0	owens corning 1	-0.005026	-0.002812	+0.000163	+1.86
0.0490	+45.0	owens corning 1	-0.003437	-0.003590	+0.002005	+3.00
0.0490	+0.0	owens corning 1	-0.004007	-0.002211	+0.000144	+2.58
0.0490	+45.0	owens corning 1	-0.002637	-0.002771	+0.001586	+4.18
0.0490	+0.0	owens corning 1	-0.002987	-0.001610	+0.000125	+3.81
0.0490	+45.0	owens corning 1	-0.001836	-0.001951	+0.001168	+6.36
0.3750	+0.0	STEEL (125 HT)	-0.000272	-0.000010	+0.000074	+12.95

Total Thickness = 1.0120 in



### LHS Hull Shell at Bolt #6 Margin of Safety

Cynthia Woods - Loadcase: Bolt Loads - Bolt #6 - 1/28/2009  
 Laminate Strength - t = 0.637" - Element #2630

DTLAM Version 13.35 Laminate Strength Analysis

#### Laminate Boundary Conditions

Nx (lb/in)	= +2426.00	ex (in/in)	= +0.003938
Ny (lb/in)	= -2689.00	ey (in/in)	= -0.004136
Nxy (lb/in)	= -1548.00	rxxy (in/in)	= -0.004514
Mx (in-lb/in)	= +1027.0000	kx (rad/in)	= +0.012899
My (in-lb/in)	= +1728.0000	ky (rad/in)	= +0.048552
Mxy (in-lb/in)	= +740.0000	kxy (rad/in)	= +0.059308

Delta Temperature (deg F) = +0

#### Laminate Principle Strains (in/in):

Surface 1:	emax = +0.017060	eOHT = +0.006000	MS = -0.65
	emin = +0.002314		
Surface 2:	emax = +0.005323	eOHT = +0.006000	MS = +0.13
	emin = -0.025094	eOHC = -0.006000	MS = -0.76

#### Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	+0.015396	+0.002473	+0.002408	+0.15
0.0490	+0.0	owens corning 1	+0.007098	+0.007759	+0.010017	+1.28
0.0490	+45.0	owens corning 1	+0.009478	+0.002368	-0.001086	+0.86
0.0490	+0.0	owens corning 1	+0.005834	+0.003001	+0.004205	+2.03
0.0490	+45.0	owens corning 1	+0.003561	+0.002263	-0.004580	+3.96
0.0490	+0.0	owens corning 1	+0.004570	-0.001757	-0.001608	+2.86
0.0490	+45.0	owens corning 1	-0.002356	+0.002158	-0.008074	+3.70
0.0490	+0.0	owens corning 1	+0.003306	-0.006515	-0.007420	+1.20
0.0490	+45.0	owens corning 1	-0.008273	+0.002053	-0.011568	+0.74
0.0490	+0.0	owens corning 1	+0.002041	-0.011273	-0.013232	+0.27
0.0490	+45.0	owens corning 1	-0.014190	+0.001948	-0.015062	+0.01
0.0490	+0.0	owens corning 1	+0.000777	-0.016031	-0.019044	-0.10
0.0490	+45.0	owens corning 1	-0.020108	+0.001843	-0.018556	-0.29

Total Thickness = 0.6370 in

## 7.2 Loadcase #2

Loadcase #2 is the 90 degree keel weight applied at the center of gravity of the keel. This load is beamed to the keel bolt locations using rigid body elements (RBE3's) to distribute this load, according to the back-up structure stiffness, to each keel bolt. The keel bolt loads &, thus, the deflections are lower for this loadcase, since the hull shell/floor structure combination is not treated as a rigid body but is flexible & attempts to give a truer representation of the actual Cape Fear 38 hull structural stiffness. The results for this loadcase is as follows:

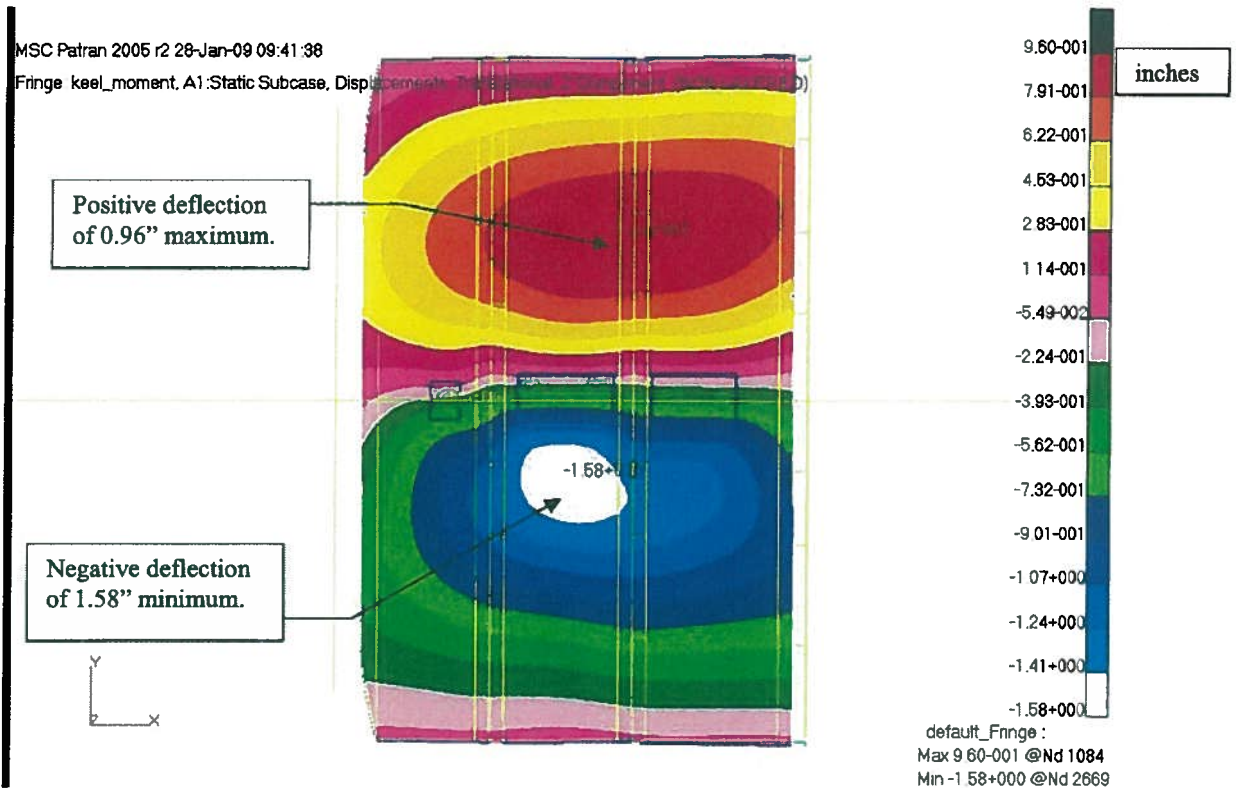
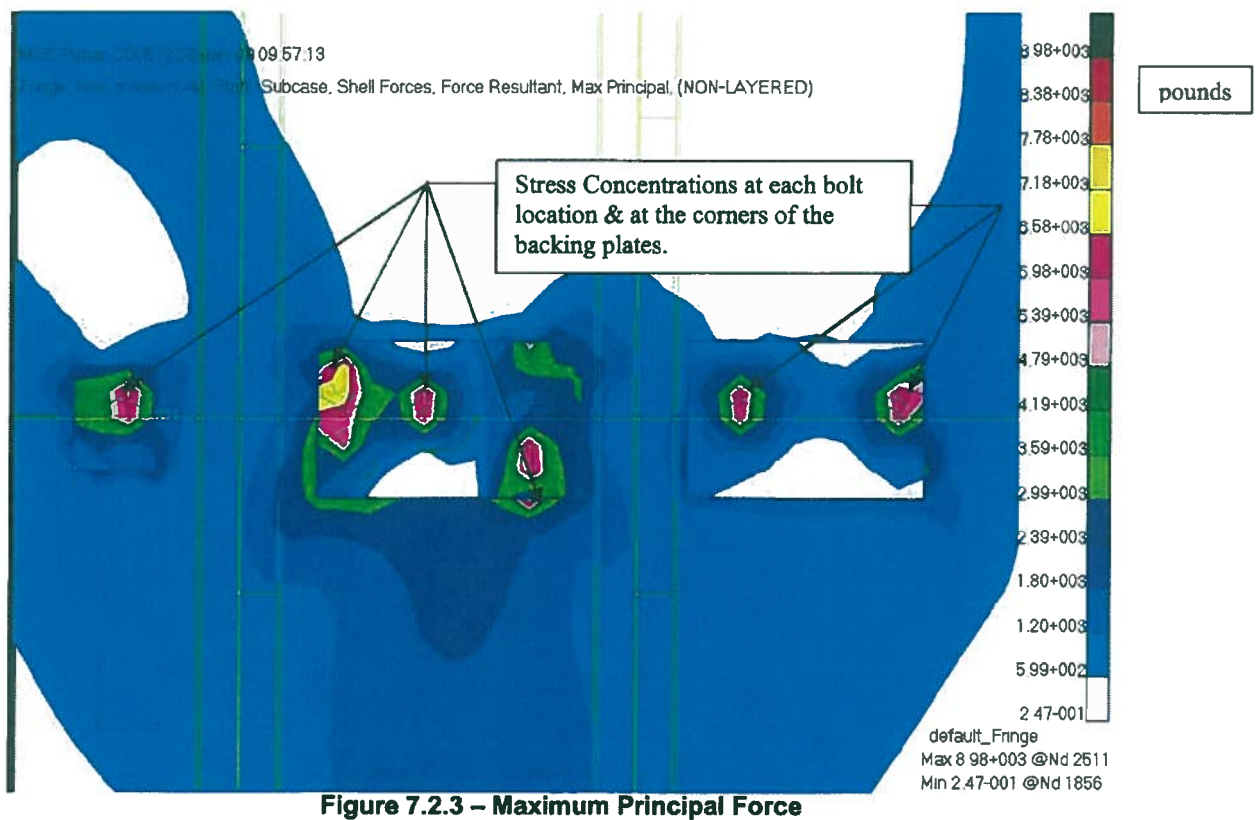
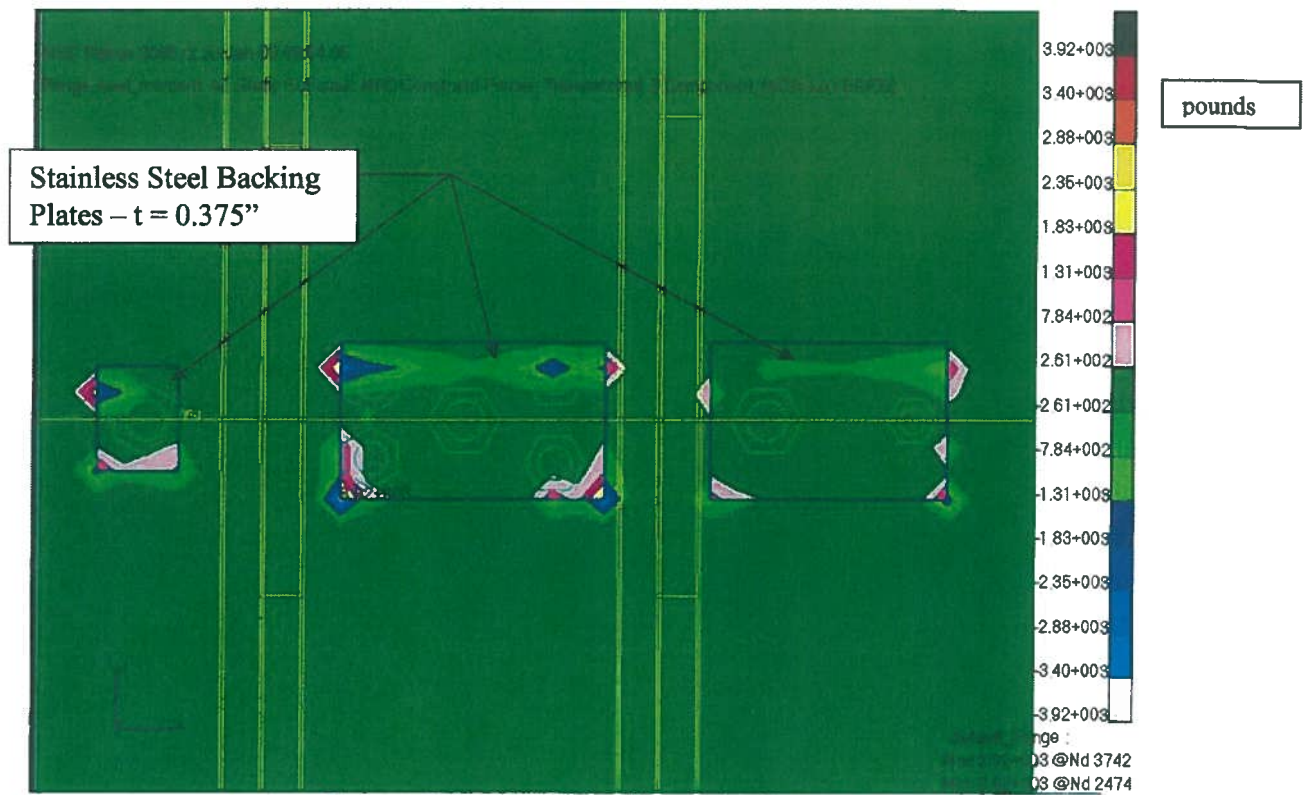
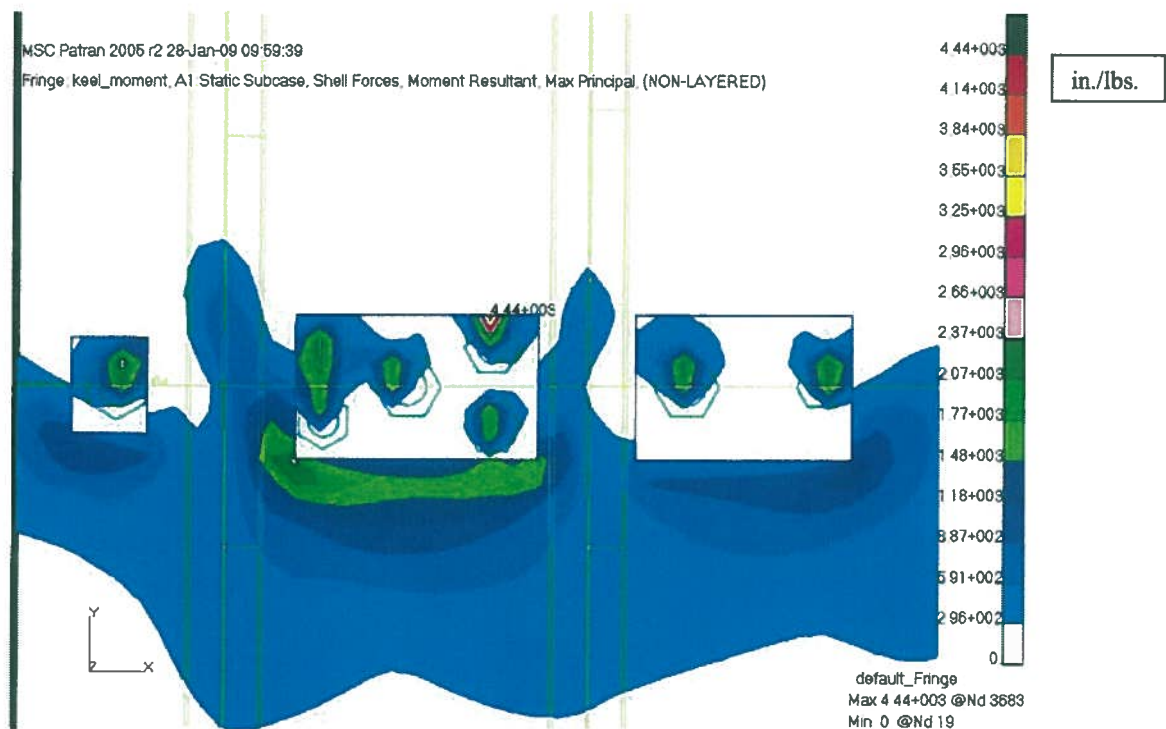


Figure 7.2.1 – Z (Vertical) Displacement



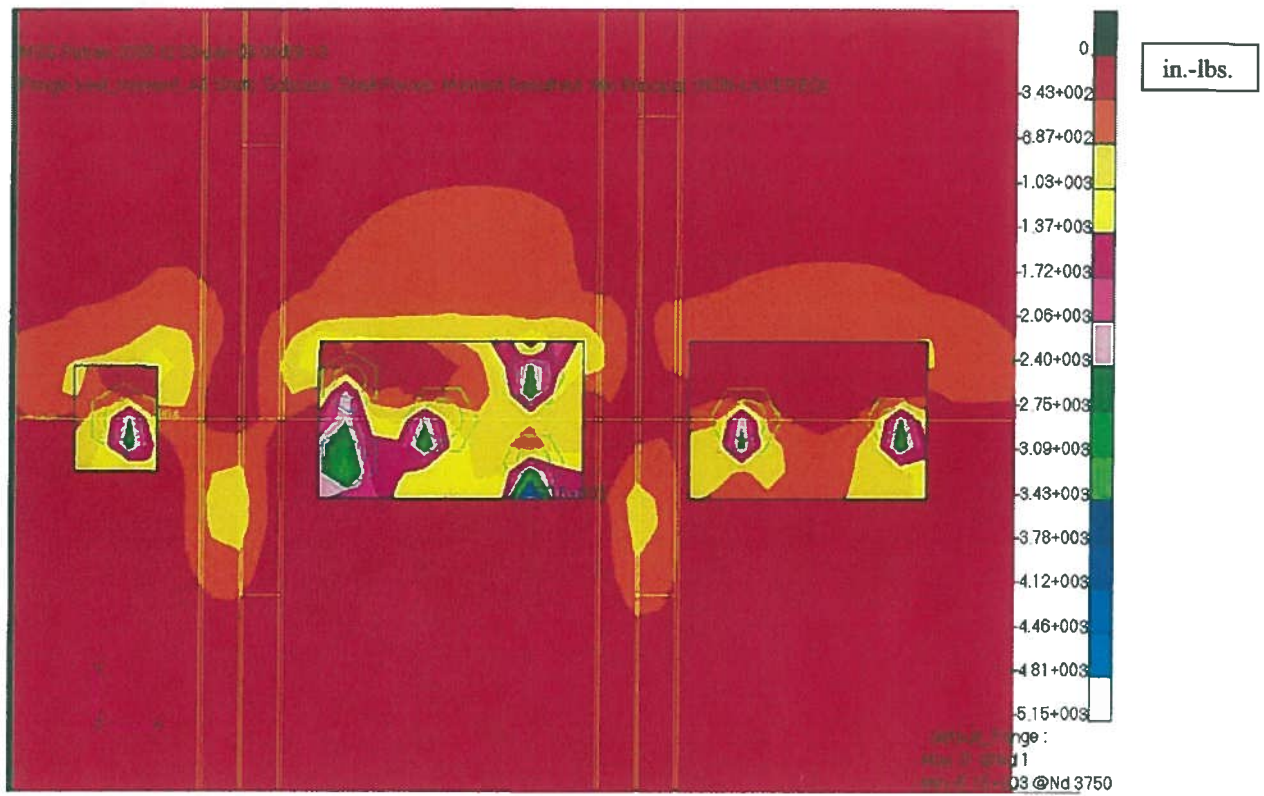


**Figure 7.2.4 – Minimum Principal Force**



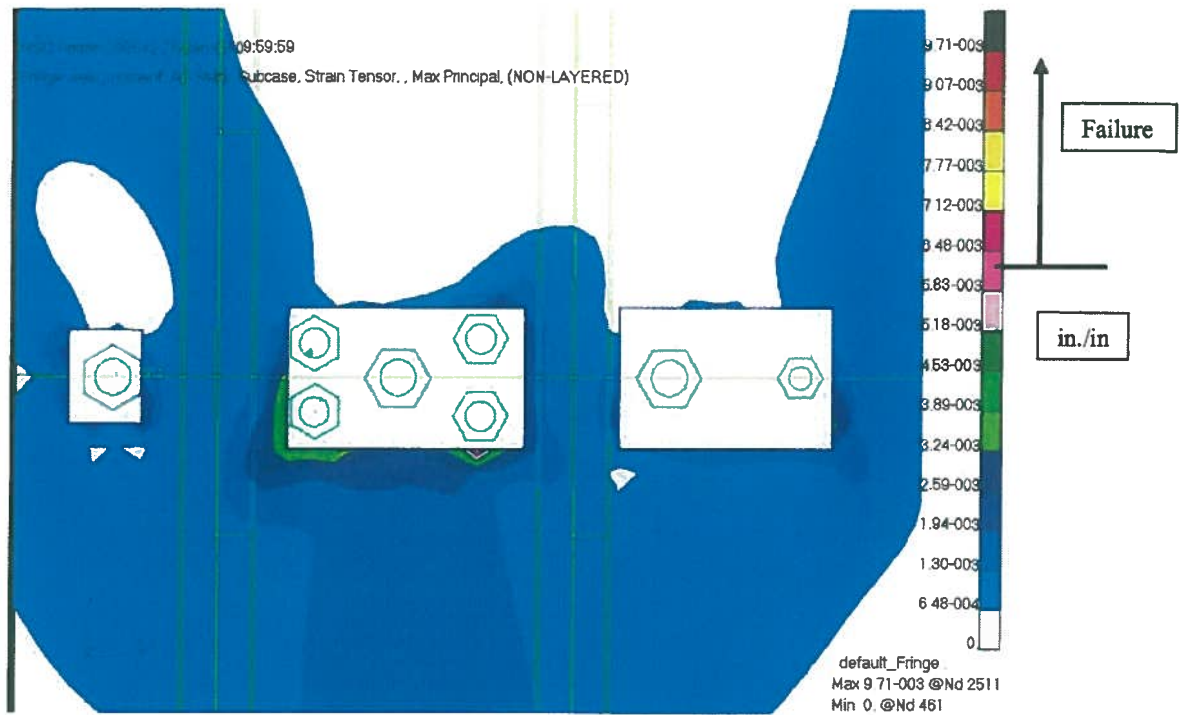
**Figure 7.2.5 – Maximum Principal Moment**



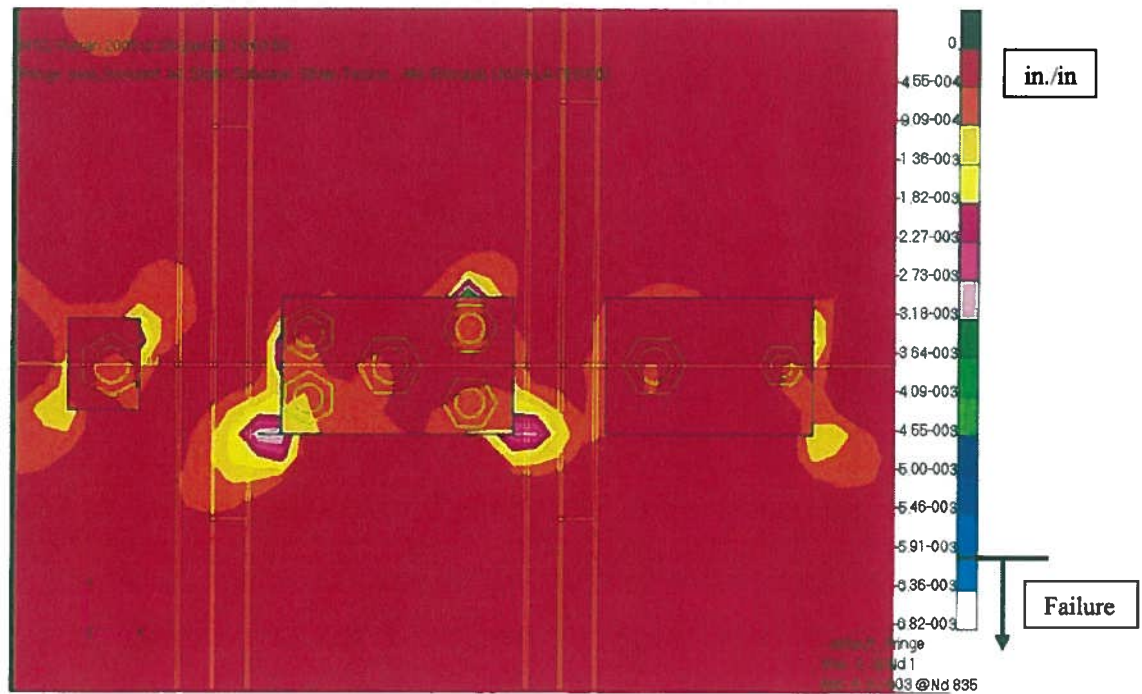


**Figure 7.2.6 – Minimum Principal Moment**

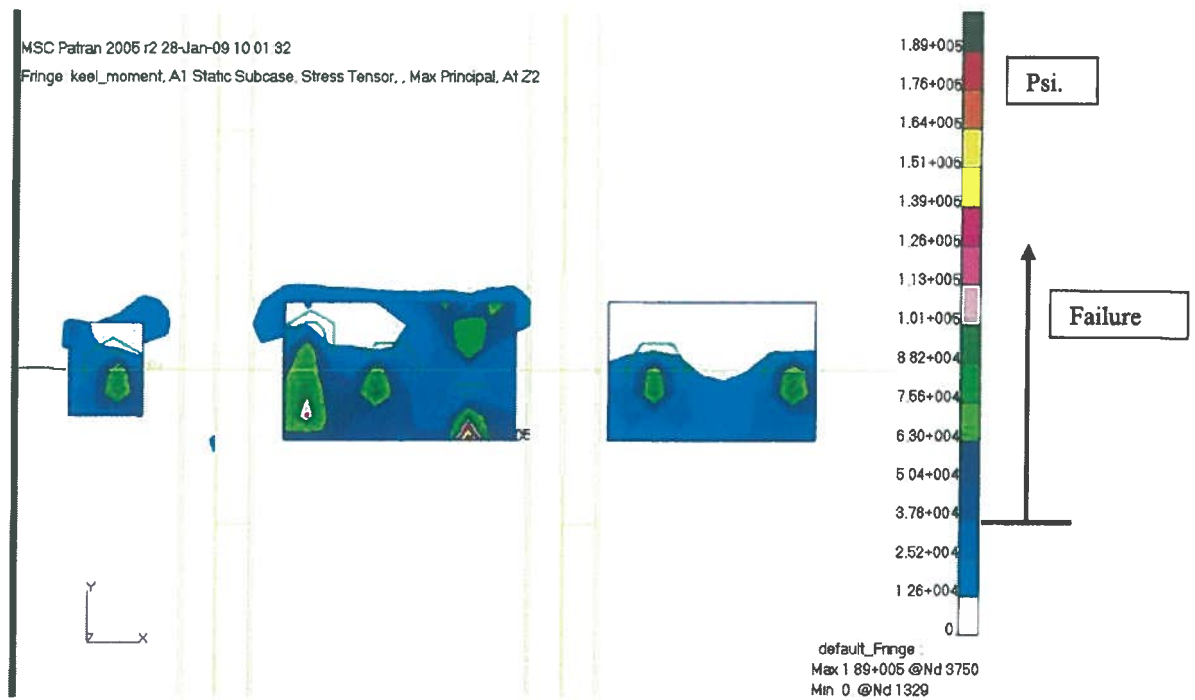




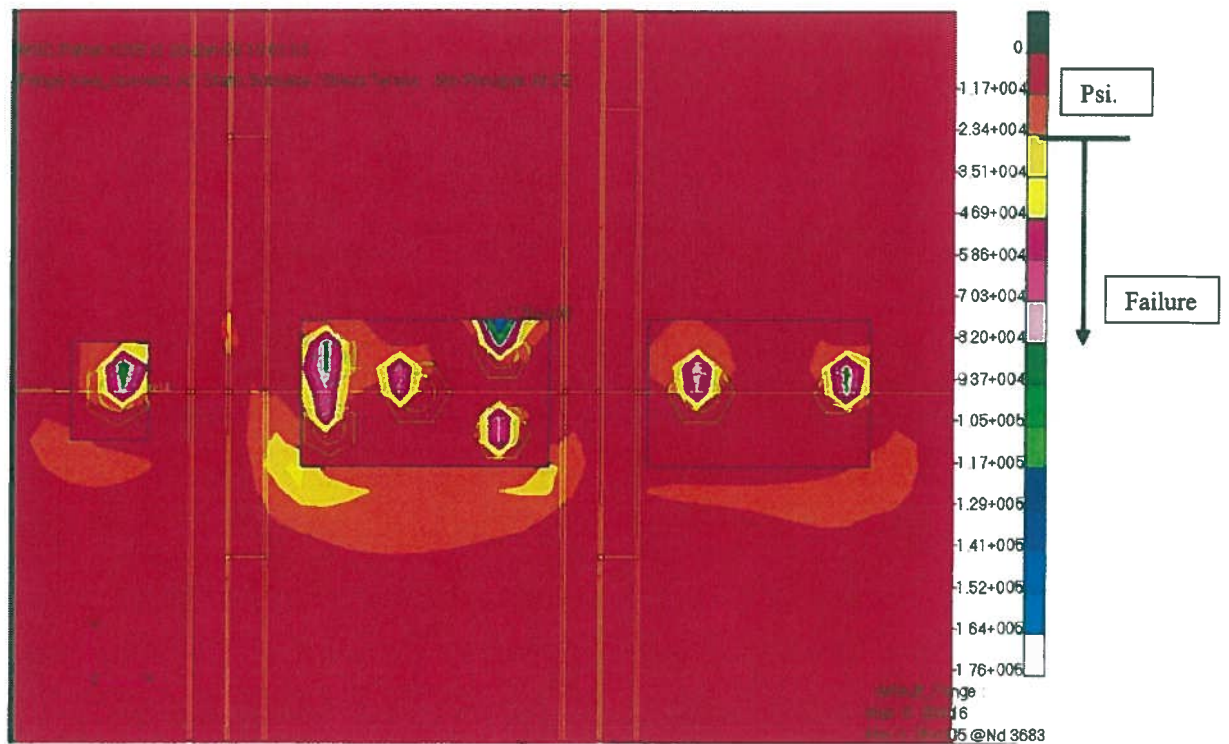
**Figure 7.2.7 – Maximum Principal Strain**



**Figure 7.2.8 – Minimum Principal Strain**



**Figure 7.2.9 – Maximum Principal Stress**



**Figure 7.2.10 – Minimum Principal Stress**

Margin of Safety calculations using CLAM for most critical hull shell elements adjacent to the keel bolts for limit loads, showing that the hull shell & the hull shell plus the stainless steel backing plates are significantly under designed (negative margins of safety). The results of these margin of safety calculations follow:

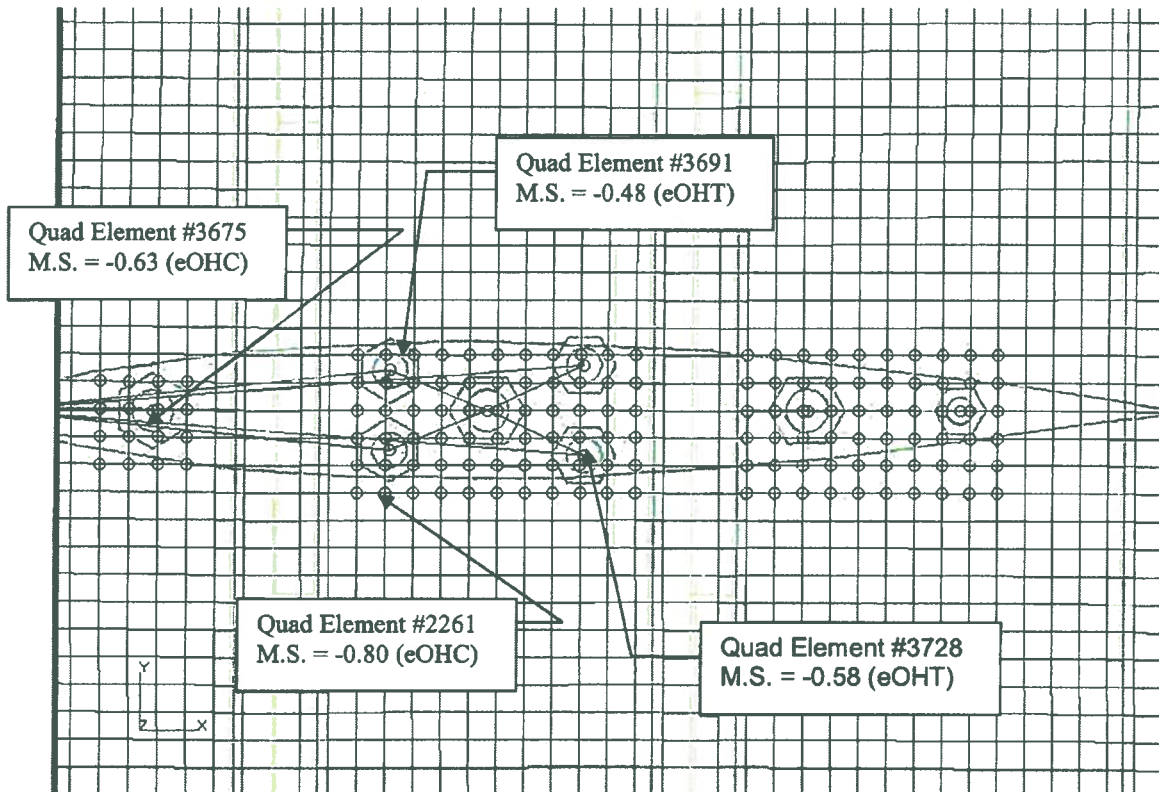


Figure 7.2.7 – Locations of Most Critical Elements

### RHS Hull Shell Element at Bolt #1 Margin of Safety

Cynthia Woods - Loadcase: Keel Moment - Bolt #1 - 1/28/2009  
Laminate Strength - t = 0.637" + 0.375" ss - Element #3675

DTLAM Version 13.35 Laminate Strength Analysis

#### Laminate Boundary Conditions

Nx (lb/in)	= -1741.00	ex (in/in)	= +0.000148
Ny (lb/in)	= -5801.00	ey (in/in)	= -0.003317
Nxy (lb/in)	= +3951.00	rxxy (in/in)	= +0.004864
Mx (in-lb/in)	= -728.0000	kx (rad/in)	= +0.000444
My (in-lb/in)	= -2440.0000	ky (rad/in)	= -0.010210
Mxy (in-lb/in)	= +914.0000	kxy (rad/in)	= +0.014229

Delta Temperature (deg F) = +0

#### Laminate Principle Strains (in/in):

Surface 1:	emax = +0.003427	eOHT = +0.004310	MS = +0.26
	emin = -0.011538	eOHC = -0.004310	MS = <b>-0.63</b>
Surface 2:	emax = +0.002400	eOHT = +0.004310	MS = +0.80
	emin = -0.000628	eOHC = -0.004310	MS = +5.87

#### Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	+0.001922	-0.009793	-0.008595	+0.47
0.0490	+0.0	owens corning 1	+0.000340	-0.007733	+0.011018	+0.86
0.0490	+45.0	owens corning 1	+0.001703	-0.008617	-0.007551	+0.67
0.0490	+0.0	owens corning 1	+0.000297	-0.006732	+0.009623	+1.13
0.0490	+45.0	owens corning 1	+0.001484	-0.007442	-0.006507	+0.93
0.0490	+0.0	owens corning 1	+0.000253	-0.005732	+0.008229	+1.50
0.0490	+45.0	owens corning 1	+0.001266	-0.006266	-0.005463	+1.29
0.0490	+0.0	owens corning 1	+0.000210	-0.004731	+0.006834	+2.03
0.0490	+45.0	owens corning 1	+0.001047	-0.005090	-0.004418	+1.82
0.0490	+0.0	owens corning 1	+0.000166	-0.003731	+0.005440	+2.85
0.0490	+45.0	owens corning 1	+0.000828	-0.003914	-0.003374	+2.67
0.0490	+0.0	owens corning 1	+0.000122	-0.002730	+0.004045	+4.26
0.0490	+45.0	owens corning 1	+0.000610	-0.002739	-0.002330	+4.24
0.3750	+0.0	STEEL (125 HT)	+0.000006	-0.000065	+0.000332	+20.93

Total Thickness = 1.0120 in

### RHS Hull Shell Element at Bolt #2 Margin of Safety

Cynthia Woods - Loadcase: Keel Moment - Bolt #2 - 1/28/2009

Laminate Strength - t = 0.637" + 0.375" ss - Element #3691

DTLAM Version 13.35 Laminate Strength Analysis

#### Laminate Boundary Conditions

Nx (lb/in)	= +1860.00	ex (in/in)	= -0.000052
Ny (lb/in)	= +5435.00	ey (in/in)	= +0.003096
Nxy (lb/in)	= -598.00	rxxy (in/in)	= -0.001333
Mx (in-lb/in)	= +712.0000	kx (rad/in)	= -0.000177
My (in-lb/in)	= +2311.0000	ky (rad/in)	= +0.009546
Mxy (in-lb/in)	= -441.0000	kxy (rad/in)	= -0.004287

Delta Temperature (deg F) = +0

#### Laminate Principle Strains (in/in):

Surface 1:	emax = +0.008289	eOHT = +0.004310	MS = <b>-0.48</b>
	emin = -0.000505	eOHC = -0.004310	MS = +7.54
Surface 2:	emax = +0.000131	eOHT = +0.004310	MS = +31.82
	emin = -0.001828	eOHC = -0.004310	MS = +1.36

#### Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	+0.002079	+0.005476	+0.007829	+2.22
0.0490	+0.0	owens corning 1	-0.000128	+0.007224	-0.003187	+1.44
0.0490	+45.0	owens corning 1	+0.001830	+0.004807	+0.006876	+2.67
0.0490	+0.0	owens corning 1	-0.000111	+0.006289	-0.002767	+1.81
0.0490	+45.0	owens corning 1	+0.001581	+0.004138	+0.005923	+3.27
0.0490	+0.0	owens corning 1	-0.000094	+0.005353	-0.002346	+2.30
0.0490	+45.0	owens corning 1	+0.001332	+0.003469	+0.004970	+4.09
0.0490	+0.0	owens corning 1	-0.000076	+0.004418	-0.001926	+3.00
0.0490	+45.0	owens corning 1	+0.001083	+0.002799	+0.004018	+5.31
0.0490	+0.0	owens corning 1	-0.000059	+0.003482	-0.001506	+4.07
0.0490	+45.0	owens corning 1	+0.000834	+0.002130	+0.003065	+7.29
0.0490	+0.0	owens corning 1	-0.000042	+0.002547	-0.001086	+5.93
0.0490	+45.0	owens corning 1	+0.000585	+0.001461	+0.002112	+11.08
0.3750	+0.0	STEEL (125 HT)	+0.000004	+0.000055	+0.000033	+76.81

Total Thickness = 1.0120 in



### LHS Hull Shell Element at Bolt #3 Margin of Safety

Cynthia Woods - Loadcase: Keel Moment - Bolt #3 - 1/28/2009  
Laminate Strength - t = 0.637" - Element #2261

DTLAM Version 13.35 Laminate Strength Analysis

#### Laminate Boundary Conditions

Nx (lb/in)	= -510.00	ex (in/in)	= -0.001290
Ny (lb/in)	= +1688.00	ey (in/in)	= +0.002179
Nxy (lb/in)	= +1389.00	rxxy (in/in)	= +0.004050
Mx (in-lb/in)	= +2585.0000	kx (rad/in)	= +0.079789
My (in-lb/in)	= +1035.0000	ky (rad/in)	= +0.000956
Mxy (in-lb/in)	= -655.0000	kxy (rad/in)	= -0.052496

Delta Temperature (deg F) = +0

#### Laminate Principle Strains (in/in):

Surface 1:	emax = +0.025840	eOHT = +0.006000	MS = -0.77
	emin = +0.000765		
Surface 2:	emax = +0.005250	eOHT = +0.006000	MS = +0.14
	emin = -0.030078	eOHC = -0.006000	MS = -0.80

#### Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	+0.006622	+0.018006	-0.019707	-0.02
0.0490	+0.0	owens corning 1	+0.018258	+0.002413	-0.008811	-0.03
0.0490	+45.0	owens corning 1	+0.005238	+0.011477	-0.011982	+0.54
0.0490	+0.0	owens corning 1	+0.010439	+0.002320	-0.003667	+0.69
0.0490	+45.0	owens corning 1	+0.003853	+0.004948	-0.004256	+2.57
0.0490	+0.0	owens corning 1	+0.002619	+0.002226	+0.001478	+5.74
0.0490	+45.0	owens corning 1	+0.002469	-0.001581	+0.003469	+6.15
0.0490	+0.0	owens corning 1	-0.005200	+0.002132	+0.006622	+1.76
0.0490	+45.0	owens corning 1	+0.001085	-0.008110	+0.011195	+0.77
0.0490	+0.0	owens corning 1	-0.013019	+0.002038	+0.011767	+0.10
0.0490	+45.0	owens corning 1	-0.000299	-0.014638	+0.018921	-0.02
0.0490	+0.0	owens corning 1	-0.020839	+0.001945	+0.016911	-0.31
0.0490	+45.0	owens corning 1	-0.001684	-0.021167	+0.026646	-0.32

Total Thickness = 0.6370 in

### LHS Hull Shell Element at Bolt #6 Margin of Safety

Cynthia Woods - Loadcase: Keel Moment - Bolt #6 - 1/28/2009  
Laminate Strength - t = 0.637" + 0.375" ss - Element #3728

DTLAM Version 13.35 Laminate Strength Analysis

#### Laminate Boundary Conditions

Nx (lb/in)	= -1686.00	ex (in/in)	= -0.001270
Ny (lb/in)	= +3348.00	ey (in/in)	= +0.002453
Nxy (lb/in)	= -4896.00	rxxy (in/in)	= -0.005870
Mx (in-lb/in)	= +29.0000	kx (rad/in)	= -0.003646
My (in-lb/in)	= +1607.0000	ky (rad/in)	= +0.007536
Mxy (in-lb/in)	= -1053.0000	kxy (rad/in)	= -0.017071

Delta Temperature (deg F) = +0

#### Laminate Principle Strains (in/in):

Surface 1:	emax = +0.010214	eOHT = +0.004310	MS = <b>-0.58</b>
	emin = -0.007063	eOHC = -0.004310	MS = -0.39
Surface 2:	emax = +0.001296	eOHT = +0.004310	MS = +2.33
	emin = -0.002082	eOHC = -0.004310	MS = +1.07

#### Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	-0.005517	+0.008573	+0.009106	+1.06
0.0490	+0.0	owens corning 1	-0.002847	+0.005712	-0.013253	+1.86
0.0490	+45.0	owens corning 1	-0.004871	+0.007546	+0.008010	+1.34
0.0490	+0.0	owens corning 1	-0.002489	+0.004973	-0.011580	+2.27
0.0490	+45.0	owens corning 1	-0.004225	+0.006519	+0.006915	+1.71
0.0490	+0.0	owens corning 1	-0.002132	+0.004235	-0.009907	+2.83
0.0490	+45.0	owens corning 1	-0.003579	+0.005491	+0.005819	+2.21
0.0490	+0.0	owens corning 1	-0.001775	+0.003496	-0.008234	+3.60
0.0490	+45.0	owens corning 1	-0.002934	+0.004464	+0.004723	+2.95
0.0490	+0.0	owens corning 1	-0.001417	+0.002758	-0.006561	+4.78
0.0490	+45.0	owens corning 1	-0.002288	+0.003437	+0.003627	+4.14
0.0490	+0.0	owens corning 1	-0.001060	+0.002019	-0.004888	+6.75
0.0490	+45.0	owens corning 1	-0.001642	+0.002410	+0.002531	+6.32
0.3750	+0.0	STEEL (125 HT)	-0.000109	+0.000052	-0.000433	+15.81

Total Thickness = 1.0120 in

### 7.3 Loadcase #3

Loadcase #3 is the grounding loadcase with the grounding load applied at the forward tip of the keel. This load is beamed to the keel bolt locations using rigid body elements (RBE3's) to distribute this load, according to the back-up structure stiffness, to each keel bolt. The results for this loadcase is as follows:

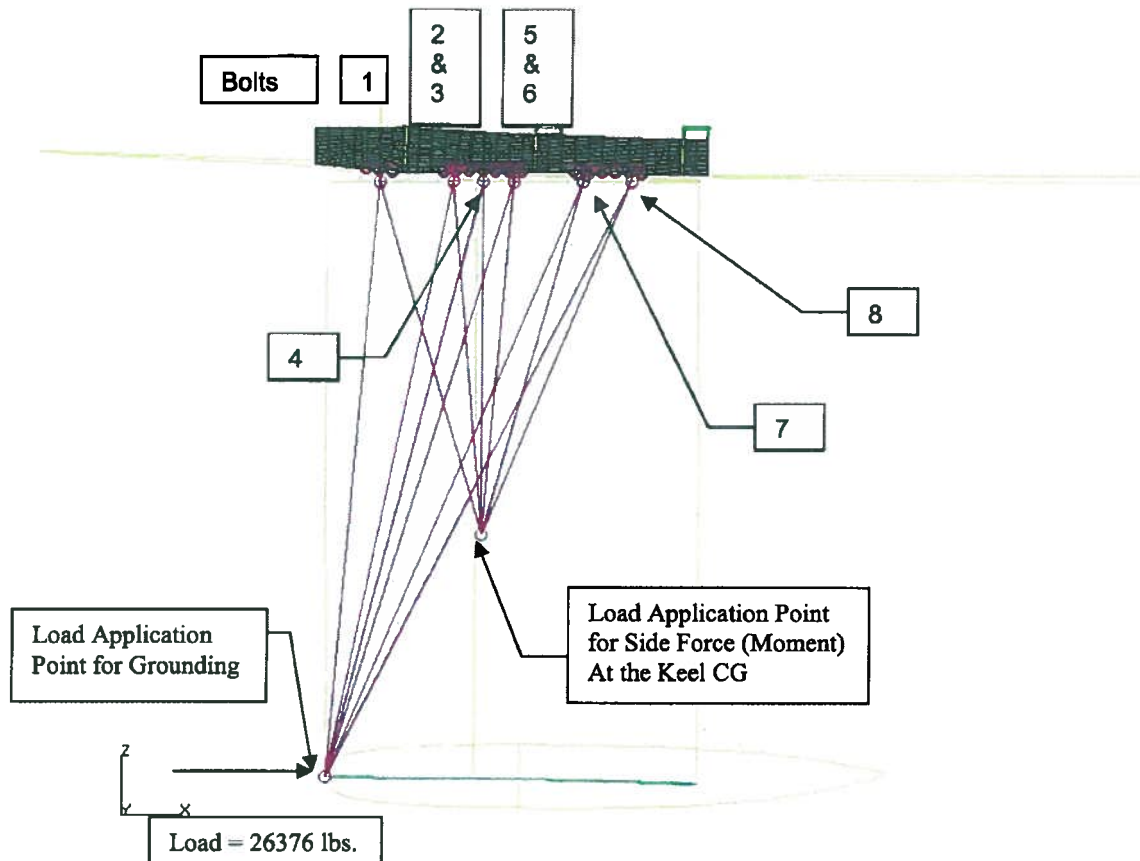
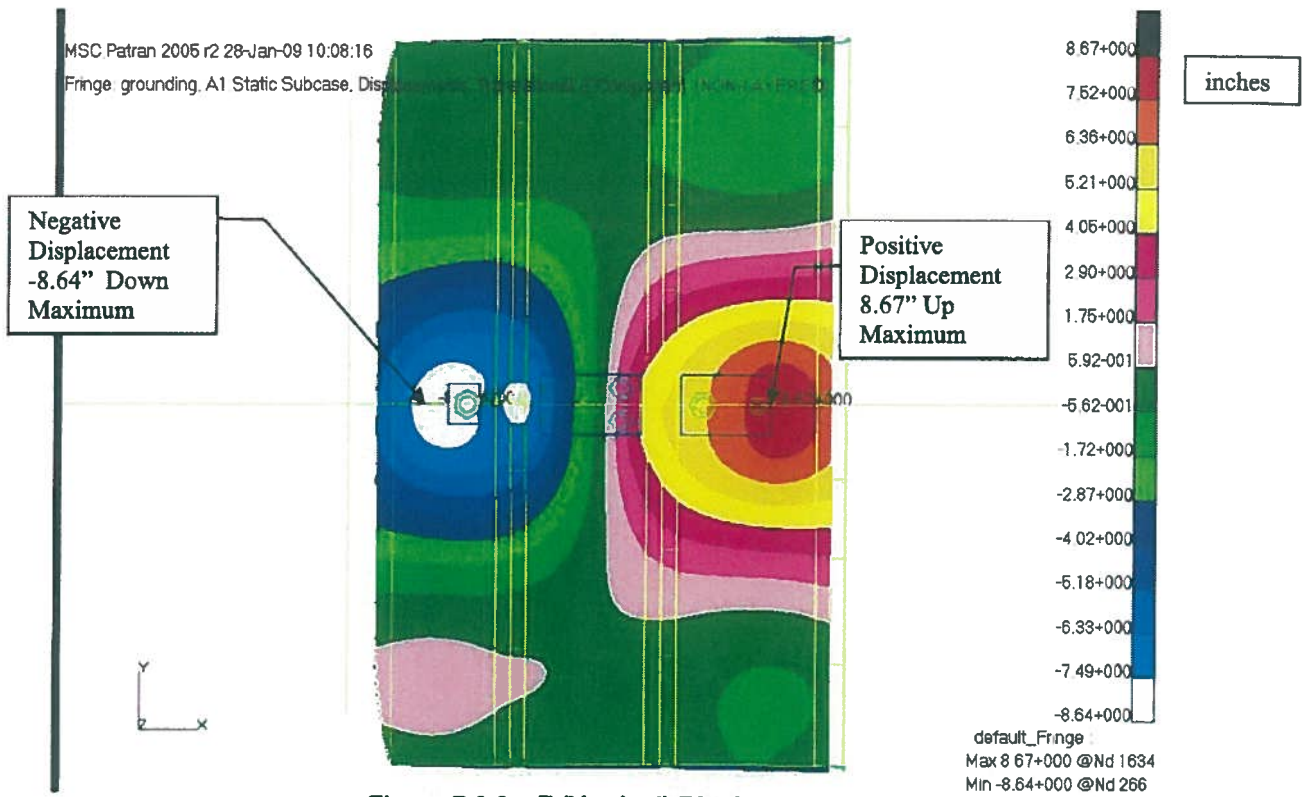
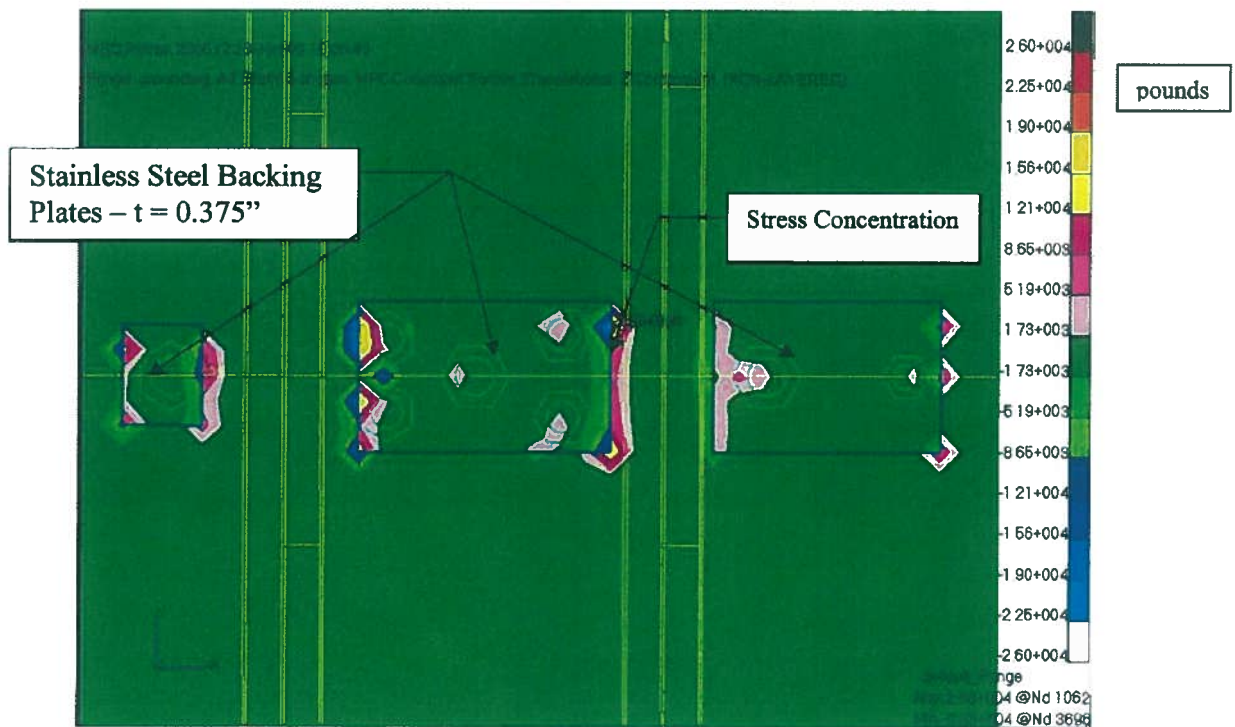


Figure 7.3.1 – Floor Structure, Applied Load & Keel Bolt Locations



**Figure 7.3.2 – Z (Vertical) Displacement**



**Figure 7.3.3 – Multipoint Constraint Forces**

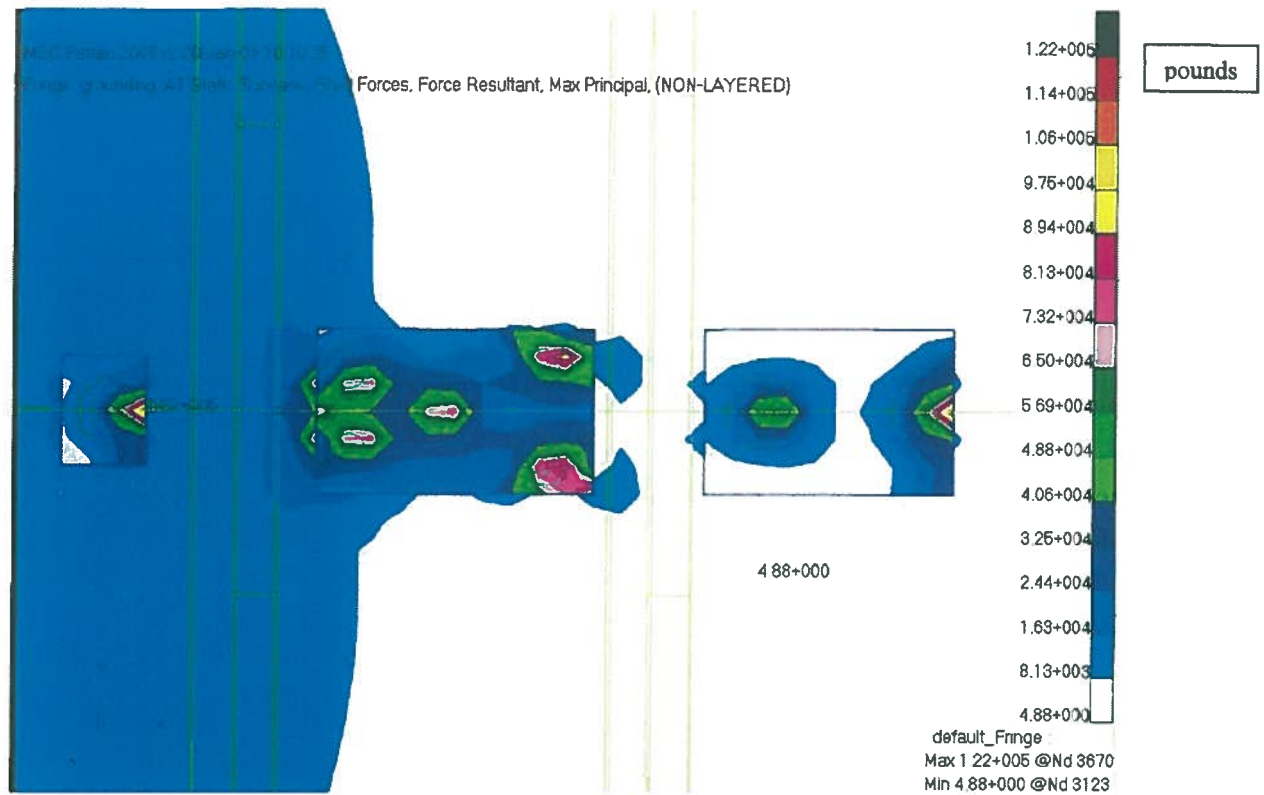


Figure 7.3.4 – Maximum Principal Force

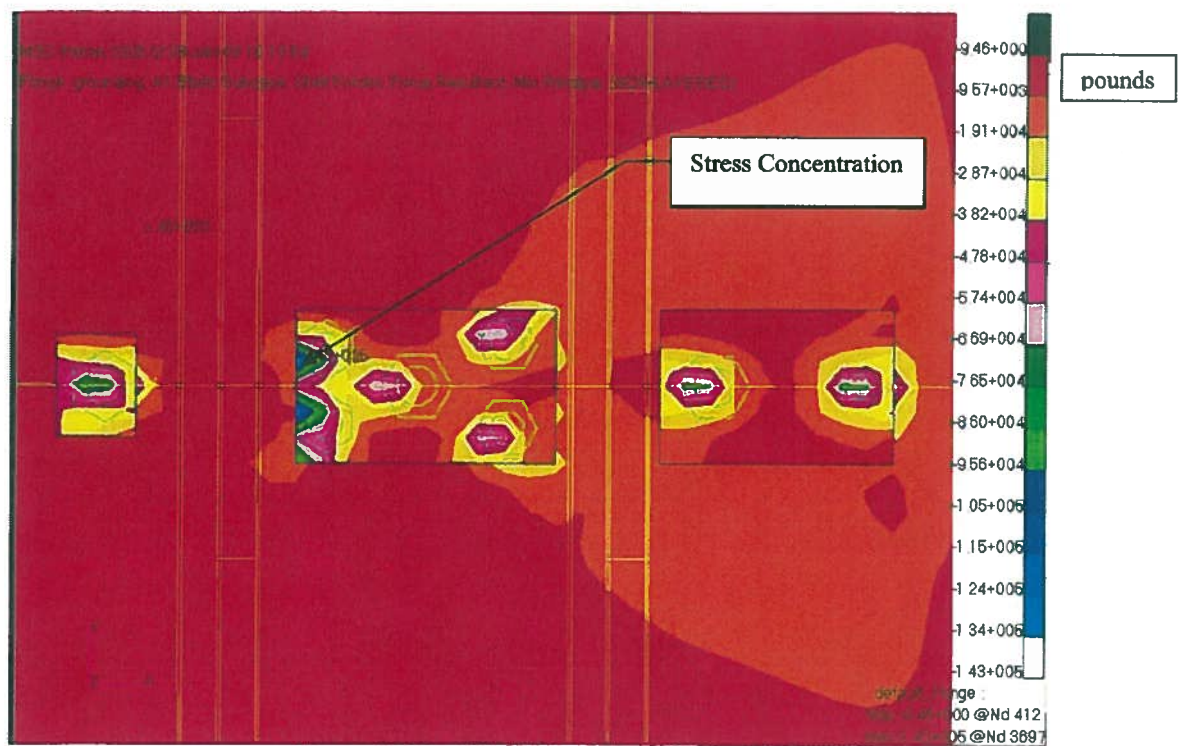
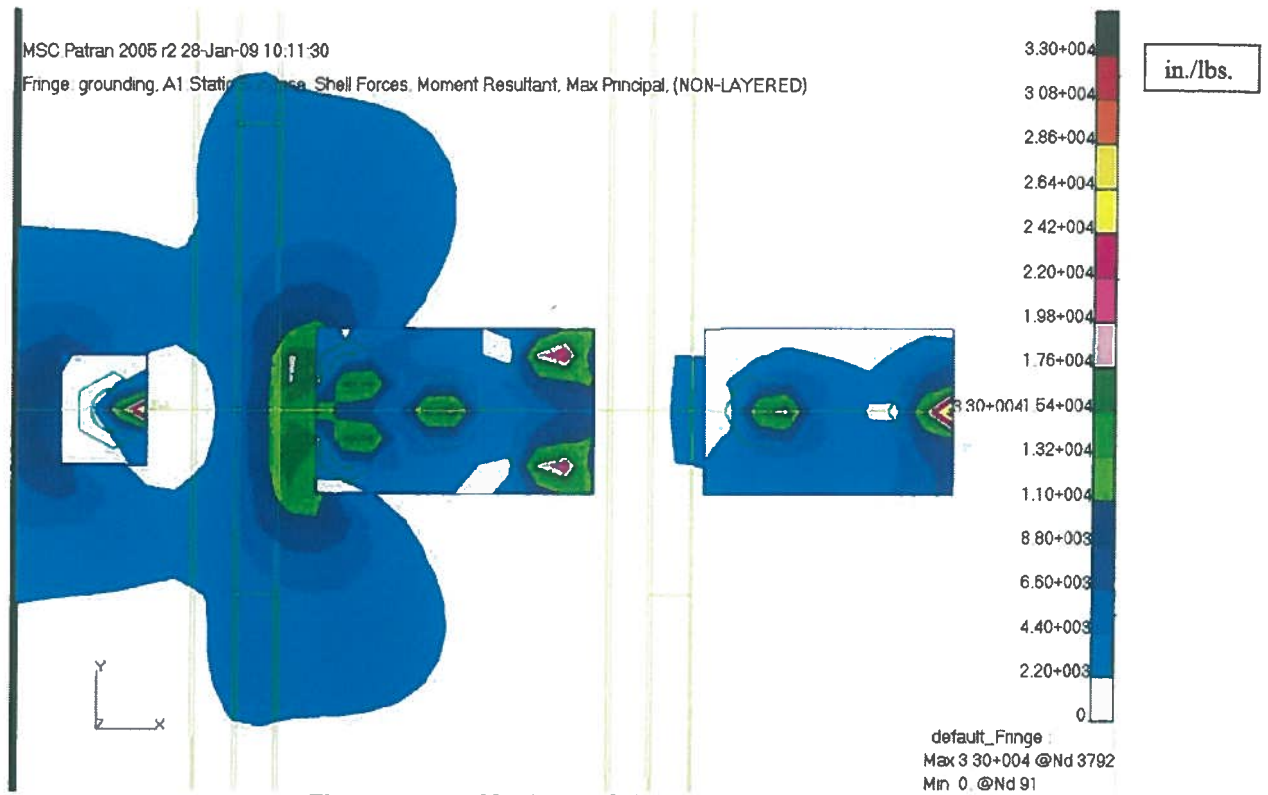


Figure 7.3.5 – Minimum Principal Force

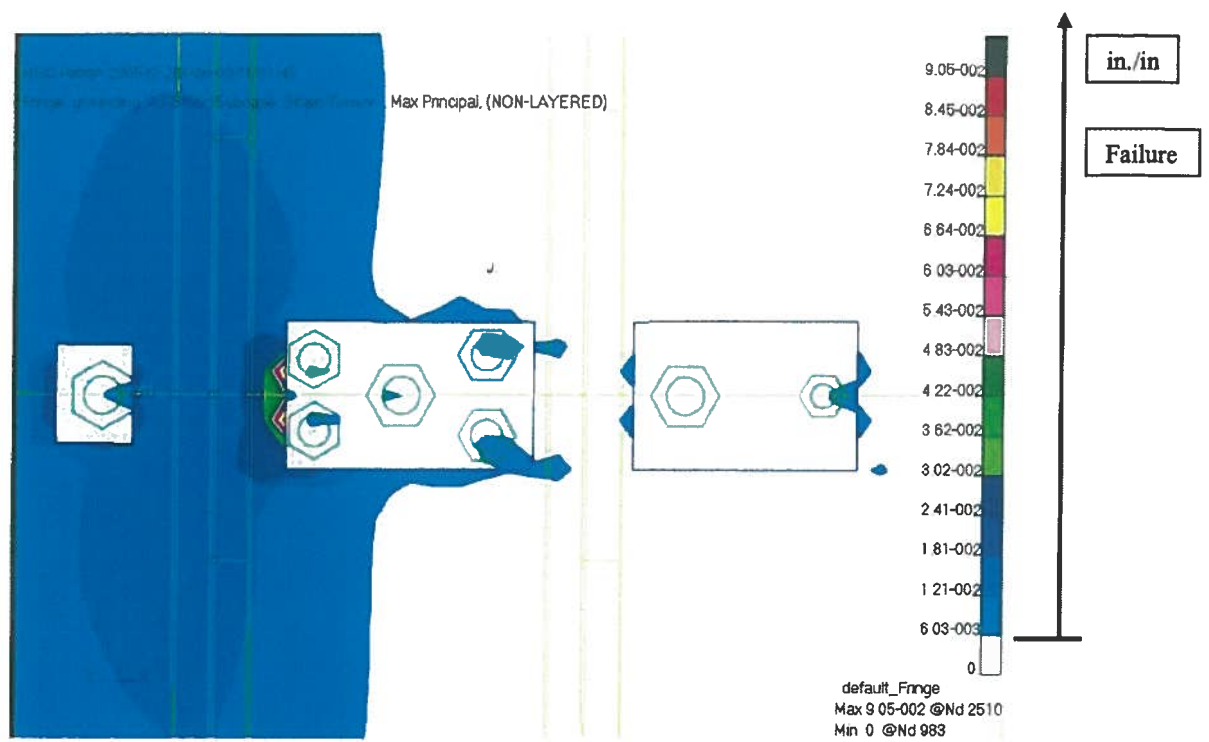




**Figure 7.3.6 – Maximum Principal Moment**



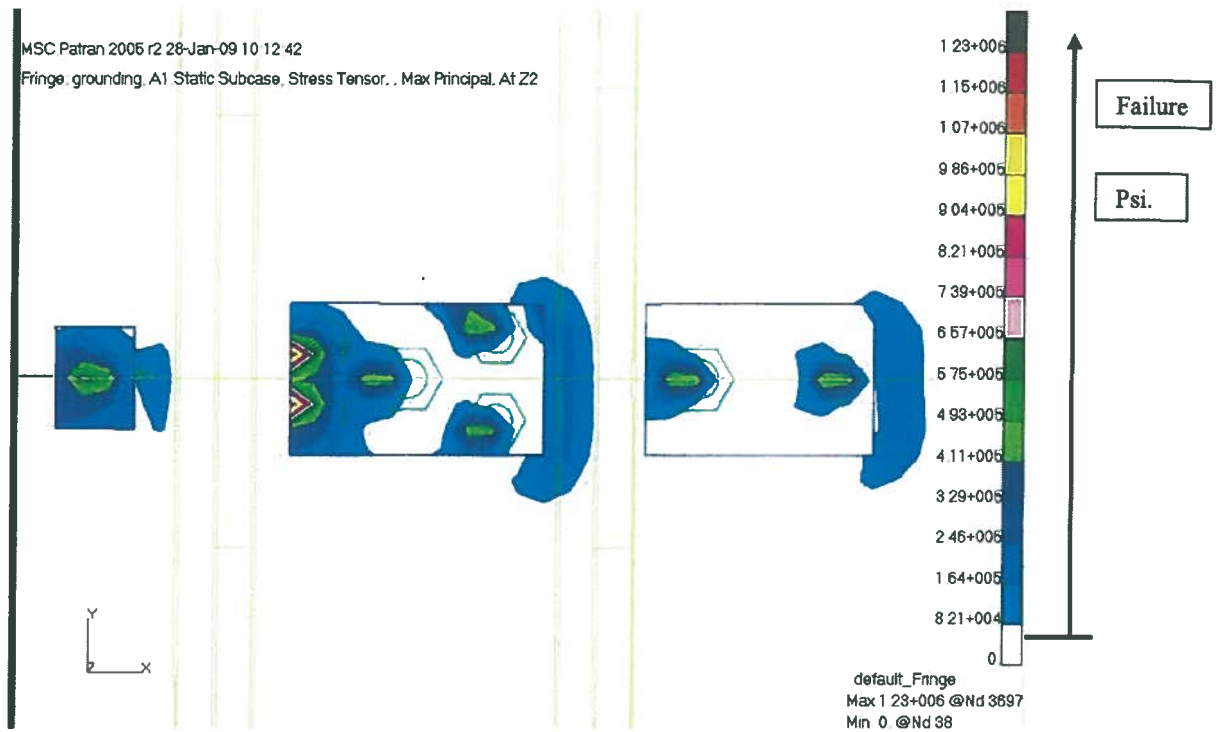
**Figure 7.3.7 – Minimum Principal Moment**



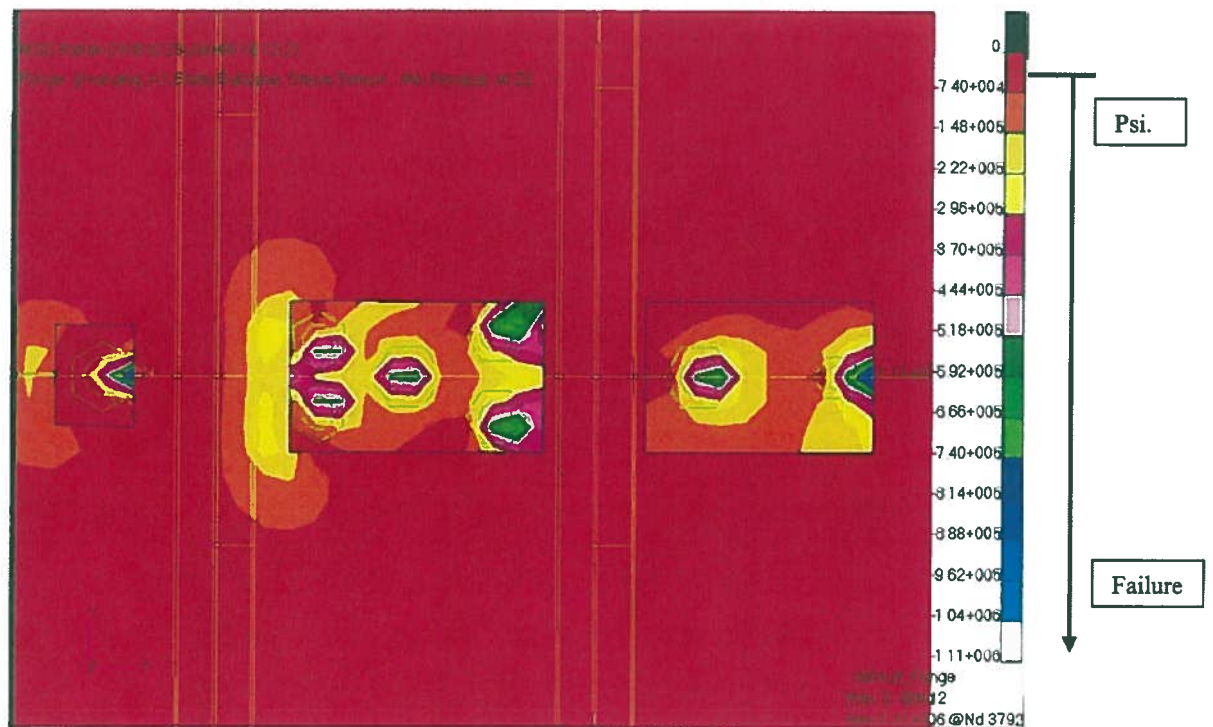
**Figure 7.3.8 – Maximum Principal Strain**



**Figure 7.3.9 – Minimum Principal Strain**



**Figure 7.3.10 – Maximum Principal Stress**



**Figure 7.3.11 – Minimum Principal Stress**

Margin of Safety calculations using CLAM for most critical hull shell elements adjacent to the keel bolts for limit loads, showing that the hull shell & the hull shell plus the stainless steel backing plates are significantly under designed (negative margins of safety). The results of these margin of safety calculations follow:

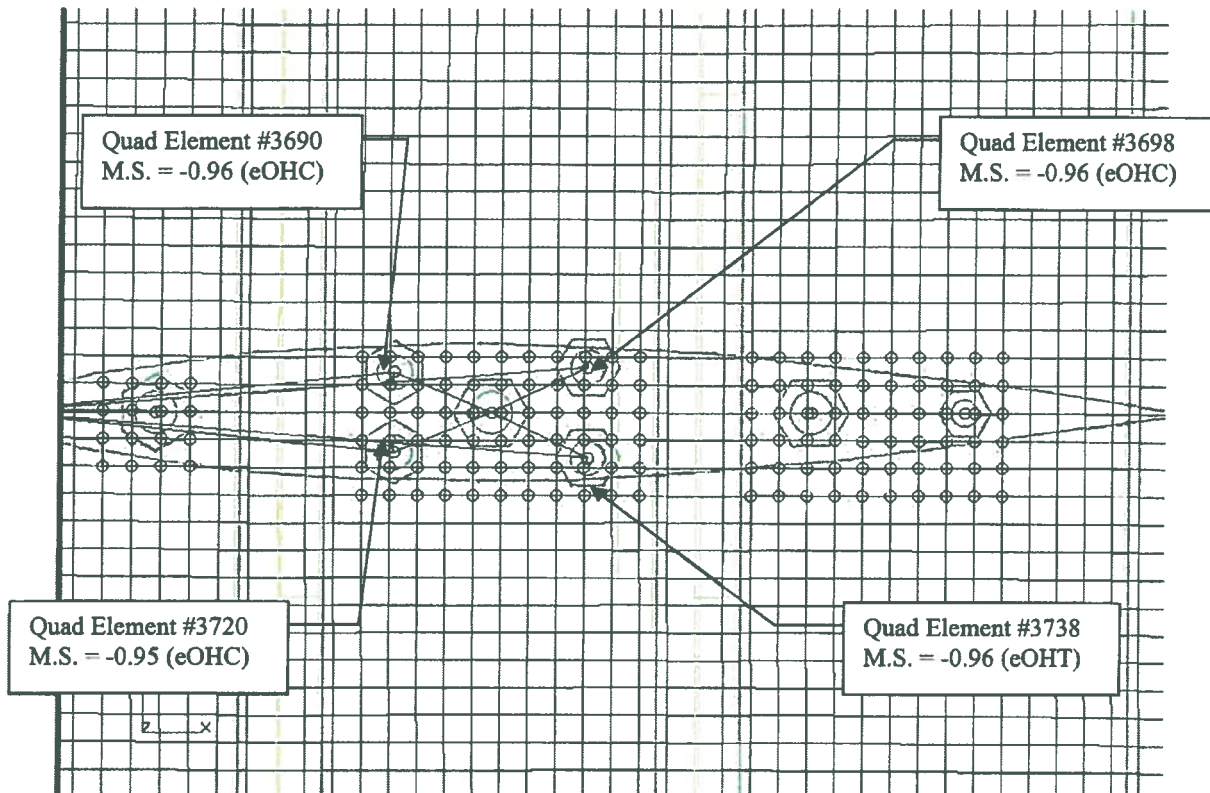


Figure 7.3.8 – Locations of Critical Elements for Grounding Condition



**RHS Element #3690****Bolt #2**

Cynthia Woods - Loadcase: Keel Moment - Bolt #2 - 1/28/2009

Laminate Strength - t = 0.637" + 0.375" ss - Element #3690

DTLAM Version 13.35 Laminate Strength Analysis

Laminate Boundary Conditions

Nx (lb/in)	= -64258.00	ex (in/in)	= -0.028629
Ny (lb/in)	= -31263.00	ey (in/in)	= -0.005629
Nxy (lb/in)	= -29157.00	rx (in/in)	= -0.036329
Mx (in-lb/in)	= -18879.0000	kx (rad/in)	= -0.085469
My (in-lb/in)	= -9862.0000	ky (rad/in)	= -0.017121
Mxy (in-lb/in)	= -6967.0000	kxy (rad/in)	= -0.106571

Delta Temperature (deg F) = +0

Laminate Principle Strains (in/in):

Surface 1:	emax = +0.010446	eOHT = +0.004310	MS = -0.59
	emin = -0.096614	eOHC = -0.004310	MS = <b>-0.96</b>
Surface 2:	emax = +0.019359	eOHT = +0.004310	MS = -0.78
	emin = -0.001707	eOHC = -0.004310	MS = +1.53

Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	-0.085649	+0.001994	+0.055910	-0.83
0.0490	+0.0	owens corning 1	-0.065595	-0.013033	-0.082421	-0.78
0.0490	+45.0	owens corning 1	-0.075400	+0.001799	+0.049212	-0.81
0.0490	+0.0	owens corning 1	-0.057219	-0.011355	-0.071977	-0.75
0.0490	+45.0	owens corning 1	-0.065151	+0.001604	+0.042514	-0.78
0.0490	+0.0	owens corning 1	-0.048843	-0.009678	-0.061533	-0.71
0.0490	+45.0	owens corning 1	-0.054903	+0.001409	+0.035816	-0.74
0.0490	+0.0	owens corning 1	-0.040467	-0.008000	-0.051089	-0.65
0.0490	+45.0	owens corning 1	-0.044654	+0.001214	+0.029118	-0.68
0.0490	+0.0	owens corning 1	-0.032091	-0.006322	-0.040645	-0.55
0.0490	+45.0	owens corning 1	-0.034405	+0.001019	+0.022420	-0.58
0.0490	+0.0	owens corning 1	-0.023715	-0.004644	-0.030201	-0.39
0.0490	+45.0	owens corning 1	-0.024156	+0.000824	+0.015721	-0.41
0.3750	+0.0	STEEL (125 HT)	-0.001407	-0.000176	-0.002387	+1.69

Total Thickness = 1.0120 in



**LHS Element #3720**

**Bolt #3**

Cynthia Woods - Loadcase: Keel Moment - Bolt #3 - 1/28/2009

Laminate Strength - t = 0.637" + 0.375" ss - Element #3720

DTLAM Version 13.35 Laminate Strength Analysis

Laminate Boundary Conditions

Nx (lb/in)	= -55475.00	ex (in/in)	= -0.024734
Ny (lb/in)	= -35473.00	ey (in/in)	= -0.008675
Nxy (lb/in)	= +29981.00	rxxy (in/in)	= +0.038296
Mx (in-lb/in)	= -18185.0000	kx (rad/in)	= -0.074714
My (in-lb/in)	= -10711.0000	ky (rad/in)	= -0.025801
Mxy (in-lb/in)	= +7641.0000	kxy (rad/in)	= +0.112945

Delta Temperature (deg F) = +0

Laminate Principle Strains (in/in):

Surface 1:	emax = +0.009768	eOHT = +0.004310	MS = -0.56
	emin = -0.094037	eOHC = -0.004310	MS = <b>-0.95</b>
Surface 2:	emax = +0.019106	eOHT = +0.004310	MS = -0.77
	emin = -0.001654	eOHC = -0.004310	MS = +1.61

Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	+0.005436	-0.087243	+0.039611	-0.84
0.0490	+0.0	owens corning 1	-0.057047	-0.019834	+0.087145	-0.75
0.0490	+45.0	owens corning 1	+0.004827	-0.076783	+0.034817	-0.81
0.0490	+0.0	owens corning 1	-0.049725	-0.017305	+0.076077	-0.71
0.0490	+45.0	owens corning 1	+0.004218	-0.066324	+0.030024	-0.78
0.0490	+0.0	owens corning 1	-0.042404	-0.014777	+0.065008	-0.66
0.0490	+45.0	owens corning 1	+0.003609	-0.055864	+0.025230	-0.74
0.0490	+0.0	owens corning 1	-0.035082	-0.012248	+0.053939	-0.59
0.0490	+45.0	owens corning 1	+0.003000	-0.045405	+0.020437	-0.68
0.0490	+0.0	owens corning 1	-0.027760	-0.009720	+0.042871	-0.48
0.0490	+45.0	owens corning 1	+0.002391	-0.034945	+0.015643	-0.59
0.0490	+0.0	owens corning 1	-0.020438	-0.007191	+0.031802	-0.30
0.0490	+45.0	owens corning 1	+0.001782	-0.024486	+0.010850	-0.41
0.3750	+0.0	STEEL (125 HT)	-0.000937	-0.000457	+0.002323	+2.13

Total Thickness = 1.0120 in

**RHS Element #3698**

**Bolt #5**

Cynthia Woods - Loadcase: Keel Moment - Bolt #5 - 1/28/2009

Laminate Strength - t = 0.637" + 0.375" ss - Element #3698

DTLAM Version 13.35 Laminate Strength Analysis

Laminate Boundary Conditions

Nx (lb/in)	= +74242.00	ex (in/in)	= +0.035847
Ny (lb/in)	= +3467.00	ey (in/in)	= -0.005278
Nxy (lb/in)	= +21059.00	rxxy (in/in)	= +0.027022
Mx (in-lb/in)	= +20077.0000	kx (rad/in)	= +0.105360
My (in-lb/in)	= +8530.0000	ky (rad/in)	= -0.012217
Mxy (in-lb/in)	= +5429.0000	kxy (rad/in)	= +0.079770

Delta Temperature (deg F) = +0

Laminate Principle Strains (in/in):

Surface 1:	emax = +0.099399	eOHT = +0.004310	MS = <b>-0.96</b>
	emin = -0.021700	eOHC = -0.004310	MS = -0.80
Surface 2:	emax = +0.003071	eOHT = +0.004310	MS = +0.40
	emin = -0.019632	eOHC = -0.004310	MS = -0.78

Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	+0.070424	+0.004993	-0.097738	-0.75
0.0490	+0.0	owens corning 1	+0.081415	-0.010562	+0.061522	-0.78
0.0490	+45.0	owens corning 1	+0.061951	+0.004337	-0.086215	-0.72
0.0490	+0.0	owens corning 1	+0.071089	-0.009365	+0.053705	-0.75
0.0490	+45.0	owens corning 1	+0.053479	+0.003682	-0.074693	-0.67
0.0490	+0.0	owens corning 1	+0.060764	-0.008167	+0.045887	-0.71
0.0490	+45.0	owens corning 1	+0.045006	+0.003027	-0.063170	-0.61
0.0490	+0.0	owens corning 1	+0.050439	-0.006970	+0.038070	-0.65
0.0490	+45.0	owens corning 1	+0.036533	+0.002372	-0.051648	-0.52
0.0490	+0.0	owens corning 1	+0.040114	-0.005773	+0.030252	-0.56
0.0490	+45.0	owens corning 1	+0.028060	+0.001716	-0.040125	-0.37
0.0490	+0.0	owens corning 1	+0.029788	-0.004576	+0.022435	-0.41
0.0490	+45.0	owens corning 1	+0.019588	+0.001061	-0.028603	-0.10
0.3750	+0.0	STEEL (125 HT)	+0.002290	-0.001387	+0.001615	+0.88

Total Thickness = 1.0120 in

### LHS Hull Shell Element #3738

#### Bolt #6

Cynthia Woods - Loadcase: Keel Moment - Bolt #6 - 1/28/2009

Laminate Strength - t = 0.637" + 0.375" ss - Element #3738

DTLAM Version 13.35 Laminate Strength Analysis

#### Laminate Boundary Conditions

Nx (lb/in)	= +75749.00	ex (in/in)	= +0.034532
Ny (lb/in)	= +16097.00	ey (in/in)	= -0.003327
Nxy (lb/in)	= +23922.00	rx (in/in)	= +0.028064
Mx (in-lb/in)	= +18521.0000	kx (rad/in)	= +0.101409
My (in-lb/in)	= +5754.0000	ky (rad/in)	= -0.008993
Mxy (in-lb/in)	= +4832.0000	kxy (rad/in)	= +0.081205

Delta Temperature (deg F) = +0

#### Laminate Principle Strains (in/in):

Surface 1:	emax = +0.097220	eOHT = +0.004310	MS = -0.96
	emin = -0.019253	eOHC = -0.004310	MS = -0.78
Surface 2:	emax = +0.003332	eOHT = +0.004310	MS = +0.29
	emin = -0.018890	eOHC = -0.004310	MS = -0.77

#### Ply Strain (in/in) and Max-Strain Margin Details

Thick	Angle	Material	Strn-1	Strn-2	Strn-12	Margin
0.0490	+45.0	owens corning 1	+0.071434	+0.004269	-0.091017	-0.75
0.0490	+0.0	owens corning 1	+0.078391	-0.007217	+0.063185	-0.77
0.0490	+45.0	owens corning 1	+0.062926	+0.003720	-0.080198	-0.72
0.0490	+0.0	owens corning 1	+0.068453	-0.006335	+0.055227	-0.74
0.0490	+45.0	owens corning 1	+0.054419	+0.003170	-0.069378	-0.68
0.0490	+0.0	owens corning 1	+0.058515	-0.005454	+0.047269	-0.70
0.0490	+45.0	owens corning 1	+0.045911	+0.002621	-0.058559	-0.62
0.0490	+0.0	owens corning 1	+0.048577	-0.004573	+0.039311	-0.64
0.0490	+45.0	owens corning 1	+0.037404	+0.002072	-0.047740	-0.53
0.0490	+0.0	owens corning 1	+0.038639	-0.003691	+0.031353	-0.54
0.0490	+45.0	owens corning 1	+0.028896	+0.001523	-0.036920	-0.39
0.0490	+0.0	owens corning 1	+0.028701	-0.002810	+0.023395	-0.38
0.0490	+45.0	owens corning 1	+0.020389	+0.000973	-0.026101	-0.13
0.3750	+0.0	STEEL (125 HT)	+0.002233	-0.000463	+0.002200	+0.93

Total Thickness = 1.0120 in

## 8.0 FAILURE ANALYSIS

As can be seen for both hull shell elements adjacent to the keel bolts & also for hull shell elements near the berth fronts at the outboard ends of the keel floors & for all three (3) of the load cases run, the results show very negative margins of safety for each element. This result is confirmed by looking at the laminate ply-by-ply strains, which are given in the Nastran output files for each loadcase. The generally accepted maximum allowable strain with a factor of safety on the applied load (this report examines a limit load applied with no factor of safety – actual keel load) to prevent failure is  $1/100 = 0.01 \text{ in./in.} = 1.0\text{E-}02 \text{ in./in.}$  for a solid laminate without holes. For example, the ply-by-ply strain results for the limit load 90 degree heel loadcase #2 are as follows:

### Ply Strains: Quad Element #1962 Adjacent to Bolt #1

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	MAX
ID	ID	In./in.	In./in.	In./in.	In./in.	In./in.	SHEAR
							In./in.
1962	1	1.19E-02	-1.04E-03	1.15E-02	1.41E-02	-3.21E-03	1.73E-02
1962	2	-2.57E-04	1.03E-02	1.20E-02	1.30E-02	-2.97E-03	1.60E-02
1962	3	1.01E-02	-9.12E-04	9.70E-03	1.20E-02	-2.74E-03	1.47E-02
1962	4	-2.09E-04	8.61E-03	1.01E-02	1.09E-02	-2.50E-03	1.34E-02
1962	5	8.36E-03	-7.83E-04	7.94E-03	9.84E-03	-2.27E-03	1.21E-02
1962	6	-1.60E-04	6.90E-03	8.18E-03	8.78E-03	-2.03E-03	1.08E-02
1962	7	6.57E-03	-6.54E-04	6.19E-03	7.71E-03	-1.80E-03	9.51E-03
1962	8	-1.12E-04	5.20E-03	6.26E-03	6.65E-03	-1.56E-03	8.21E-03
1962	9	4.78E-03	-5.25E-04	4.43E-03	5.58E-03	-1.33E-03	6.91E-03
1962	10	-6.32E-05	3.49E-03	4.34E-03	4.52E-03	-1.09E-03	5.61E-03
1962	11	2.99E-03	-3.96E-04	2.67E-03	3.45E-03	-8.60E-04	4.31E-03
1962	12	-1.48E-05	1.78E-03	2.43E-03	2.39E-03	-6.27E-04	3.02E-03
1962	13	1.20E-03	-2.68E-04	9.12E-04	1.33E-03	-3.98E-04	1.73E-03

**Table 8.0.1 – Ply Strains for Element #1962**

Examining the major axis (major principal), minor axis (minor principal) & maximum shear strains the allowable value of  $1.0\text{E-}02 \text{ in./in.}$  is exceeded for certain plies in the hull laminate, resulting in modes of failure. The margin of safety calculations for each loadcase give a better picture of which mode of failure was most critical.

Other examples are as follows:

**Ply Strains: Quad Element #665 Adjacent to Bolt #2**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	MAX
ID	ID	In./in.	In./in.	In./in.	In./in.	In./in.	SHEAR In./in.
665	1	-7.55E-03	-2.30E-03	-1.06E-02	9.96E-04	-1.09E-02	1.18E-02
665	2	3.62E-04	-9.42E-03	-4.79E-03	9.17E-04	-9.98E-03	1.09E-02
665	3	-6.30E-03	-1.97E-03	-8.96E-03	8.39E-04	-9.11E-03	9.95E-03
665	4	3.23E-04	-7.80E-03	-3.87E-03	7.61E-04	-8.24E-03	9.00E-03
665	5	-5.05E-03	-1.64E-03	-7.29E-03	6.83E-04	-7.37E-03	8.05E-03
665	6	2.84E-04	-6.18E-03	-2.95E-03	6.05E-04	-6.50E-03	7.10E-03
665	7	-3.80E-03	-1.31E-03	-5.63E-03	5.27E-04	-5.63E-03	6.16E-03
665	8	2.45E-04	-4.55E-03	-2.03E-03	4.51E-04	-4.76E-03	5.21E-03
665	9	-2.54E-03	-9.73E-04	-3.97E-03	3.75E-04	-3.89E-03	4.27E-03
665	10	2.06E-04	-2.93E-03	-1.11E-03	3.01E-04	-3.02E-03	3.32E-03
665	11	-1.29E-03	-6.42E-04	-2.30E-03	2.31E-04	-2.16E-03	2.39E-03
665	12	1.67E-04	-1.30E-03	-1.86E-04	1.73E-04	-1.31E-03	1.48E-03
665	13	-3.55E-05	-3.10E-04	-6.40E-04	1.76E-04	-5.21E-04	6.96E-04

**Table 8.0.2 – Ply Strains for Element #665**

Again, the same result as above, but only two (2) of the plies failed, #1 & #2.

**Ply Strains: Quad Element #2261 Adjacent to Bolt #3**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	MAX
ID	ID	In./in.	In./in.	In./in.	In./in.	In./in.	SHEAR In./in.
2261	1	2.12E-02	1.03E-02	1.45E-02	2.48E-02	6.67E-03	1.81E-02
2261	2	7.42E-03	1.90E-02	8.54E-03	2.04E-02	6.02E-03	1.44E-02
2261	3	1.37E-02	7.62E-03	8.70E-03	1.60E-02	5.37E-03	1.06E-02
2261	4	5.25E-03	1.11E-02	3.71E-03	1.16E-02	4.71E-03	6.90E-03
2261	5	6.27E-03	4.98E-03	2.94E-03	7.23E-03	4.02E-03	3.21E-03
2261	6	3.07E-03	3.13E-03	-1.13E-03	3.66E-03	2.53E-03	1.13E-03
2261	7	-1.20E-03	2.34E-03	-2.82E-03	2.83E-03	-1.70E-03	4.53E-03
2261	8	8.89E-04	-4.81E-03	-5.96E-03	2.16E-03	-6.08E-03	8.25E-03
2261	9	-8.68E-03	-3.03E-04	-8.58E-03	1.50E-03	-1.05E-02	1.20E-02
2261	10	-1.29E-03	-1.27E-02	-1.08E-02	8.51E-04	-1.49E-02	1.57E-02
2261	11	-1.62E-02	-2.94E-03	-1.43E-02	1.99E-04	-1.93E-02	1.95E-02
2261	12	-3.47E-03	-2.07E-02	-1.56E-02	-4.52E-04	-2.37E-02	2.32E-02
2261	13	-2.36E-02	-5.59E-03	-2.01E-02	-1.10E-03	-2.81E-02	2.70E-02

**Table 8.0.3 – Ply Strains for Element #2261**

A worst result than above with many of the hull laminate outer plies failed.



**Ply Strains: Quad Element #2555 Adjacent to Bolt #6**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	MAX
ID	ID	In./in.	In./in.	In./in.	In./in.	In./in.	SHEAR In./in.
2555	1	-1.07E-02	5.61E-03	-9.73E-03	6.95E-03	-1.20E-02	1.90E-02
2555	2	2.13E-03	-6.78E-03	-1.52E-02	6.49E-03	-1.11E-02	1.76E-02
2555	3	-9.17E-03	4.95E-03	-8.08E-03	6.02E-03	-1.02E-02	1.63E-02
2555	4	1.73E-03	-5.52E-03	-1.30E-02	5.56E-03	-9.35E-03	1.49E-02
2555	5	-7.64E-03	4.28E-03	-6.43E-03	5.09E-03	-8.46E-03	1.36E-02
2555	6	1.34E-03	-4.27E-03	-1.08E-02	4.63E-03	-7.57E-03	1.22E-02
2555	7	-6.12E-03	3.62E-03	-4.79E-03	4.17E-03	-6.68E-03	1.09E-02
2555	8	9.45E-04	-3.02E-03	-8.64E-03	3.72E-03	-5.79E-03	9.51E-03
2555	9	-4.60E-03	2.95E-03	-3.14E-03	3.26E-03	-4.91E-03	8.18E-03
2555	10	5.51E-04	-1.77E-03	-6.45E-03	2.82E-03	-4.04E-03	6.86E-03
2555	11	-3.07E-03	2.29E-03	-1.50E-03	2.39E-03	-3.18E-03	5.56E-03
2555	12	1.58E-04	-5.17E-04	-4.26E-03	1.98E-03	-2.34E-03	4.32E-03
2555	13	-1.55E-03	1.62E-03	1.48E-04	1.62E-03	-1.55E-03	3.17E-03

**Table 8.0.4 – Ply Strains for Element #2555**

The similar result to above with many of the hull laminate plies failed due to shear.

As can be seen for both hull shell elements adjacent to the keel bolts & also for hull shell elements near the berth fronts at the outboard ends of the keel floors & for all three (3) of the load cases run, the results show higher than allowable stresses for certain of the elements, especially near the keel bolt backing plates. This result is confirmed by looking at the laminate ply-by-ply stresses, which are given in the Nastran output files for each loadcase. The maximum allowable stresses with a factor of safety on the applied load (this report examines a limit load applied with no factor of safety – actual keel load) are applied to the Nastran results. For example, the ply-by-ply stress results for the limit load 90 degree heel loadcase #2 are as follows:

**Ply Stresses: Quad Element #1962 Adjacent to Bolt #1**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	MAX
ID	ID	psi.	psi.	psi.	psi.	psi.	SHEAR psi.
1962	1	1.68E+04	9.01E+02	7.04E+03	1.95E+04	-1.76E+03	1.06E+04
1962	2	1.70E+03	1.47E+04	7.38E+03	1.80E+04	-1.64E+03	9.83E+03
1962	3	1.43E+04	7.27E+02	5.96E+03	1.66E+04	-1.52E+03	9.03E+03
1962	4	1.42E+03	1.23E+04	6.20E+03	1.51E+04	-1.39E+03	8.23E+03
1962	5	1.18E+04	5.53E+02	4.88E+03	1.36E+04	-1.27E+03	7.44E+03
1962	6	1.15E+03	9.83E+03	5.02E+03	1.21E+04	-1.15E+03	6.64E+03
1962	7	9.25E+03	3.79E+02	3.80E+03	1.07E+04	-1.03E+03	5.84E+03
1962	8	8.79E+02	7.40E+03	3.85E+03	9.18E+03	-9.03E+02	5.04E+03
1962	9	6.72E+03	2.05E+02	2.72E+03	7.70E+03	-7.81E+02	4.24E+03
1962	10	6.07E+02	4.97E+03	2.67E+03	6.23E+03	-6.59E+02	3.44E+03
1962	11	4.19E+03	3.13E+01	1.64E+03	4.76E+03	-5.38E+02	2.65E+03
1962	12	3.34E+02	2.53E+03	1.49E+03	3.29E+03	-4.18E+02	1.85E+03
1962	13	1.66E+03	-1.43E+02	5.60E+02	1.82E+03	-3.03E+02	1.06E+03

**Table 8.0.1 – Ply Stresses for Element #1962**

Examining the major axis (major principal), minor axis (minor principal) & maximum shear stresses the allowable values of tensile stress  $F1t = F2t = 31,600$  psi., compressive stress  $F1c = F2c = 25,700$  psi. & shear stress  $F12 = 9,500$  psi. are exceeded for certain plies in the hull laminate, resulting in all modes of failure. The margin of safety calculations for each loadcase give a better picture of which mode of failure was most critical.

Other examples are as follows:

**Ply Stresses: Quad Element #665 Adjacent to Bolt #2**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	MAX
ID	ID	psi.	psi.	psi.	psi.	psi.	SHEAR
							psi.
665	1	-1.12E+04	-4.80E+03	-6.52E+03	-7.47E+02	-1.53E+04	7.27E+03
665	2	-1.37E+03	-1.34E+04	-2.94E+03	-6.85E+02	-1.41E+04	6.69E+03
665	3	-9.39E+03	-4.07E+03	-5.50E+03	-6.23E+02	-1.28E+04	6.11E+03
665	4	-1.10E+03	-1.11E+04	-2.38E+03	-5.61E+02	-1.16E+04	5.53E+03
665	5	-7.54E+03	-3.35E+03	-4.48E+03	-4.98E+02	-1.04E+04	4.94E+03
665	6	-8.29E+02	-8.76E+03	-1.81E+03	-4.35E+02	-9.16E+03	4.36E+03
665	7	-5.68E+03	-2.62E+03	-3.46E+03	-3.72E+02	-7.93E+03	3.78E+03
665	8	-5.60E+02	-6.45E+03	-1.25E+03	-3.08E+02	-6.70E+03	3.20E+03
665	9	-3.82E+03	-1.90E+03	-2.44E+03	-2.42E+02	-5.48E+03	2.62E+03
665	10	-2.91E+02	-4.14E+03	-6.80E+02	-1.75E+02	-4.26E+03	2.04E+03
665	11	-1.97E+03	-1.17E+03	-1.41E+03	-1.02E+02	-3.04E+03	1.47E+03
665	12	-2.24E+01	-1.83E+03	-1.14E+02	-1.52E+01	-1.84E+03	9.11E+02
665	13	-1.13E+02	-4.49E+02	-3.93E+02	1.47E+02	-7.09E+02	4.28E+02

**Table 8.0.2 – Ply Stresses for Element #665**

Again, a similar result to above, but no stresses exceeding their allowable.

**Ply Stresses: Quad Element #2261 Adjacent to Bolt #3**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	MAX
ID	ID	psi.	psi.	psi.	psi.	psi.	SHEAR
							psi.
2261	1	3.24E+04	1.89E+04	8.88E+03	3.68E+04	1.45E+04	1.11E+04
2261	2	1.44E+04	2.86E+04	5.24E+03	3.03E+04	1.27E+04	8.83E+03
2261	3	2.12E+04	1.36E+04	5.34E+03	2.39E+04	1.09E+04	6.53E+03
2261	4	9.70E+03	1.68E+04	2.28E+03	1.75E+04	9.04E+03	4.24E+03
2261	5	9.95E+03	8.37E+03	1.80E+03	1.11E+04	7.19E+03	1.97E+03
2261	6	5.01E+03	5.08E+03	-6.91E+02	5.73E+03	4.35E+03	6.92E+02
2261	7	-1.25E+03	3.10E+03	-1.73E+03	3.70E+03	-1.86E+03	2.78E+03
2261	8	3.08E+02	-6.69E+03	-3.66E+03	1.87E+03	-8.26E+03	5.06E+03
2261	9	-1.25E+04	-2.17E+03	-5.27E+03	5.22E+01	-1.47E+04	7.36E+03
2261	10	-4.39E+03	-1.85E+04	-6.63E+03	-1.76E+03	-2.11E+04	9.67E+03
2261	11	-2.37E+04	-7.43E+03	-8.80E+03	-3.57E+03	-2.75E+04	1.20E+04
2261	12	-9.09E+03	-3.02E+04	-9.59E+03	-5.38E+03	-3.39E+04	1.43E+04
2261	13	-3.49E+04	-1.27E+04	-1.23E+04	-7.20E+03	-4.04E+04	1.66E+04

**Table 8.0.3 – Ply Stresses for Element #2261**

A worst result than above with many of the hull laminate outer plies failed.

**Ply Stresses: Quad Element #2555 Adjacent to Bolt #6**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	MAX
ID	ID	psi.	psi.	psi.	psi.	psi.	SHEAR
							psi.
2555	1	-1.41E+04	5.88E+03	-5.97E+03	7.52E+03	-1.58E+04	1.17E+04
2555	2	1.68E+03	-9.25E+03	-9.34E+03	7.04E+03	-1.46E+04	1.08E+04
2555	3	-1.21E+04	5.23E+03	-4.96E+03	6.55E+03	-1.34E+04	9.99E+03
2555	4	1.37E+03	-7.54E+03	-8.00E+03	6.07E+03	-1.22E+04	9.15E+03
2555	5	-1.01E+04	4.59E+03	-3.95E+03	5.58E+03	-1.11E+04	8.32E+03
2555	6	1.06E+03	-5.83E+03	-6.65E+03	5.10E+03	-9.88E+03	7.49E+03
2555	7	-8.02E+03	3.94E+03	-2.94E+03	4.62E+03	-8.70E+03	6.66E+03
2555	8	7.46E+02	-4.12E+03	-5.31E+03	4.15E+03	-7.53E+03	5.84E+03
2555	9	-5.98E+03	3.29E+03	-1.93E+03	3.68E+03	-6.36E+03	5.02E+03
2555	10	4.34E+02	-2.42E+03	-3.96E+03	3.22E+03	-5.20E+03	4.21E+03
2555	11	-3.93E+03	2.65E+03	-9.20E+02	2.77E+03	-4.06E+03	3.42E+03
2555	12	1.22E+02	-7.07E+02	-2.62E+03	2.36E+03	-2.94E+03	2.65E+03
2555	13	-1.89E+03	2.00E+03	9.07E+01	2.00E+03	-1.89E+03	1.95E+03

**Table 8.0.4 – Ply Stresses for Element #2555**

The similar result to above with three (3) of the hull laminate plies failed due to shear.

For example, the ply-by-ply strain results for the grounding load loadcase #3 are as follows:

**Ply Strains: Quad Element #628 Adjacent to Bolt #2 at the Forward End of the Keel  
Keel pulling away from the hull shell.**

Element	Ply	NORMAL-1	NORMAL-2	Shear-12	MAJOR	MINOR	MAX
ID	ID	in./in.	in./in.	in./in.	in./in.	in./in.	SHEAR in./in.
628	1	4.55E-03	1.26E-01	-7.43E-02	1.36E-01	-5.94E-03	1.42E-01
628	2	9.61E-02	2.65E-02	-1.14E-01	1.28E-01	-5.39E-03	1.33E-01
628	3	4.27E-03	1.11E-01	-6.49E-02	1.20E-01	-4.85E-03	1.25E-01
628	4	8.39E-02	2.36E-02	-9.93E-02	1.12E-01	-4.30E-03	1.16E-01
628	5	3.98E-03	9.60E-02	-5.56E-02	1.04E-01	-3.75E-03	1.07E-01
628	6	7.17E-02	2.08E-02	-8.48E-02	9.56E-02	-3.21E-03	9.88E-02
628	7	3.70E-03	8.12E-02	-4.62E-02	8.76E-02	-2.66E-03	9.02E-02
628	8	5.94E-02	1.79E-02	-7.03E-02	7.95E-02	-2.12E-03	8.16E-02
628	9	3.41E-03	6.64E-02	-3.68E-02	7.14E-02	-1.57E-03	7.30E-02
628	10	4.72E-02	1.51E-02	-5.58E-02	6.33E-02	-1.03E-03	6.44E-02
628	11	3.13E-03	5.16E-02	-2.75E-02	5.53E-02	-4.89E-04	5.57E-02
628	12	3.50E-02	1.22E-02	-4.13E-02	4.72E-02	5.01E-05	4.71E-02
628	13	2.84E-03	3.69E-02	-1.81E-02	3.91E-02	5.85E-04	3.85E-02

**Table 8.0.4 – Ply Strains for Element #628 From Grounding**

Examining the major axis (major principal) & maximum shear strains the allowable value of 1.0E-02 in./in. is exceeded for every ply in the hull laminate, resulting in all modes of failure. The margin of safety calculations for each loadcase give a better picture of which mode of failure was most critical.

**Ply Strains: Quad Element #2259 Adjacent to Bolt #3 at the Forward End of the Keel  
Keel pulling away from hull shell.**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	SHEAR
ID	ID	in./in.	in./in.	in./in.	in./in.	in./in.	in./in.
2259	1	1.31E-01	-1.18E-03	-6.32E-02	1.38E-01	-8.35E-03	1.47E-01
2259	2	9.08E-02	3.14E-02	1.24E-01	1.30E-01	-7.72E-03	1.38E-01
2259	3	1.15E-01	-8.08E-04	-5.55E-02	1.22E-01	-7.08E-03	1.29E-01
2259	4	7.93E-02	2.77E-02	1.08E-01	1.14E-01	-6.45E-03	1.20E-01
2259	5	9.99E-02	-4.32E-04	-4.77E-02	1.05E-01	-5.81E-03	1.11E-01
2259	6	6.79E-02	2.40E-02	9.24E-02	9.71E-02	-5.18E-03	1.02E-01
2259	7	8.44E-02	-5.55E-05	-4.00E-02	8.89E-02	-4.54E-03	9.34E-02
2259	8	5.64E-02	2.04E-02	7.65E-02	8.07E-02	-3.91E-03	8.46E-02
2259	9	6.89E-02	3.21E-04	-3.22E-02	7.25E-02	-3.27E-03	7.57E-02
2259	10	4.50E-02	1.67E-02	6.06E-02	6.43E-02	-2.64E-03	6.69E-02
2259	11	5.34E-02	6.97E-04	-2.44E-02	5.61E-02	-2.00E-03	5.81E-02
2259	12	3.35E-02	1.30E-02	4.47E-02	4.78E-02	-1.37E-03	4.92E-02
2259	13	3.78E-02	1.07E-03	-1.67E-02	3.96E-02	-7.32E-04	4.04E-02

**Table 8.0.5 – Ply Strains for Element #2259 From Grounding**

Again, the ply-by-ply strains at the forward end of the keel exceed the allowable. In fact, a number of the ply strains are close to or greater than 10 times the allowable strain.



**Ply Strains: Quad Element #924 Adjacent to Bolt #5 toward the aft end of the Keel  
Keel pushing into the hull shell.**

Element	Ply	NORMAL-1	NORMAL-2	Shear-12	MAJOR	MINOR	MAX
ID	ID	in./in.	in./in.	in./in.	in./in.	in./in.	SHEAR
							in./in.
924	1	-1.50E-02	-1.02E-01	1.10E-01	1.18E-02	-1.29E-01	1.41E-01
924	2	-1.07E-01	-2.62E-03	8.15E-02	1.14E-02	-1.21E-01	1.32E-01
924	3	-1.31E-02	-8.90E-02	9.84E-02	1.11E-02	-1.13E-01	1.24E-01
924	4	-9.35E-02	-1.12E-03	7.02E-02	1.07E-02	-1.05E-01	1.16E-01
924	5	-1.13E-02	-7.58E-02	8.63E-02	1.04E-02	-9.75E-02	1.08E-01
924	6	-8.00E-02	3.75E-04	5.89E-02	1.00E-02	-8.96E-02	9.96E-02
924	7	-9.42E-03	-6.27E-02	7.43E-02	9.68E-03	-8.18E-02	9.15E-02
924	8	-6.65E-02	1.87E-03	4.76E-02	9.35E-03	-7.39E-02	8.33E-02
924	9	-7.57E-03	-4.95E-02	6.23E-02	9.02E-03	-6.61E-02	7.51E-02
924	10	-5.30E-02	3.37E-03	3.63E-02	8.71E-03	-5.83E-02	6.70E-02
924	11	-5.72E-03	-3.64E-02	5.03E-02	8.42E-03	-5.05E-02	5.89E-02
924	12	-3.95E-02	4.87E-03	2.50E-02	8.15E-03	-4.28E-02	5.09E-02
924	13	-3.87E-03	-2.32E-02	3.83E-02	7.92E-03	-3.50E-02	4.29E-02

**Table 8.0.4 – Ply Strains for Element #924 From Grounding**

Examining the major axis (major principal), minor axis (minor principal) & maximum shear strains the allowable value of 1.0E-02 in./in. is exceeded for practically every ply in the hull laminate, resulting in all modes of failure towards the aft end of the keel. The margin of safety calculations for each loadcase give a better idea of which mode of failure was most critical.

**Ply Strains: Quad Element #2556 Adjacent to Bolt #6 toward the aft end of the Keel  
Keel pushing into the hull shell.**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	SHEAR
ID	ID	in./in.	in./in.	in./in.	in./in.	in./in.	in./in.
2556	1	-1.25E-02	-1.03E-01	1.03E-01	1.07E-02	-1.26E-01	1.37E-01
2556	2	-1.02E-01	-6.46E-03	8.52E-02	9.73E-03	-1.19E-01	1.28E-01
2556	3	-1.12E-02	-9.14E-02	8.93E-02	8.75E-03	-1.11E-01	1.20E-01
2556	4	-8.94E-02	-6.75E-03	7.52E-02	7.78E-03	-1.04E-01	1.12E-01
2556	5	-9.81E-03	-7.99E-02	7.60E-02	6.81E-03	-9.66E-02	1.03E-01
2556	6	-7.63E-02	-7.04E-03	6.51E-02	5.85E-03	-8.92E-02	9.51E-02
2556	7	-8.47E-03	-6.85E-02	6.26E-02	4.89E-03	-8.19E-02	8.68E-02
2556	8	-6.33E-02	-7.33E-03	5.50E-02	3.93E-03	-7.45E-02	7.85E-02
2556	9	-7.12E-03	-5.71E-02	4.93E-02	2.98E-03	-6.72E-02	7.02E-02
2556	10	-5.02E-02	-7.62E-03	4.49E-02	2.05E-03	-5.99E-02	6.19E-02
2556	11	-5.77E-03	-4.57E-02	3.59E-02	1.12E-03	-5.26E-02	5.37E-02
2556	12	-3.72E-02	-7.91E-03	3.49E-02	2.27E-04	-4.53E-02	4.55E-02
2556	13	-4.42E-03	-3.43E-02	2.26E-02	-6.31E-04	-3.80E-02	3.74E-02

**Table 8.0.5 – Ply Strains for Element #2556 From Grounding**

Again, the ply-by-ply strains at the aft end of the keel exceed the allowable. In fact, a number of the ply strains are close to or greater than 10 times the allowable strain.

For example, the ply-by-ply stress results for the grounding load loadcase #3 are as follows:

**Ply Stresses: Quad Element #628 Adjacent to Bolt #2 at the Forward End of the Keel  
Keel pulling away from the hull shell.**

Element	Ply	NORMAL-1	NORMAL-2	Shear-12	MAJOR	MINOR	MAX
ID	ID	psi.	psi.	psi.	psi.	psi.	SHEAR
							psi.
628	1	3.16E+04	1.80E+05	-4.56E+04	1.93E+05	1.87E+04	8.72E+04
628	2	1.43E+05	5.70E+04	-6.98E+04	1.82E+05	1.79E+04	8.19E+04
628	3	2.82E+04	1.59E+05	-3.99E+04	1.70E+05	1.70E+04	7.66E+04
628	4	1.24E+05	5.05E+04	-6.09E+04	1.59E+05	1.62E+04	7.13E+04
628	5	2.49E+04	1.38E+05	-3.41E+04	1.47E+05	1.54E+04	6.60E+04
628	6	1.06E+05	4.40E+04	-5.20E+04	1.36E+05	1.45E+04	6.07E+04
628	7	2.15E+04	1.17E+05	-2.84E+04	1.25E+05	1.37E+04	5.54E+04
628	8	8.85E+04	3.75E+04	-4.31E+04	1.13E+05	1.29E+04	5.01E+04
628	9	1.81E+04	9.55E+04	-2.26E+04	1.02E+05	1.20E+04	4.48E+04
628	10	7.04E+04	3.10E+04	-3.42E+04	9.02E+04	1.12E+04	3.95E+04
628	11	1.48E+04	7.44E+04	-1.69E+04	7.88E+04	1.03E+04	3.42E+04
628	12	5.24E+04	2.45E+04	-2.53E+04	6.74E+04	9.50E+03	2.89E+04
628	13	1.14E+04	5.32E+04	-1.11E+04	5.60E+04	8.65E+03	2.37E+04

**Table 8.0.4 – Ply Stresses for Element #628 From Grounding**

Examining the major axis (major principal) & maximum shear stresses the allowable values of tensile stress  $F1t = F2t = 31,600$  psi. & shear stress  $F12 = 9,500$  psi. are exceeded for every ply in the hull laminate, resulting in all modes of failure. The margin of safety calculations for each loadcase give a better picture of which mode of failure was most critical.

**Ply Stresses: Quad Element #2259 Adjacent to Bolt #3 at the Forward End of the Keel  
Keel pulling away from hull shell.**

ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	SHEAR
ID	ID	psi.	psi.	psi.	psi.	psi.	psi.
2259	1	1.87E+05	2.45E+04	-3.88E+04	1.96E+05	1.57E+04	9.00E+04
2259	2	1.36E+05	6.30E+04	7.63E+04	1.84E+05	1.50E+04	8.45E+04
2259	3	1.65E+05	2.19E+04	-3.41E+04	1.72E+05	1.42E+04	7.91E+04
2259	4	1.19E+05	5.55E+04	6.65E+04	1.61E+05	1.35E+04	7.37E+04
2259	5	1.43E+05	1.94E+04	-2.93E+04	1.49E+05	1.28E+04	6.82E+04
2259	6	1.02E+05	4.79E+04	5.67E+04	1.38E+05	1.20E+04	6.28E+04
2259	7	1.21E+05	1.68E+04	-2.45E+04	1.26E+05	1.13E+04	5.74E+04
2259	8	8.46E+04	4.03E+04	4.70E+04	1.14E+05	1.06E+04	5.19E+04
2259	9	9.84E+04	1.42E+04	-1.98E+04	1.03E+05	9.82E+03	4.65E+04
2259	10	6.76E+04	3.28E+04	3.72E+04	9.12E+04	9.08E+03	4.11E+04
2259	11	7.63E+04	1.17E+04	-1.50E+04	7.96E+04	8.35E+03	3.56E+04
2259	12	5.05E+04	2.52E+04	2.75E+04	6.81E+04	7.61E+03	3.02E+04
2259	13	5.42E+04	9.10E+03	-1.02E+04	5.65E+04	6.88E+03	2.48E+04

**Table 8.0.5 – Ply Stresses for Element #2259 From Grounding**

Again, the ply-by-ply stresses at the forward end of the keel exceed the allowables. In fact, a number of the ply shear stresses are close to 10 times the allowable stress.

**Ply Stresses: Quad Element #924 Adjacent to Bolt #5 toward the aft end of the Keel  
Keel pushing into the hull shell.**

Element	Ply	NORMAL-1	NORMAL-2	Shear-12	MAJOR	MINOR	MAX
ID	ID	psi.	psi.	psi.	psi.	psi.	SHEAR
							psi.
924	1	-4.18E+04	-1.49E+05	6.78E+04	-8.96E+03	-1.82E+05	8.63E+04
924	2	-1.53E+05	-2.51E+04	5.00E+04	-7.89E+03	-1.71E+05	8.13E+04
924	3	-3.65E+04	-1.30E+05	6.04E+04	-6.83E+03	-1.59E+05	7.63E+04
924	4	-1.34E+05	-2.03E+04	4.31E+04	-5.76E+03	-1.48E+05	7.12E+04
924	5	-3.12E+04	-1.11E+05	5.30E+04	-4.69E+03	-1.37E+05	6.62E+04
924	6	-1.14E+05	-1.55E+04	3.62E+04	-3.61E+03	-1.26E+05	6.12E+04
924	7	-2.60E+04	-9.14E+04	4.56E+04	-2.53E+03	-1.15E+05	5.62E+04
924	8	-9.45E+04	-1.06E+04	2.92E+04	-1.44E+03	-1.04E+05	5.11E+04
924	9	-2.07E+04	-7.22E+04	3.83E+04	-3.34E+02	-9.26E+04	4.61E+04
924	10	-7.50E+04	-5.78E+03	2.23E+04	7.84E+02	-8.15E+04	4.12E+04
924	11	-1.54E+04	-5.31E+04	3.09E+04	1.92E+03	-7.05E+04	3.62E+04
924	12	-5.54E+04	-9.42E+02	1.54E+04	3.09E+03	-5.94E+04	3.13E+04
924	13	-1.02E+04	-3.39E+04	2.35E+04	4.31E+03	-4.84E+04	2.64E+04

**Table 8.0.4 – Ply Stresses for Element #924 From Grounding**

Examining the minor axis (minor principal) & maximum shear stresses the allowable values of tensile stress  $F1t = F2t = 31,600$  psi., compressive stress  $F1c = F2c = 25,700$  psi. & shear stress  $F12 = 9,500$  psi. are exceeded for practically every ply in the hull laminate, resulting in all modes of failure towards the aft end of the keel. The margin of safety calculations for each loadcase give a better idea of which mode of failure was most critical.

**Ply Stresses: Quad Element #2556 Adjacent to Bolt #6 toward the aft end of the Keel  
Keel pushing into the hull shell.**

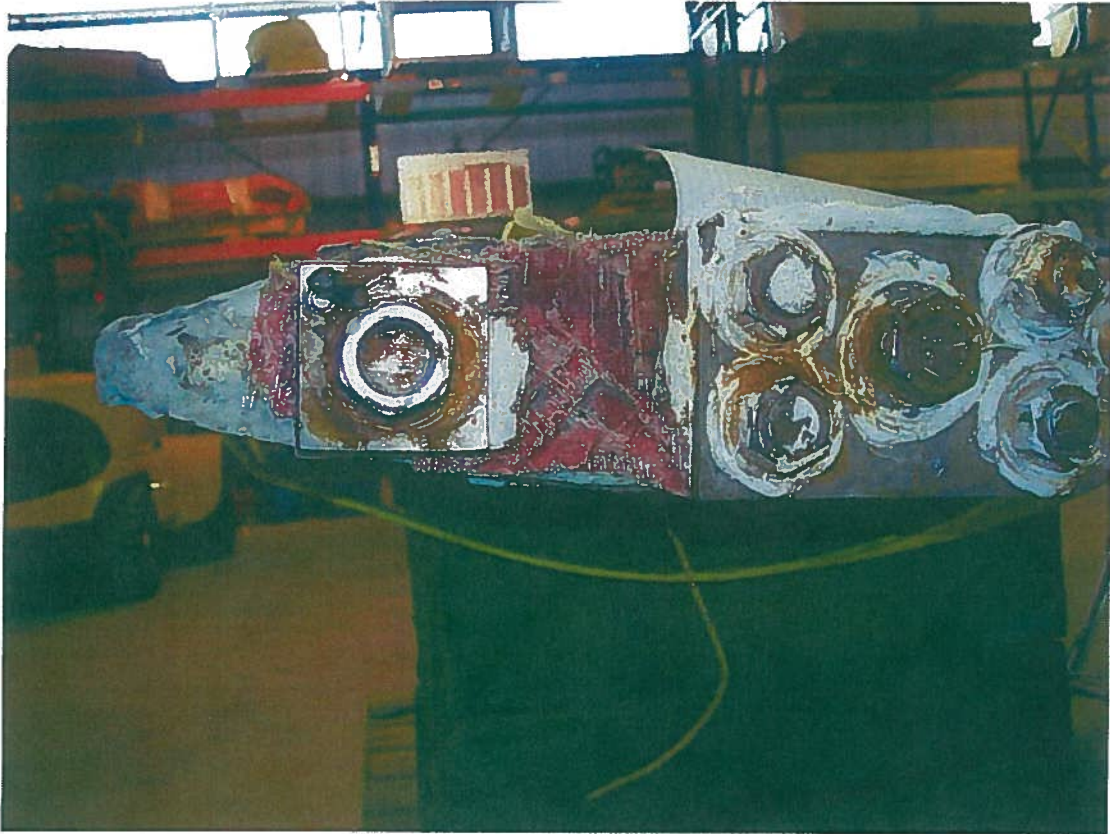
ELEMENT	PLY	NORMAL-1	NORMAL-2	SHEAR-12	MAJOR	MINOR	SHEAR
ID	ID	psi.	psi.	psi.	psi.	psi.	psi.
2556	1	-3.84E+04	-1.49E+05	6.30E+04	-9.90E+03	-1.78E+05	8.39E+04
2556	2	-1.48E+05	-2.97E+04	5.23E+04	-9.82E+03	-1.67E+05	7.88E+04
2556	3	-3.42E+04	-1.33E+05	5.48E+04	-9.74E+03	-1.57E+05	7.37E+04
2556	4	-1.29E+05	-2.75E+04	4.61E+04	-9.66E+03	-1.47E+05	6.86E+04
2556	5	-3.00E+04	-1.16E+05	4.66E+04	-9.57E+03	-1.37E+05	6.35E+04
2556	6	-1.10E+05	-2.53E+04	4.00E+04	-9.48E+03	-1.26E+05	5.84E+04
2556	7	-2.58E+04	-9.95E+04	3.84E+04	-9.39E+03	-1.16E+05	5.33E+04
2556	8	-9.18E+04	-2.31E+04	3.38E+04	-9.29E+03	-1.06E+05	4.82E+04
2556	9	-2.16E+04	-8.30E+04	3.03E+04	-9.17E+03	-9.54E+04	4.31E+04
2556	10	-7.32E+04	-2.09E+04	2.76E+04	-9.05E+03	-8.51E+04	3.80E+04
2556	11	-1.74E+04	-6.64E+04	2.21E+04	-8.90E+03	-7.48E+04	3.30E+04
2556	12	-5.46E+04	-1.87E+04	2.14E+04	-8.73E+03	-6.46E+04	2.79E+04
2556	13	-1.32E+04	-4.98E+04	1.39E+04	-8.51E+03	-5.45E+04	2.30E+04

**Table 8.0.5 – Ply Stresses for Element #2556 From Grounding**

Again, the ply-by-ply stresses at the aft end of the keel exceed the allowables. In fact, a number of the ply stresses are close to 10 times the allowable stress.

From a number of the pictures of the hull shell failure that I received, there is clear evidence of both delamination (caused by exceeding the allowable interlaminar shear strength) & vertical shear of the hull shell at the outboard (tension) edge of the backing plates (caused by exceeding the vertical shear allowable of the hull shell laminate).

A few examples of these pictures are as follows:

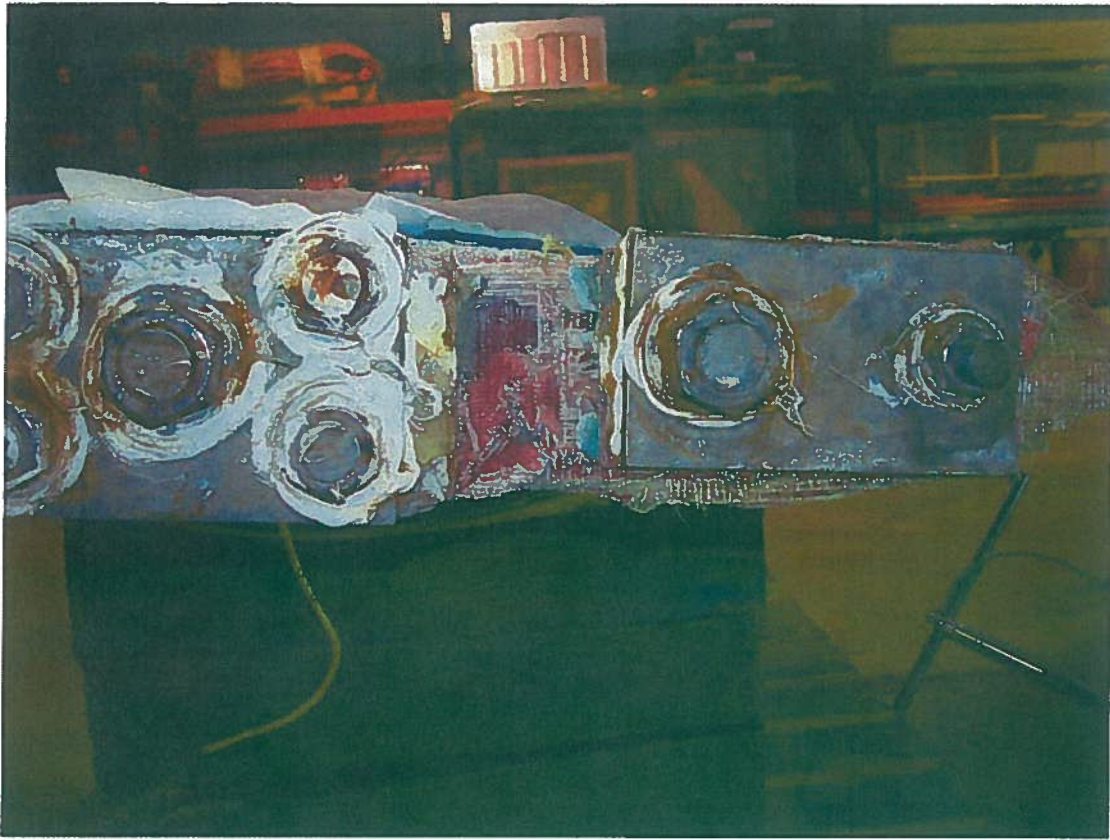


**Figure 8.0.1 – View of Forward & Middle Backing Plates**

This photograph clearly shows the vertical shear of the hull shell laminate on the tension side (weather side), especially along the middle backing plate which would be the highest loaded backing plate from the five (5) highest loaded bolts on the tension side. There is a good possibility that the hull shell failure initiated at the weather side of this plate.

Note the washers of the outboard bolts overhanging the corners of the middle backing plate. This is a good indication that the backing plates are neither wide enough or long enough to distribute the keel bolt loads to the hull shell & keel floors. Standard airframe practice is to use a minimum edge distance of  $2D + 0.06"$  (Reference #8), which is not met by the corner bolts shown above.

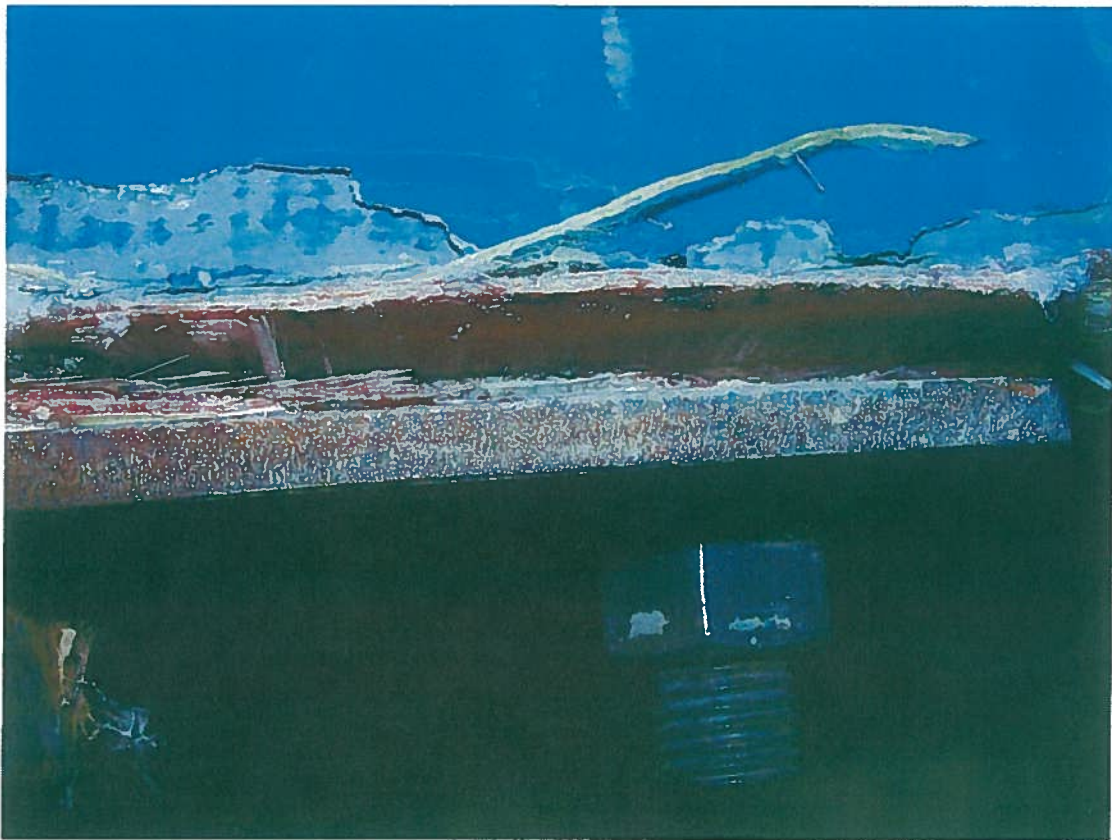




**Figure 8.0.2 – View of Middle & Aft backing Plates**

Again, this picture shows the clean cut vertical shear of the hull shell at the edge of the middle backing plate. The failure of the hull shell at the aft backing plate is not so clean along the edge of the plate, indicating that the hull shell had failed along the edge of the middle plate first & propagated forward & aft (Note – Figure 7.0.1 verifies this with the ragged edge show by the forward plate).





**Figure 8.0.3 – Delamination of the Hull Shell**

In this picture, the delamination of the hull shell can clearly be seen. It is likely that this delamination occurred prior to the shearing of the hull shell. Once the hull shell laminate is delaminated & weakened, the laminate fibers will fracture. This delamination was most likely caused by the repeated tension & compression loading over time (fatigue) at the root of the keel due to tacking & other sailing maneuvers.



**Figure 8.0.4 – Delamination of the Hull Shell**

Another photograph showing delamination of the hull shell at the aft backing plate.



**Figure 8.0.5 – Area of Failed Hull Shell Laminate**

This photograph also shows the delamination & shearing of the hull shell laminate along the outboard edges of the narrow backing plates.

## **9.0 CONCLUSIONS**

1. The hull shell in way of the keel mounting structure is significantly under designed, even for the keel limit load (no factor of safety) applied.
2. The keel bolt backing plates are not wide enough to distribute the keel bolt loads to the hull shell & keel floors. The shear & bending loads in the hull shell at the edges of these backing plates are not reduced enough to be below the laminate allowable loads, as evidenced by the negative margins, exceeding high strains & exceeding high stresses for these elements. My first estimate is that the hull shell requires 3 times the laminate thickness for reinforcement over the keel & the backing plates should be a minimum of 3 times wider to evenly distribute the keel bolt loads into the keel mounting structure.
3. The vertical faces of the keel floors are not thick enough (0.13" thick) to adequately transfer the loads to the floor caps. The vertical faces (sides) of the keel floors will fail in shear. This thickness should probably be doubled & then examined. The caps of the keel floors (0.44" thick) appear to be of adequate thickness for the applied loads.
4. The aft keel floor is located too far aft to adequately react the keel grounding loads. This is shown by the contour plots in Section 7.3, where the loads are not adequately being transferred by the hull shell to the aft floor. The grounding load causing the keel to push into the hull (rotate about the forward floor) is mostly being reacted by the aft, middle keel floor forward of the aft floor, as shown by the stress/strain concentrations on the contour plots at the aft end of the middle keel bolt backup plate. This floor should be located more directly over the aft end of the keel or, at a minimum, as close as possible to the most aft keel bolt.
5. There is sufficient evidence from the delamination of the hull shell laminate (pictures in Section 8.0) to support a progressive failure theory where the hull shell laminate began to delaminate from repeated loading from the keel from sailing maneuvers (fatigue), which weakened the hull shell laminate. This was followed by the catastrophic failure of the hull shell (vertical shear through the hull shell) when the laminate fibers fractured & the keel separated from the hull.
6. These events could have been the result of fitting the deeper, bulb keel without adding reinforcement to the hull shell &/or the keel floors, along with moving the aft keel floor closer to the aft end of the keel & backing plates. The deeper, bulb keel with the shorter root section would increase all of the loads on the keel mounting structure.

Nastran Bulk Data File - .bdf file (Translated from Patran Model):



cape-0129-load\_cas  
es-01.bdf