SSC-337

(PART 1)

SHIP FRACTURE MECHANISMS INVESTIGATION

SHIP STRUCTURE COMMITTEE

1990

SHIP STRUCTURE COMMITTEE

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SHIP FRACTURE MECHANISMS INVESTIGATION

Fracture mechanics and methods to control cracking in ship structures have been areas of fundamental research by the Ship Structure Committee since its inception in 1946. As this work continues, new technologies and theories concerning crack initiation and growth are evolving. It is only through continued research and careful observation of structural failures that we can gain further insight into controlling fractures in ship structures.

This report is divided into two volumes. Part 1 contains the details and conclusions of the investigation into ship fracture mechanisms. The investigation was based on existing research and case studies and on inspections of more recent hull girder fractures. Part 2 is a guide for investigators who are unfamiliar with fracture mechanics. It should prove to be a useful tool for evaluating and documenting ship fractures and in determining the cause of these failures.

J. D. SIPES
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

This report presents the results of a three year investigation conducted to review past research on fractures and existing fracture case studies, and to inspect new ship fractures in an effort to determine the modes of serious fractures in ship structure; to evaluate existing approaches to fracture control, and to suggest the applicable components of an approach to ship fracture control. Numerous on-site examinations of fractures and laboratory analyses of fracture samples were conducted.

Information presented in this report describes recent ship fractures occuring in the hull girder with various levels of severity. These include fatigue cracking and brittle fractures, and range from minor cracks to complete hull girder failures. These recent occurrences indicate that those who are concerned with ship structures cannot relegate brittle fracture to the past but must exercise extreme diligence to avoid not only major structural fractures but also the minor fatigue and nuisance cracks which often lead to major fractures if undetected or ignored.

Furthermore, the authors concluded that ship fracture control is the responsibiity of those who design, classify, build, operate, inspect and repair ship structures. Specific recommendations are directed to each of these groups and toward research required to develop a comprehensive fracture control approach through the development and validation of fracture mechanics techniques.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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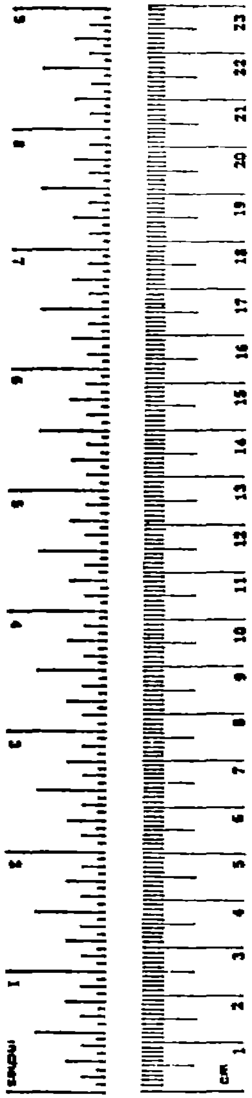
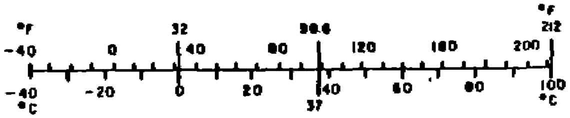
*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



METRIC CONVERSION FACTORS

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1.0 INTRODUCTION

In the past decades extensive research has been conducted to establish procedures to control fracture of ship structures. Early research concentrated to a large extent on empirical correlations with service experiences. More recent research has been directed toward the development of a fracture control approach based on technologies which characterize material crack tolerance. This research has fostered approaches to control fractures in ship structures; several of these approaches have been adapted from methods developed for non-ship metal structures, while others were developed specifically for ship structures. These approaches to fracture control include those which attempt to inhibit crack initiation, and those which attempt to limit crack growth or propagation. Because these approaches are varied and in several cases divergent, future research in this area should be based on the examination of actual ship fractures. After the failure mechanisms are understood, a rational approach to fracture control can be developed to achieve more economical structures which perform to acceptable levels of safety. Validation and refinement of such an approach is dependent on the continued investigation, analysis, and evaluation of actual fractures.

1.1 OBJECTIVES

The characteristics associated with structural fractures often provide insight into their cause and into methods that may be used to control them. To this end, Giannotti & Associates, Inc. and its consultants have been tasked by the Ship Structure Committee to conduct a three year investigation. This investigation has been initiated to review past research on fractures and existing fracture case studies, and to inspect new ship fractures in an effort to determine the modes of serious ship structural fractures; to evaluate existing approaches to fracture control; and to suggest the applicable components of an approach to ship fracture control. Accordingly, five tasks have been developed to obtain the necessary information to fulfill the objectives. These tasks are:

1. Conduct a literature survey to provide a base description of fracture control approaches that will be highlighted as a result of the examination of actual ship fractures.

2. Survey and review marine structure fractures, the early ones as well as the recent experiences, in light of today's knowledge of fracture mechanics.

3. Relate serious failures with the numerous failures documented in SSC-272 and SSC-294.

4. Comment on the relevance of the various approaches to fracture control now being proposed by comparing the consequences of failure with the mechanisms at work.

5. Develop a guide for the non-expert to be able to evaluate the causes of significant structural failures.

6. Examine potential courses for future research in light of the results from the previous tasks, including, if appropriate, proposals for on-going survey and review of hull failures.

1.2 SUMMARY

This report presents the results of the investigation and is organized according to the tasks described above. Various fracture control approaches and related structural design philosophies are described briefly in Section 2.0. A more detailed description of the fracture control approaches is presented in Appendix A. Actual ship fractures are documented in Section 3.0 for 16 different fracture case histories. The structural details associated with these fractures are compared to those presented in the literature and presented in Section 4.0. The evaluation of these fractures and their possible influence on fracture control approaches are presented in Section 5.0. The objectives for the guide for the non-expert are presented in Section 6.0, with the actual guide presented in Part 2. Recommendations for further research are presented in Section 7.0. Readers who are not familiar with the examination of ship structural fractures should review the Guide in Part 2 prior to reading the information presented in Section 3.0.

2.0 REVIEW OF FRACTURE CONTROL APPROACHES

From a practical standpoint there are two fundamental methods of fracture control. The most common approach being used today is the design and fabrication of structures according to codes. The rules and regulations applicable to ships fall into this category. In the code approach, the design, fabrication and, to some extent, operation of a particular structure conforms to a set of rules or standards established for the general class of structures, e.g., bridges, pressure vessels, or fixed offshore structures and ships. A less common method of fracture control in use today is the performance specification approach which is used for structures where no codes exist or the inefficiencies imposed by codes, rules and regulations cannot be tolerated, e.g., aircraft and space vehicles. Other fracture control philosophies and methods are merely subsets of the code and performance specification approaches.

Subsets of the two basic approaches to fracture control are related principles for structural design. One such principle is based on redundancy assurance, which involves introducing multiple load (fracture) paths so that the failure of any one part does not result in a critical reduction of residual strength. If redundancy assurance is not feasible, an alternative is to provide fail-safe assurance. This principle uses crack-arrest provisions such as geometric interruptions or inserts of very tough materials to arrest or limit crack growth. If neither of these two approaches is feasible, the remaining alternative is to provide safe-metal assurance (sometimes known as safe-life). This principle involves the selection of metal that does not permit propagation of fast fracture at the design level of nominal stress.

Engineering procedures have been developed which can be used to characterize the resistance of a structure to the inception of fracture given a stress level and initial flaw size. This field of engineering is known as fracture mechanics and it has become a vital component to the control of fractures in metal structures through the characterization of materials and the relationships between design, fabrication, inspection and lifetime maintenance. Similarly, cyclic loading or fatigue is considered in fracture control and usually governs flaw size in fail safe design philosophies. The sum total of research that has been conducted to develop the field of fracture mechanics for metal structures is extensive. Although those involved in fracture control of ship structures have used fracture mechanics procedures in a general sense, fracture mechanics has not been utilized to its fullest advantage. Several researchers have proposed methods for fracture control of ships that are based to some degree on fracture mechanics techniques; however, the approach that is best suited to ship structures has not been determined.

Fracture control approaches for various types of metal structures are summarized and presented in Appendix A. Each approach can be categorized as being either a code (including rules and regulations) or a performance specification. These summaries provide a means to evaluate the approaches used in ship structures and in some instances to indicate where other techniques may be applied to the control of ship fractures.

3.0 REVIEW AND EXAMINATION OF SHIP STRUCTURAL FAILURES

In order to evaluate approaches to fracture control applicable to ship structures, it is necessary to examine, document, analyze, and determine the causes of actual ship fractures which is the objective of this study. A total of 16 fracture case studies were developed from actual on site examinations or examined from past documented fractures. The fractures investigated started in, extended into, or have caused fracture of the primary structure regardless of the fracture origin. The primary structure includes all items that contribute to the hull girder strength. The causes of structural fracture investigated exclude those resulting from collision, grounding, etc. Fracture examinations were limited to those cases which occurred after 1970 to obtain information on recent fractures and ensure that conclusions and findings were relevant to current fracture control methods.

When possible, references are given indicating the source of the information used to develop the case studies. Many of the case studies were based on information obtained from ship owners who requested that names and principals not be included in this report, and are indicated as a proprietary source in the text. The following text discribes the fractures investigated.

3.1 GREAT LAKES BULK CARRIER MAIN DECK FRACTURE

Description of Vessel:

A series of fractures occurred on a Great Lakes bulk carrier* that was built in 1952, lengthened 70 feet in 1957, a sheer strap added in 1959, and was converted to a self-unloader in 1980. The particulars of the vessel are:

Length overall:	698.0 ft
Length between perpendiculars:	683.0 ft
Breadth (molded):	70.0 ft
Depth:	37.0 ft
Displacement:	30054 LT
Year built (lengthened):	1952 (1957).

Figures 3-1 through 3-4 show the structural configuration of the bulk carrier. The ship is transversely framed on the bottom and up the sides to the lower boundary of the upper wing tank. Above this elevation the vessel is longitudinally framed. The calculated section modulus for the vessel is as follows:

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* The source of information is not identified due to proprietary considerations.

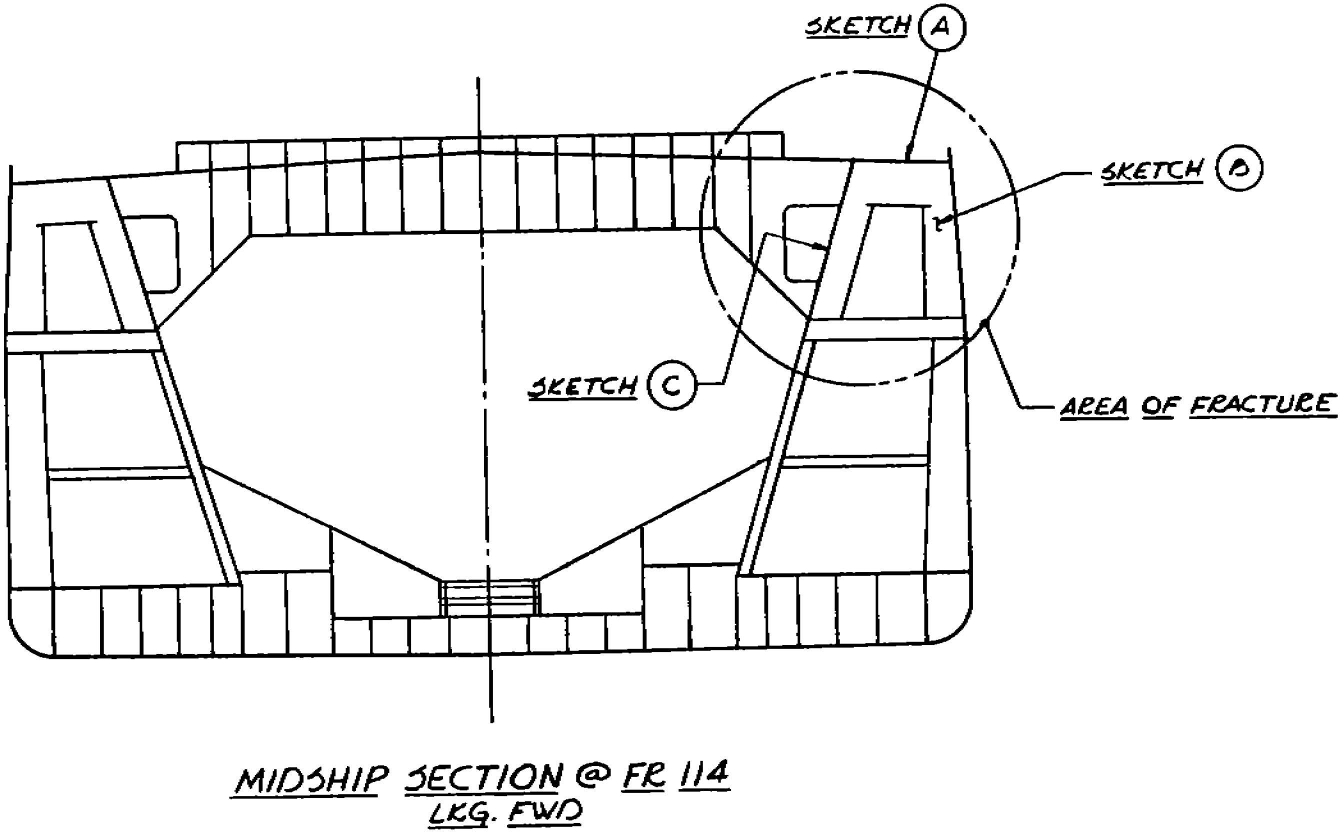
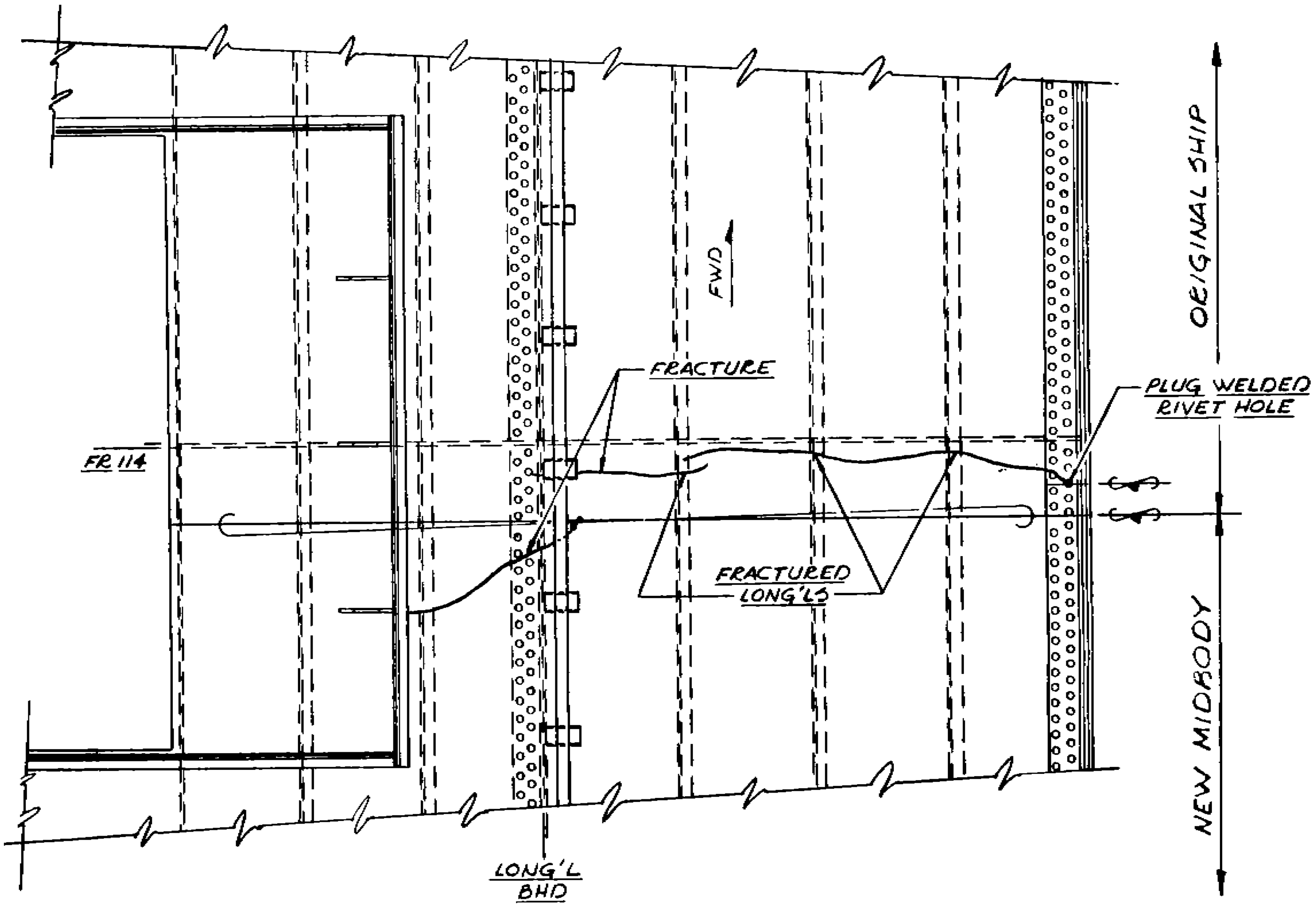


Figure 3-1 Midship section indicating the area of fracture on the Great Lakes bulk carrier



SKETCH A
PLAN OF SPAR DECK @ FR 114

Figure 3-2 Fracture path on the spar deck of the Great Lakes bulk carrier

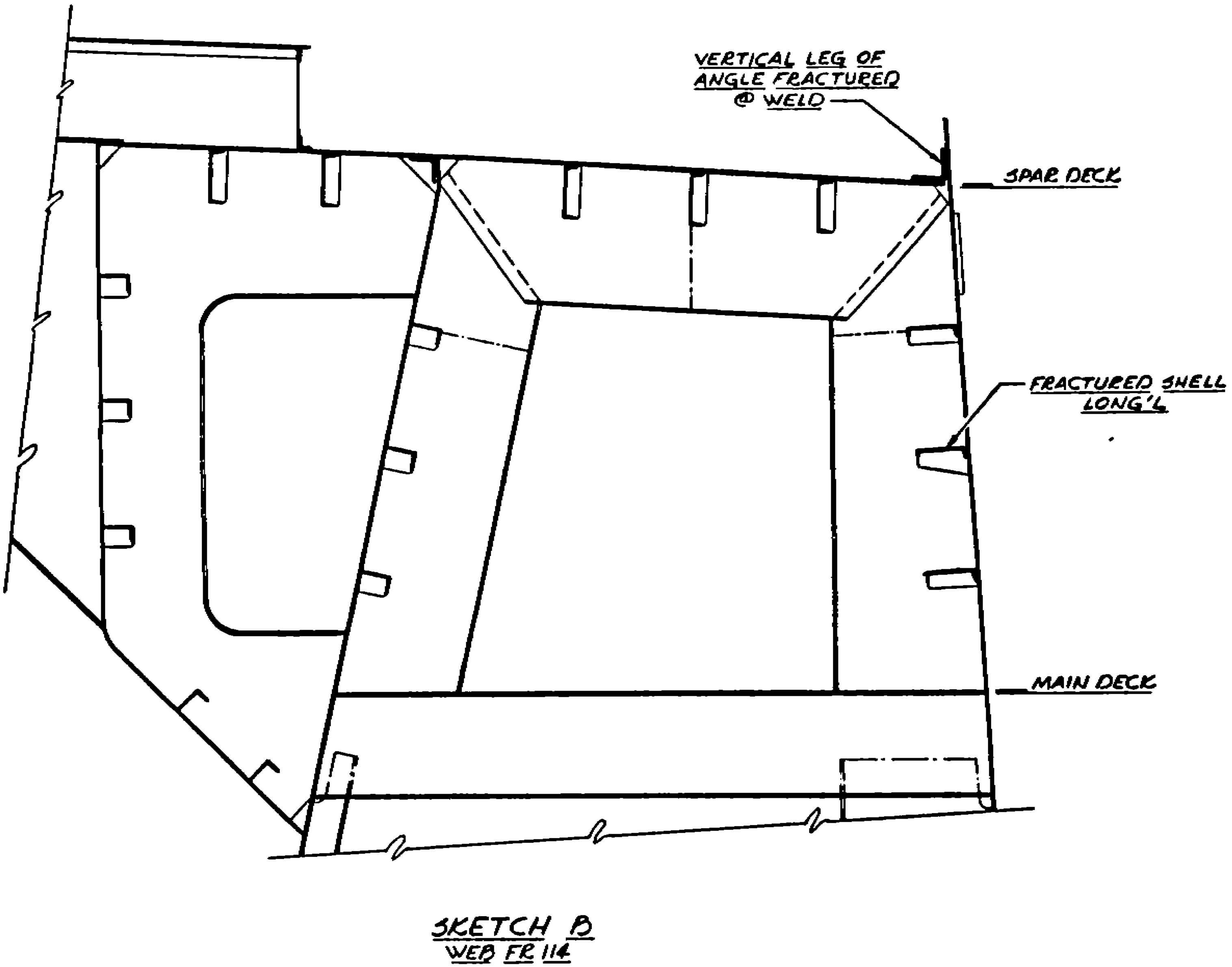


Figure 3-3 Section of the Upper Wing Tank of the Great Lakes Bulk Carrier

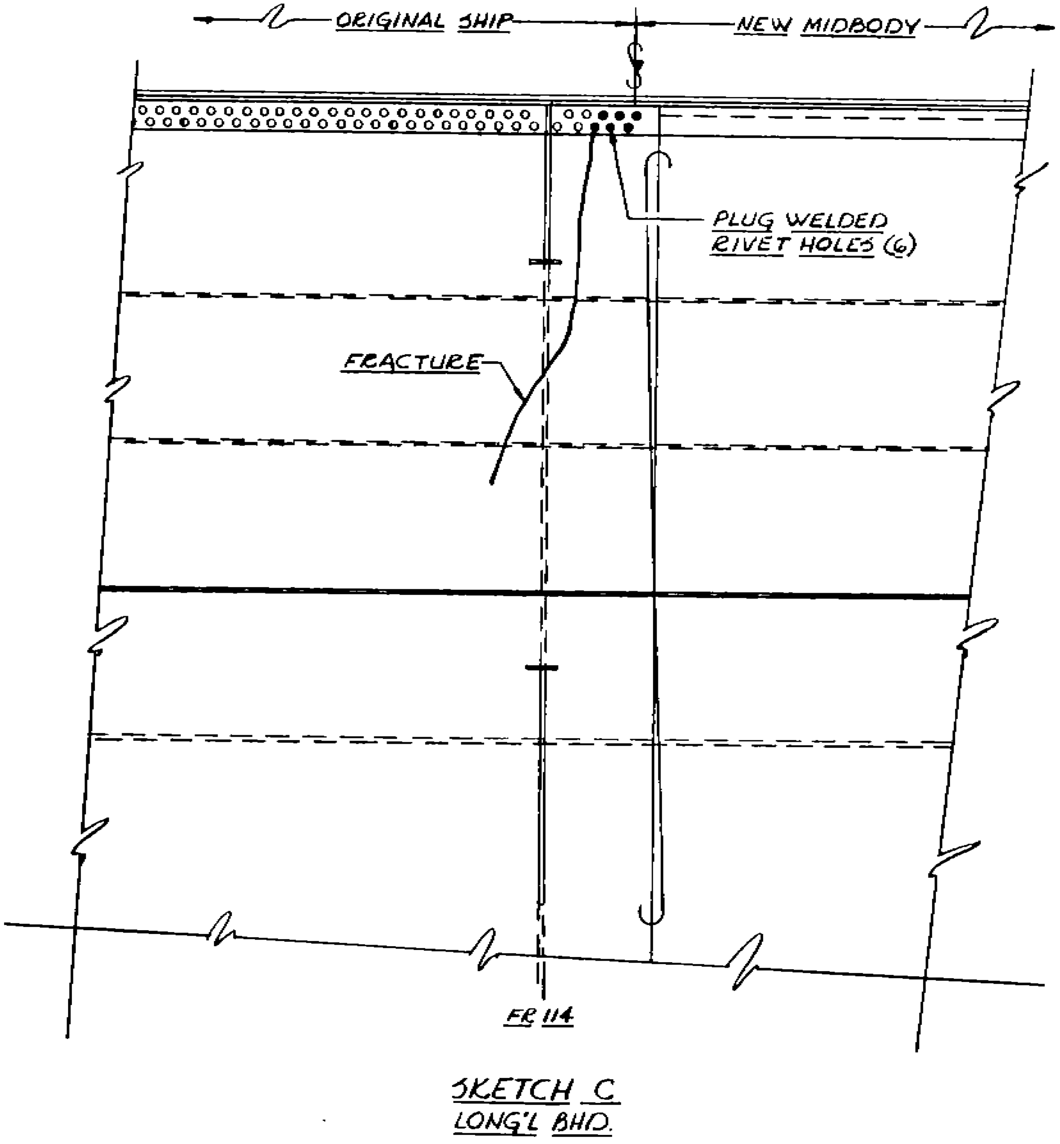


Figure 3-4 Fracture path in the Longitudinal Bulkhead of the Great Lakes Bulk Carrier

Ship status	Section Modulus in^2-ft
Original	34,800
Lengthened	34,800
Sheer strap addition	35,853
Self unloader	35,962.

Sheer straps were added in 1959 because the ship was thought to be too flexible because it exhibited large hull girder deflections during loading. After adding the sheer straps an additional 6" of load line draft was permitted by the classification society because the section modulus increased.

Description of Circumstances at the Time of Fracture:

The fractures occurred in the bulk carrier on its last voyage prior to layup for the 1984 winter season. The ship was sailing Lake Huron when the crew heard a loud noise. An inspection by the crew revealed a fracture in the main deck on the starboard side near amidships.

The available information pertaining to the ship and fracture incident includes:

• Date of fracture:	21 Dec. 1983
• Location of ship during fracture incident:	Lake Huron
• Voyage number:	56
• Observed wave height:	12'-15'
• Wind speed and direction:	45 knots, 125° true
• Ship heading:	157° true
• Air temperature:	20°F.

The ship was reportedly in a normal ballast condition at the time of fracture.

Description of the Fracture:

The fractures were examined January 13, 1985 by the project investigators. The fractures were located on the starboard side of the spar deck. There where three separate fractures crossing the spar deck where the ship had been joined during the lengthening process. Two of the fractures occurred in the original ship and one in the new midbody section. Upon examination below the spar deck the reason for the separate fractures became apparent. A number of poor fabrication details were used in lengthening the vessel and included plug welded rivet holes, mismatched structural members, weld used as filler for mismatched areas and notched longitudinals. The longitudinals under the spar deck consisted of channels with the flange welded to the underside of the deck at the toe and heel. The flange welded to the underside of the deck was coped out at the plate butt and the weld passed around the end of the coped flange, as shown in Figure 3-5. The three outboard longitudinals all fractured at this same location. The fracture path in the spar deck plate ran through the notches created at the longitudinal butt welds and into the longitudinal bulkhead. The fracture surface visible in the longitudinal bulkhead during the on-site examination exhibited the classic chevron markings indicative of a brittle fracture.

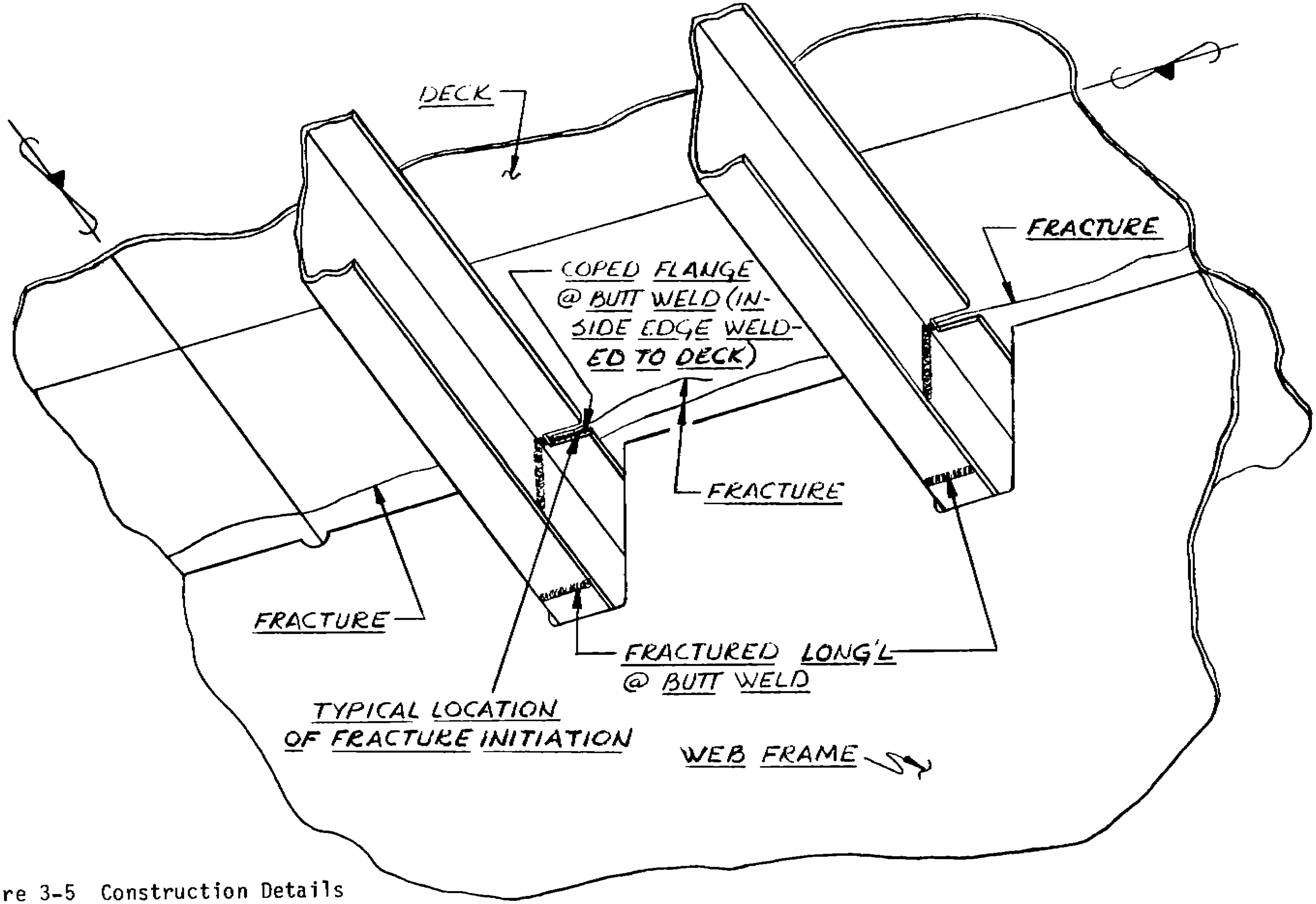


Figure 3-5 Construction Details associated with the Initiation of the Fracture on the Great Lakes Bulk Carrier

Nine samples were taken from the fractured plating and were shipped to Lehigh University for further examination of the fracture path, initiation sites, and arrest sites. The locations of these pieces in the spar deck are shown in Figure 3-6. A detailed description of the fracture samples is presented in [3-1]* and is summarized below.

The initiation of fractures in the deck was determined by sectioning the samples in as many of the fracture path samples as necessary to establish chevron marker patterns and identify initiation and termination areas. For some samples this was obvious (e.g., sample No. 1) but for others this was not so obvious (e.g., sample No. 6). The fracture surfaces were predominantly brittle in nature and as a result had developed clear chevron marks. Examples of these markings on the surface of piece No. 1, which was typical, are seen in the oblique lighting in Figure 3-7. The fracture surfaces indicate some ductility but this is limited as there are no shear lips present (as may also be seen in Figure 3-7). Unfortunately, the fracture surfaces were extensively rusted (from storage outside prior to shipment to the laboratory) and thus there was little chance to develop all of the fractographic information that would have been desirable. The overall fracture pattern in the deck can best be understood through a discussion of the individual samples examined.

Sample No. 1 is identified as the spar deck plating located at the edge of the hatch coaming and extending outboard along part of the fracture surface. The fracture surface itself, taken with oblique lighting to highlight the chevron markers, is seen in Figure 3-8. It is clear from these chevron markers that the initiation of fracture was where the coped flanges of the longitudinal had been removed. The initiation site is located in the transverse weld joining the stiffener to the deck plate at the coped out flange. A small piece of transverse weld remains attached to the edge of the fracture. The exact configuration of the rest of the weld is lost, having been removed with the channel stiffener. The fracture ran in two directions: under the hatch coaming and outboard across the deck through sample No. 9 and on into sample No. 2 where it terminated. As far as sample No. 9 is concerned, the fracture simply extended through this plate and did not directly result in propagation of fractures into the longitudinal bulkhead. The arrest in sample No. 2 was at the transverse weld between the old ship and new midbody. The reason for arrest is related to the sequence of fracture initiation and is discussed later. Holes were also drilled at the end of the fracture to prevent re-initiation.

Sample No. 6 contains two separate fractures, both of which appeared to either terminate or initiate in the sample. Cutting the sample to reveal the fracture surfaces showed that the crack extending toward the longitudinal bulkhead at the toe of a weld at the cutout in the longitudinal channel initiated in sample No. 6; see Figure 3-9. From this point the fracture ran both inboard and outboard. One end terminated in the plate a short distance outboard of the channel while the other end terminated at a rivet hole in sample No. 9. The growth directions of both of the fractures and the presence of the initiation was clear in the sample from the chevron markers.

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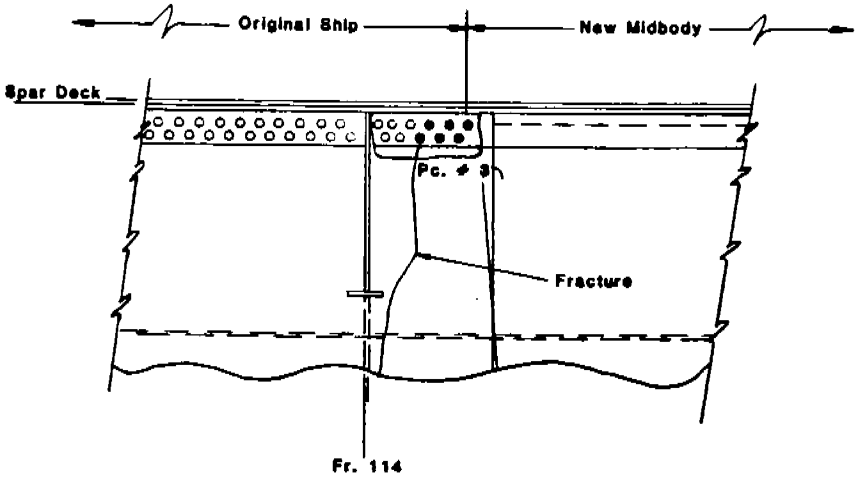
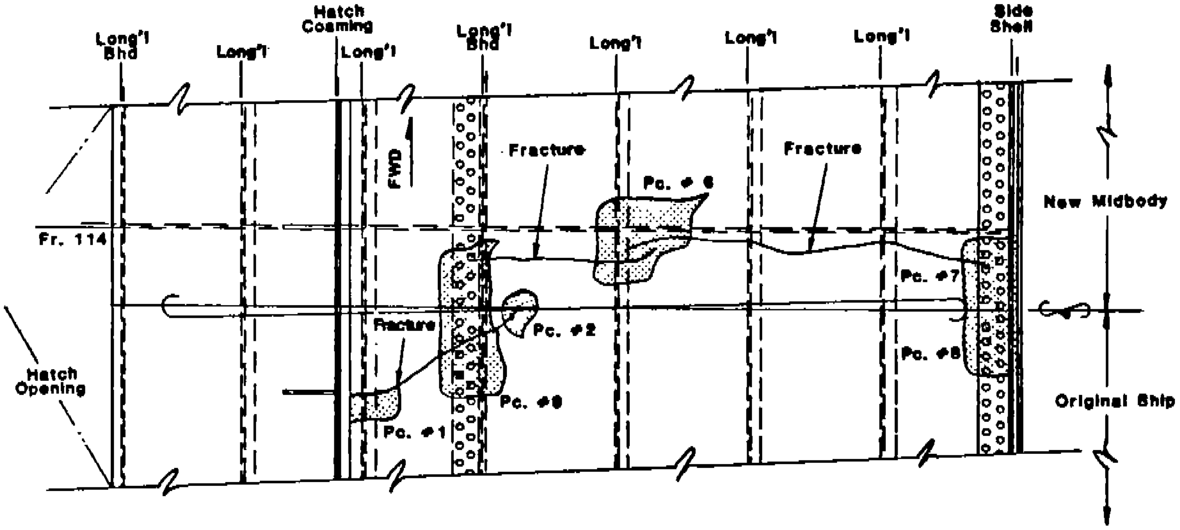
* References are indicated in brackets and are listed following Section 7.0.



ELEVATION OF LONG'L BHD



PLAN OF SPAR DECK

Figure 3-6 Location of Plating Samples from the Great Lakes Bulk Carrier

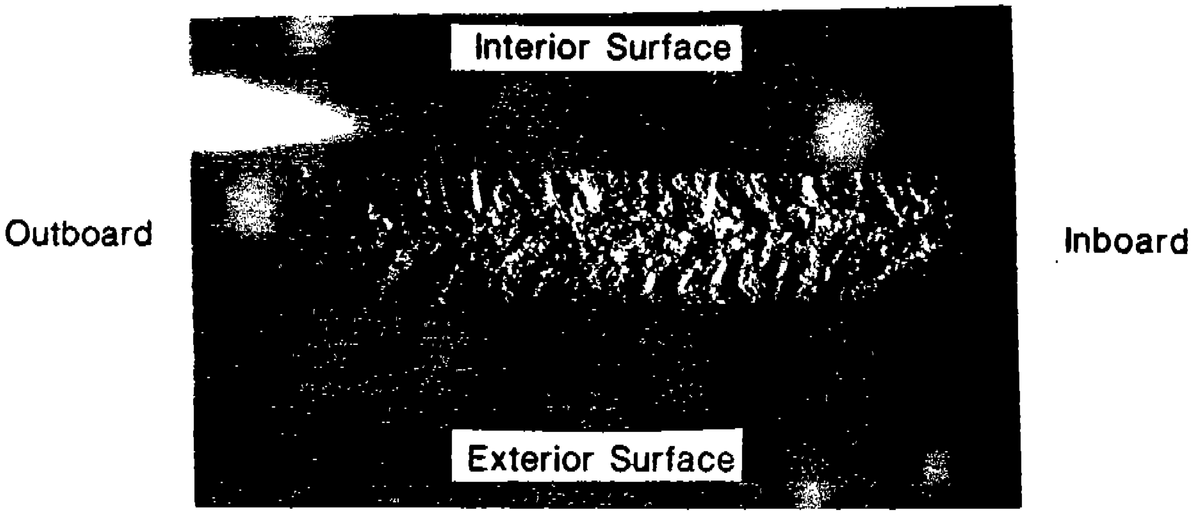


Figure 3-7a Example of chevron markers on the surface of Piece no. 1, indicating generally brittle fracture. Surface not completely flat, but markers are accentuated by oblique lighting.

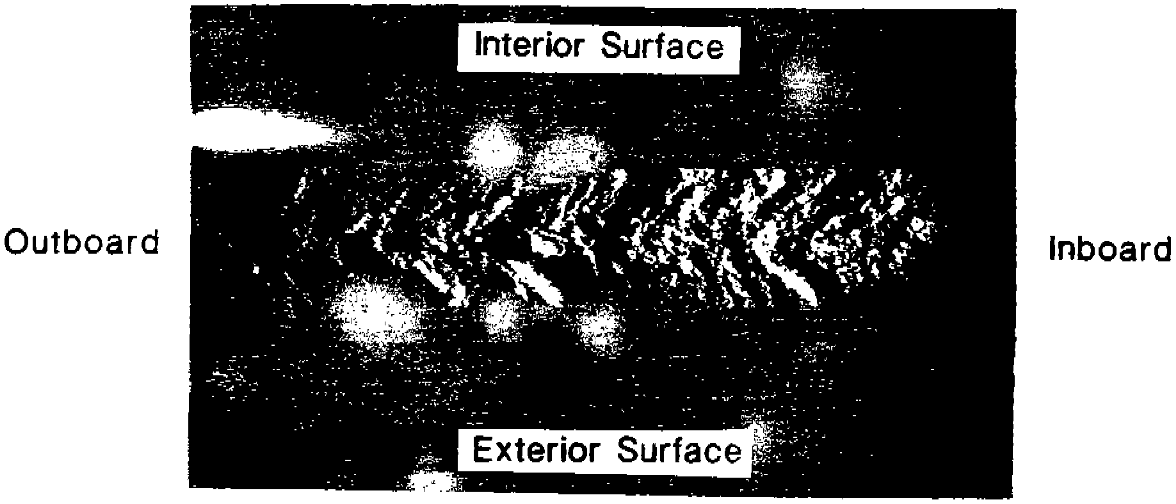


Figure 3-7b Fracture surface of Piece no. 1, oblique lighting. Somewhat more surface texture than seen in Figure 7a indicating increasing ductility in the fracture process, however no shear lip present.

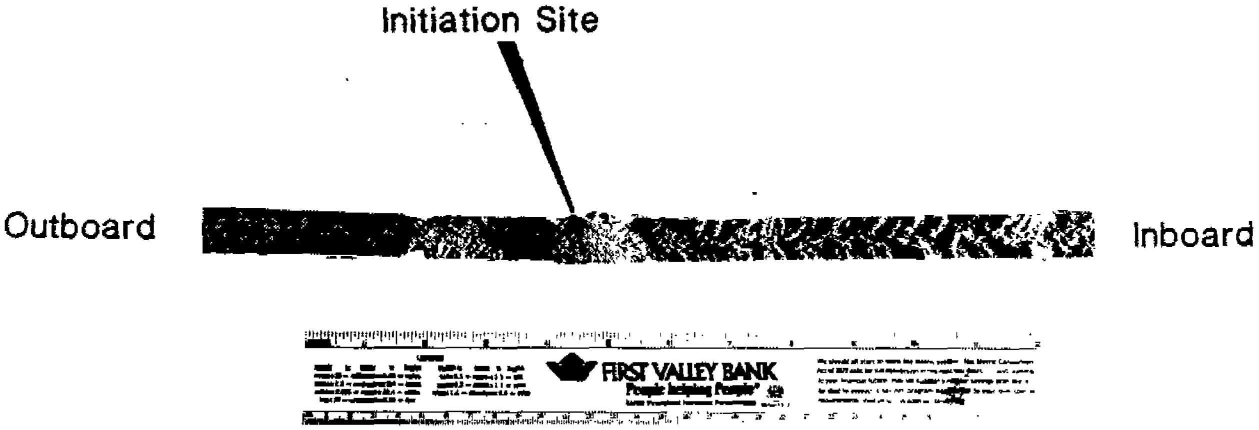


Figure 3-8 Piece no. 1. Chevron markers pointing toward initiation site. (Piece was cut for study of initiation site in scanning electron microscope.) Two surface gouges seen on interior side, one on exterior deck side.

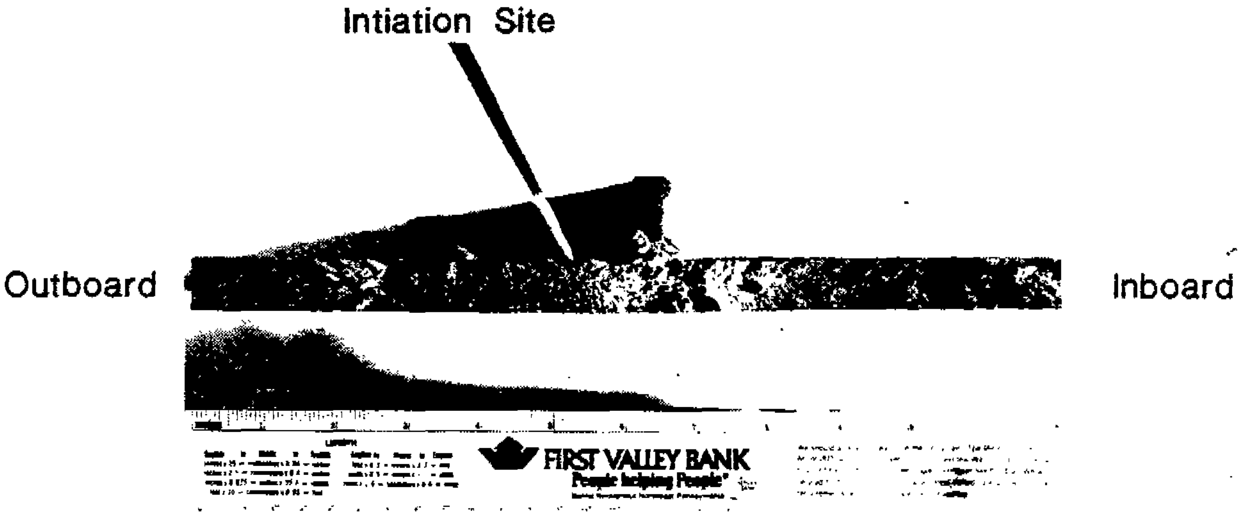


Figure 3-9 Piece no. 6. Fracture initiation site in deck at channel butt weld.

Examination of the chevron markings in samples No. 6 and 7 shows that the second fracture in sample No. 6 was moving into sample No. 6 from the direction of No. 7 and into sample No. 7 from the direction of No. 6. Therefore, this fracture initiated somewhere between samples No. 6 and 7, most likely at one of two outboard longitudinal flange copings. The initiation site in sample No. 6 is clearly at this detail. This detail produces a severe transverse notch and resulting stress concentration at each longitudinal. The initiation point in sample No. 1 is also at this type of fabrication detail. Termination of the fracture in sample No. 7 was at a rivet in the gunwale angle while termination in sample No. 6 was at the longitudinal stiffener near the initiation site of the other fracture.

The fracture in the longitudinal bulkhead originated in the butt weld of the angle riveted to the deck and longitudinal bulkhead. The two pieces of angle were poorly aligned, the weld was made from one side only and lacked depth of penetration, and the toe of the angle was welded to the longitudinal bulkhead to fill a gap. Apparently this fracture initiated after the deck fractures as some plastic deformation was noted in the angle at the termination of the fracture extending into piece No. 9 from piece No. 6. As the load path shifted to the longitudinal bulkhead, the angle butt weld cracked at a toe fillet weld which allowed the fracture to enter the longitudinal bulkhead. Figure 3-10 shows the fracture surface at the top of the longitudinal bulkhead, sample piece No. 3. The rivet hole on the right side is how the bulkhead was attached to the deck through the angle. The top middle of the photograph shows what remains of the angle toe fillet weld where the fracture entered the longitudinal bulkhead. From there the fracture ran up through the rivet hole and down the bulkhead plate until it arrested.

Analysis of the Fracture:

Scanning electron fractography of the fracture origin areas was attempted by Pense at Lehigh University but in no case were the surfaces sufficiently clean to permit good analysis. All initiation sites were subsequently cleaned in alconox in an ultrasonic cleaner. In spite of this cleaning, extensive oxidation and corrosion remained, obscuring the true fracture surface. Fractographs of the origin sites in samples No. 1, 3, and 6 are shown in Figures 3-11, 3-12, and 3-13. In spite of the evident oxide layers, it may be observed that the origin areas are quite small and tend to have a thumbnail shape. Typically, they are a depression or notch no more than 0.25 inches deep, and in some cases appear to be even smaller. It was not possible to determine if any fatigue crack growth preceded fracture, but if there was, it was very small.

A stress analysis was conducted by the project investigators to estimate the nominal bending stress in the spar deck of the ship. Longitudinal vertical bending moments were simulated using the MIT 5 degree of freedom frequency domain computer program. The hull form, approximate ballast condition, and wave heights at the time of fracture were used as input. The computed longitudinal vertical moment was 330,904 ft-ton (average of the one-tenth highest excursions) producing a nominal stress of 20,611 psi at the location where the ship fractured. This value is in excess of the 267,311 ft-tons wave induced bending moment allowed by ABS, or 16,650 psi stress in the spar deck, but is below the nominal yield for mild steel of 32,000 psi.

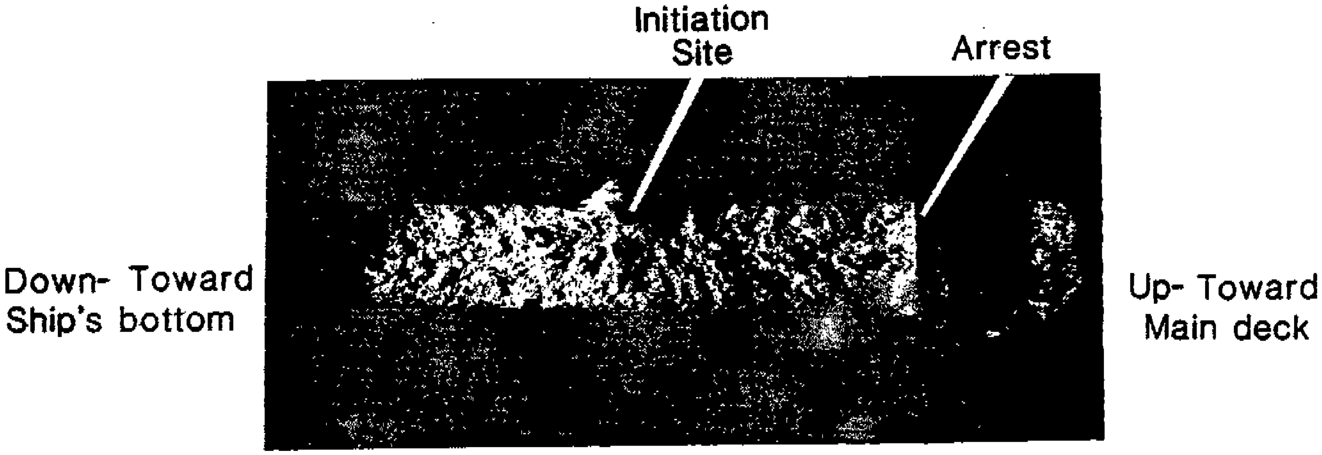


Figure 3-10 Piece no. 3 (top of longitudinal bulkhead) initiation site showing crack entering Piece no. 3 through weld of angle to Piece no. 3. Crack goes to rivet hole on right and down the bulkhead to left.

Figure 3-11 Initiation site in Piece no. 1. 10X. Scanning electron micrograph after cleaning with alconox. Surface covered with corrosion product.

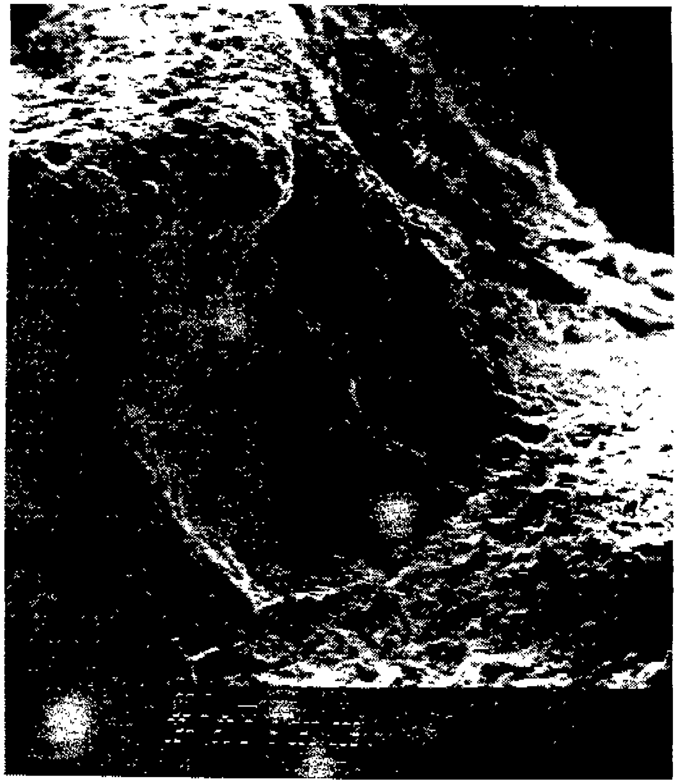


Figure 3-12 Initiation site in longitudinal bulkhead (Piece no. 3). 20X. Scanning electron micrograph after cleaning with alconox. Surface covered with corrosion product.

Figure 3-13 Initiation site in piece no. 6. 10X. Scanning electron micrograph after cleaning with alconox. Surface covered with corrosion product.

The two known fracture initiations in the spar deck were both at the notches produced by an interruption or coping in the faying flange of the longitudinal stiffeners. The fabrication detail associated with the coped out flanges resulted in a small gap on the order of 1 inch which was highly constrained due to the transverse welds at the ends. It is probable that the third initiation in the deck plate was at a similar location. The longitudinal bulkhead fracture initiated in an angle between the two deck fractures. As the load path shifted to the longitudinal bulkhead, the angle fractured at a poor quality butt weld and the fracture passed into the bulkhead through a weld at the angle toe. All fracture propagation was by brittle fracture with very little ductility.

Based on the direction of chevron markers on the fracture surfaces, it can be concluded that the first fracture to form was that between samples No. 6 and 7. The crack between samples No. 6 and No. 9 formed next and then the one between samples No. 1 and 2. The bulkhead crack probably formed last. The path of fracture across the spar deck is as shown in Figure 3-14.

Factors Contributing to Fracture Initiation

The initiating defects were small, suggesting a relatively high stress in the deck at the time of fracture. This is also suggested by the multiple reinitiations and arrests. It is surprising that the ship survived in service for many years without fracturing, which must have been related to adequate material toughness and the ship not experiencing high stresses. The cracks all initiated at longitudinals where the faying flange was coped for butt welding. Unfortunately, this ship still contains many such details.

Factors Contributing to Fracture Arrest

The spar deck fractures arrested in rivet holes at the gunwale angle, the hatch coaming, and the longitudinal bulkhead. One fracture arrested at a transverse butt weld in the deck and one in deck plating which had propagated to an area which had already been fractured. The bulkhead fracture terminated naturally from decreasing stress.

3.2 HIGH SPEED CONTAINERSHIP HATCH CORNER CRACKING

Description of Vessel:

This case study describes a fracture that occurred on the SL-7s, a class of eight high speed containerships built in the early 1970s [3-2]. These ships were the fastest commercial cargo ships when first put into service. The principal characteristics for the vessels are:

Length overall:	946.1 ft
Length between perpendiculars:	880.5 ft
Breadth (molded):	105.5 ft
Depth amidship:	65.25 ft
Displacement (deep load line):	50,315 LT
Year built:	1972 (foreign built).

Figure 3-15 shows the elevation and plan views of the SL-7. The ship had large hatch openings as is typical for all containerships. The fractures oc-

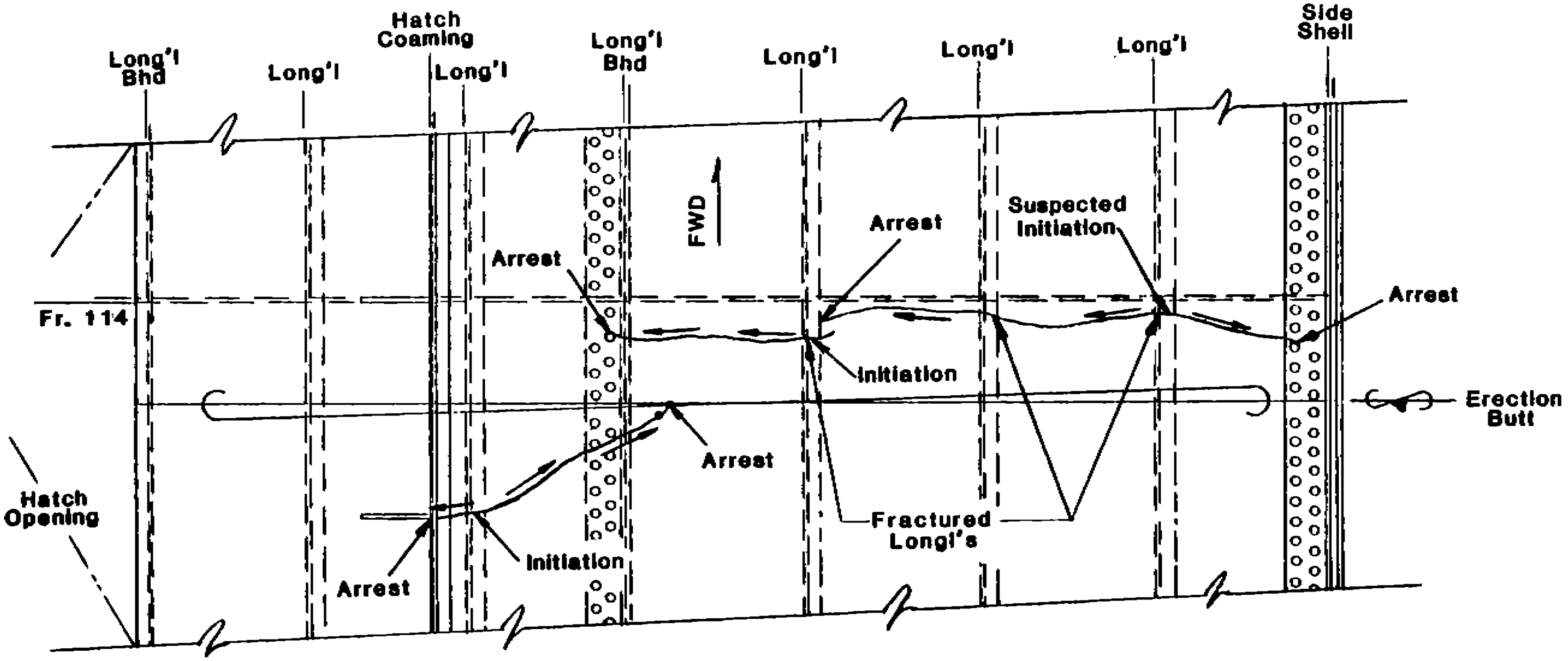


Figure 3-14 Plan of Spar Deck Fracture Initiation and Arrest Points

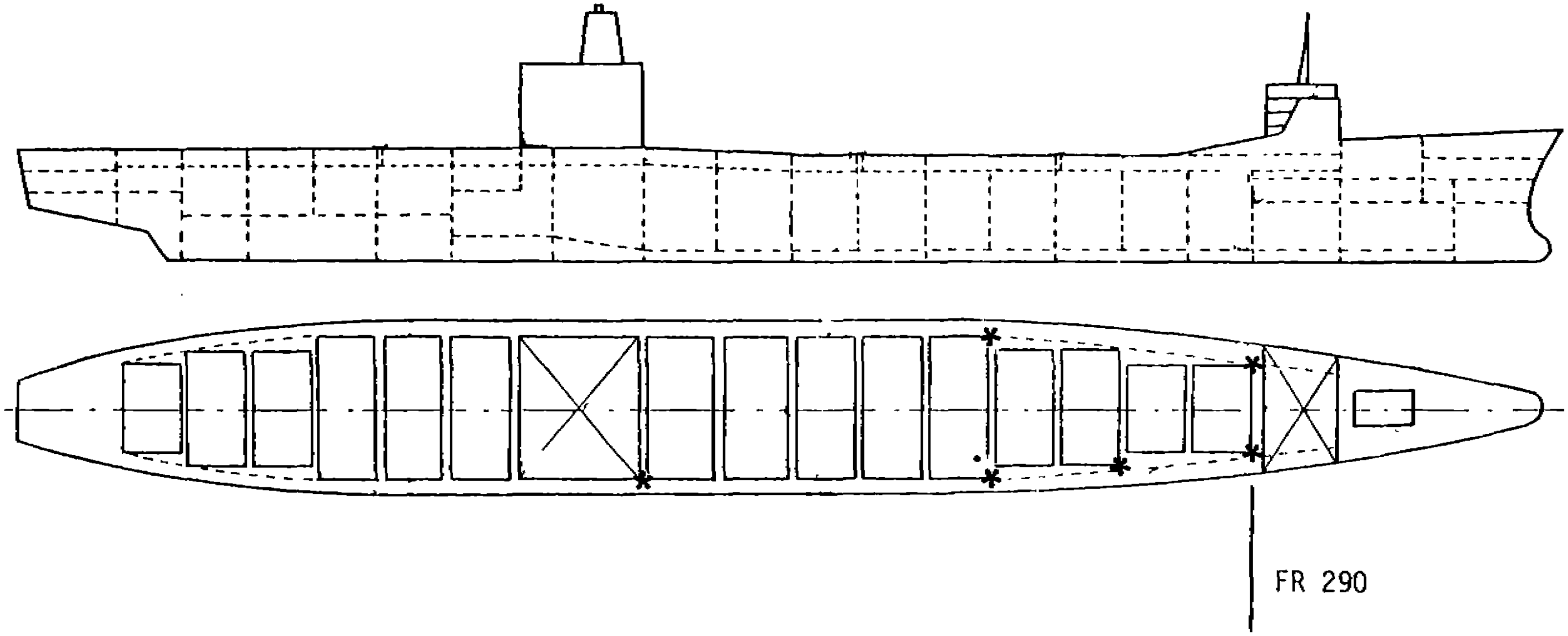


Figure 3-15 Elevation and deck lay out of the SL7 class of containerships showing frame locations of fractured hatch cut out where fatigue cracking occurred. Other locations where cracks were reported are indicated by *.

curred at forward corners of the forward hatch. The deck material in the vicinity of fracture was 46mm (1.81 inch)"EH33" normalized steel.

Description of the Circumstances at the Time of Fracture:

As mentioned above this class of containerships experienced a number of fractures in the main deck at the forward hatch corners. Although several ships of the class experienced fractures in this area, the fracture experiences of only one, the SL-7 SEA-LAND MCLEAN are presented here. Details of the fracture have been obtained from several sources including the USCG casualty database, Sea-Land Services, Inc., Teledyne Engineering Services, and the American Bureau of Shipping (ABS).

Service for the SL-7 SEA-LAND McLEAN started during the winter shipping season of 1972-1973. No hatch cutout fractures were reported the first season. However, after a severe North Atlantic storm encountered during the second season of operation, fractures were noticed extending outward from the forward hatch corners. Log book data for this storm noted:

Voyage:	29-W
Date:	12/22/73
Observed wave height:	50 ft.
Air temperature:	48 degrees
Wind speed:	90 knots.

Description of Fracture:

The fracture which was discovered after the storm of December 22, 1973 extended radially from the inside of the hatch corner as shown in Figure 3-16. A number of unsuccessful repair attempts were made before finally installing "CS" normalized steel doubler plate over the existing deck plate at the hatch corners. This repair fractured in the spring of 1976. The crack in the doubler plate is shown in Figure 3-17. Finally, a 2"x16" face plate was added to the inside face of the hatch cutout as shown in Figure 3-18, after which no additional fractures were reported except for an isolated weld failure.

Analysis of the Fracture:

Examination and analysis by ABS concluded that the fracture resulted from low cycle fatigue. The ABS grade EH 33 deck plate and the CS doubler plate exhibited sufficient toughness to prevent brittle fracture under the loading conditions and service temperatures. The hatch cutout was located in an area of known stress concentration and was one of the hot spots highlighted in the design stage [3-2]. During the design this and other "hot spots" were analyzed in detail under maximum load conditions but not under fatigue loading. Because of the size and speed of these vessels and other considerations, an instrumentation program to measure hull girder responses and strains at various locations was initiated by the owners and SSC, described in [3-2]. During the storm when the deck crack first appeared, the hull girder response was being recorded and from the records a midship vertical bending stress was determined:

- Maximum stress at wave encounter frequency, peak-to-trough (P-T) of 36,865 psi

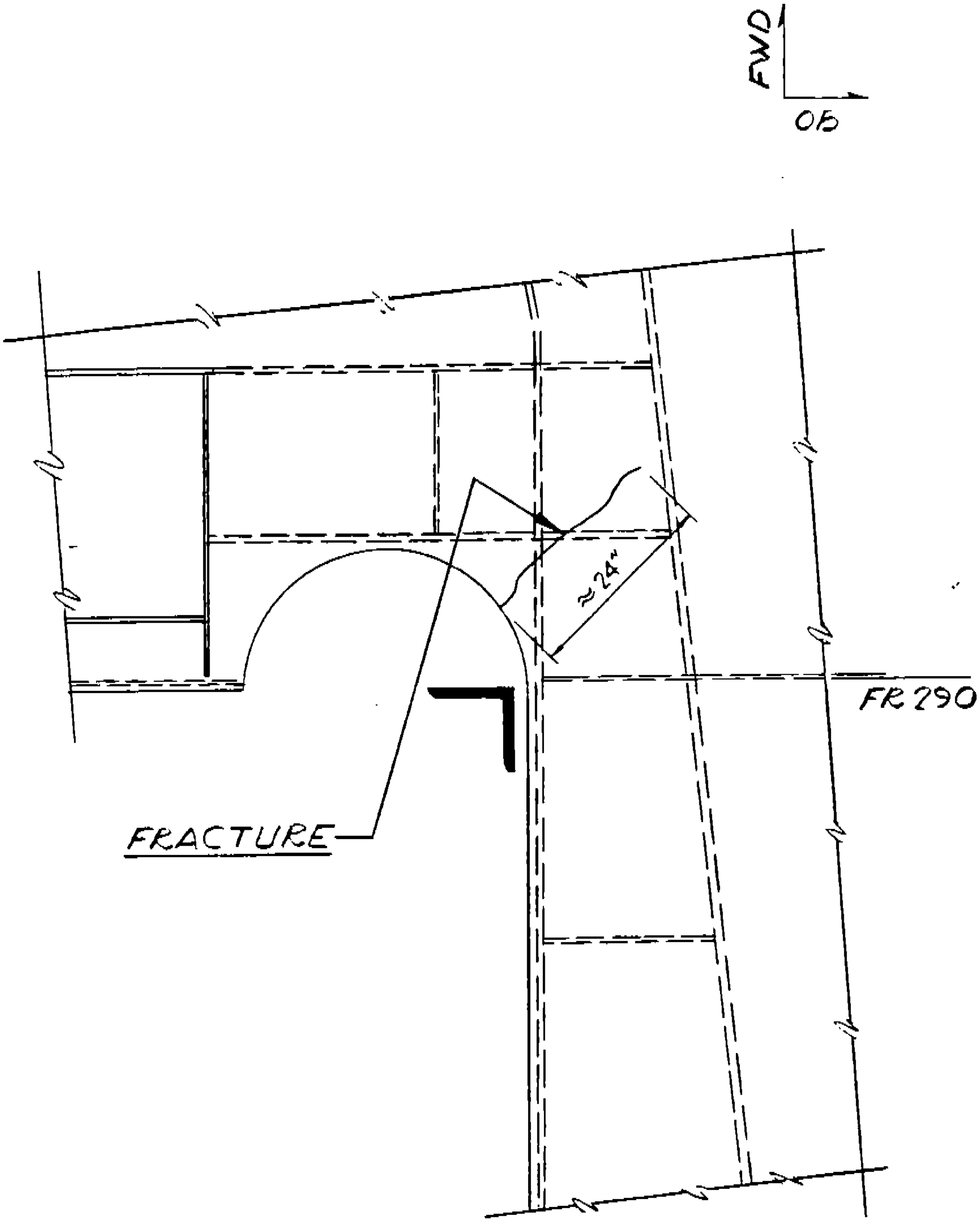


Figure 3-16 Fracture of the forward hatch cutout on the high speed containership during the second winter season

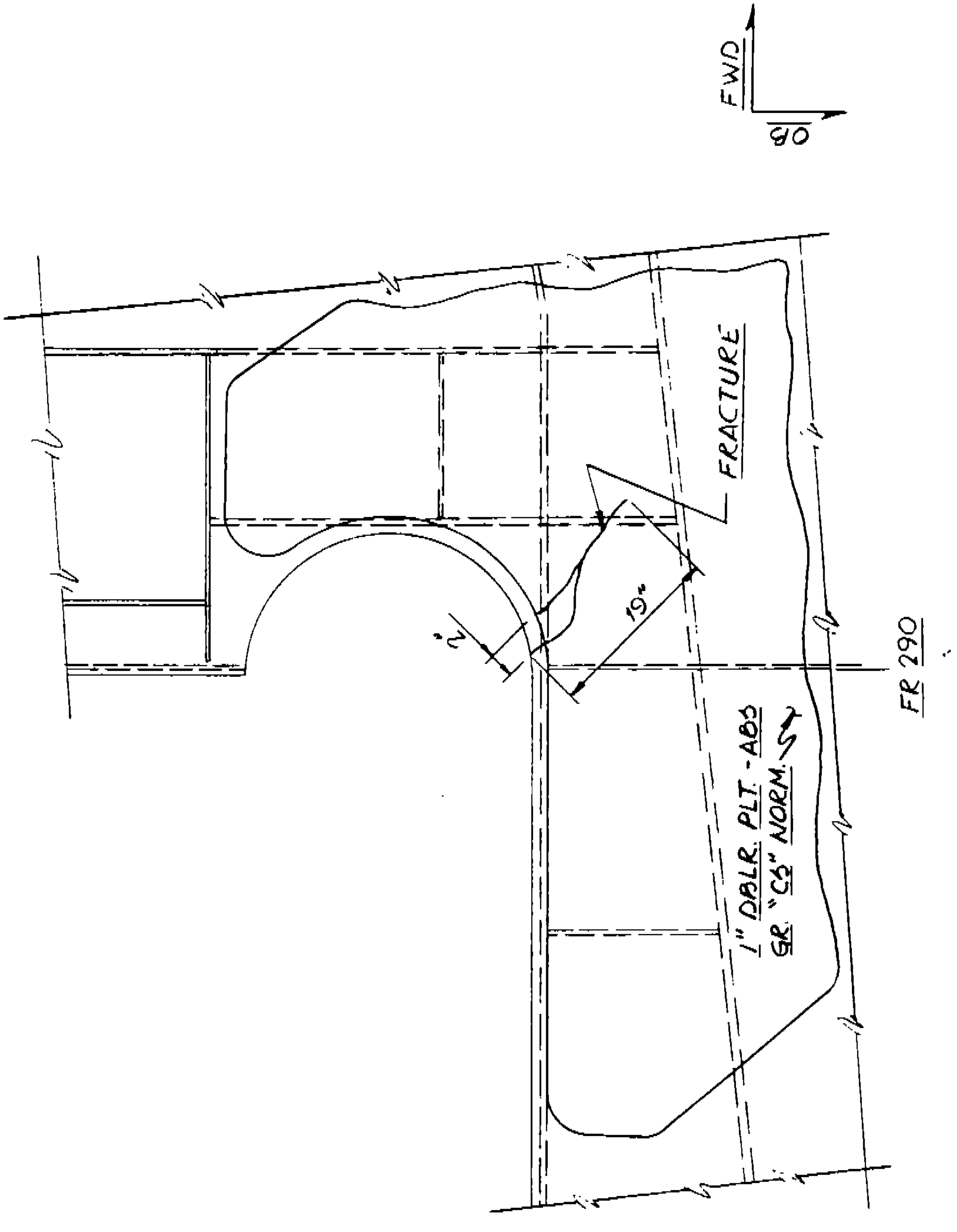


Figure 3-17 Fracture in the deck and doubler plate at the forward hatch cut out prior to 5/75

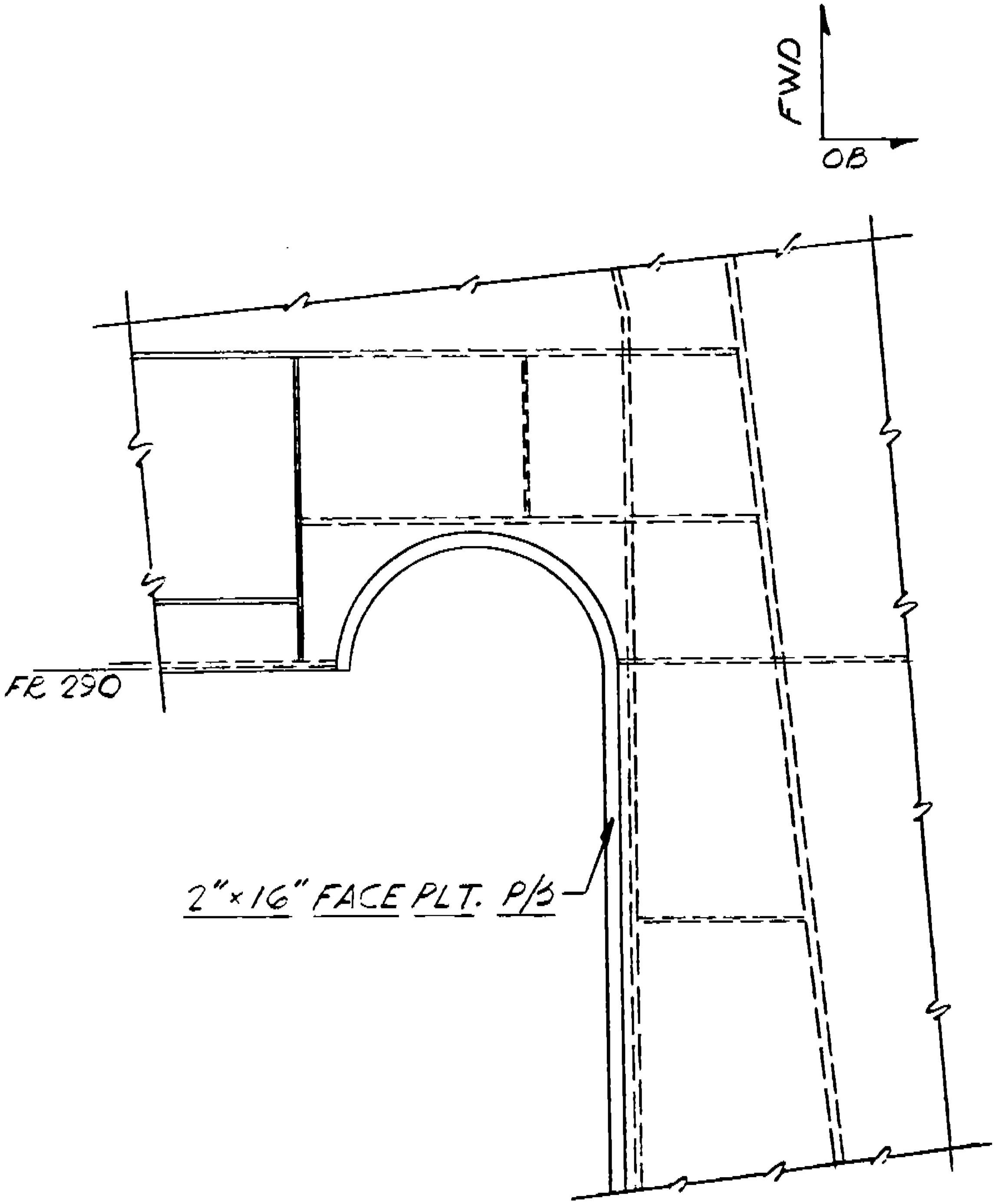


Figure 3-18 Face plate design for the forward hatch corner of the high speed containership

- Maximum stress at hull girder frequency (whipping) of 5,943 psi
- Mean stress (primarily from cargo and ballast distribution)* of 7,936 psi. hogging.

During the storm and throughout the first two operational seasons, hull girder response information was obtained in the general vicinity of the forward hatch corners. However, during the third season (after the cracks were observed) strain gauges were placed inside the hatch corner and a maximum stress (linear equivalent) of 79,000 psi was measured.

After the 2" x 16" face plate was added, additional stress data was obtained for the inside of the face plate. Afterward, an analysis conducted by ABS using the data and a cumulative damage based fatigue analysis indicated that this structural fix would inhibit further fatigue fracturing of the hatch corners.

Factors Contributing to Fracture Initiation:

The fracture of the SL-7 class containership occurred at an area where there is a major change in torsional stiffness of the hull girder from the open cargo section to the closed bow section. This is a common situation on ships with open decks. The result is stress concentrations at the forwardmost hatch corners. The particular structural detail used was selected over a pure radius or eliptical corner, to provide additional room in the hatch corner for container cell guides. Stress concentration in this area was anticipated and analyzed under maximum loading conditions. High toughness EH normalized steel was used to accommodate the predicted stresses. Although the cracking occurred in the area of local stress concentration, the extent of cracking was minimized by the fact that vertical hull girder bending in this area was fairly low and the steel had sufficient toughness to prevent brittle fracture. The crack in the forward hatch corner progressed in a sub-critical mode from cyclic loading. The hull materials, EH33 normalized deckplate and CS doubler plate probably prevented the initiation of a more serious brittle fracture. Extensive design analysis based on maximum load criteria showed the cutout to be a local area of high stress concentration; however, an analysis of the effects of cyclic loading would most likely have shown a potential for fatigue damage early in the ship's life. Typical practice in the offshore and aircraft industries is to fatigue test hot spot details on a prototype scale. The cost and time required for such a testing program for the SL-7s would probably not have supported the construction schedule for this eight-ship class; however, had a fatigue life prediction been conducted during detail design, the high probability of damage early in the service life could have been predicted.

Factors Contributing to Fracture Arrest:

The fracture propagated into a region of low local stress.

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* This mean stress figure includes a typical still water bending-induced stress departure condition from [3-3].

3.3 OIL TANKER (100,000 DWT) SIDE SHELL FRACTURE

Description of Vessel:

This case study describes a massive side shell fracture on a tanker. The vessel particulars are:

Length:	815.5 ft
Breadth:	128.2 ft
Depth:	62.8 ft
Gross tons:	51,576
DWT:	99,390 LT
Year built:	1965 (foreign built and classed).

Description of Circumstances at the Time of Fracture:

During January of 1975, a tanker* enroute to California from Dubai with a full load of oil lost a large section of steel side shell (16 feet x 54 feet) from the port side below the waterline.

Description of the Fracture:

The extent of the fracture of the shell plating is depicted in Figure 3-19. The fracture originated at a known pre-existing vertical crack in the shell approximately 3 inches long and in about the middle of the forward vertical portion of the opening as shown in Figure 3-20. An attempt was made to repair the pre-existing crack sometime prior to the voyage in question by the addition of a doubler plate; however, the repair was poorly accomplished. For some reason, a reinforcing bar was placed between the side shell and doubler plate. It was also reported that similar cracks had been repaired similarly at Frame 77 and other locations in the hull, all the same level relative to the waterline.

The fracture face was relatively flat, with a rough, grainy texture typical of brittle fracture. This appearance was characteristic of almost 100% of the lower horizontal run of the fracture, and was predominant on the other edges. On the surfaces other than the lower horizontal run there were short sections where the fracture face was smooth and at a 45 degree angle to the plate surface, which is typical of a shear fracture, a relatively slow dutile tear. The aft portion of the upper horizontal fracture was bent outward, indicating this was the last section to fail.

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* The source of information is not identified due to proprietary considerations.

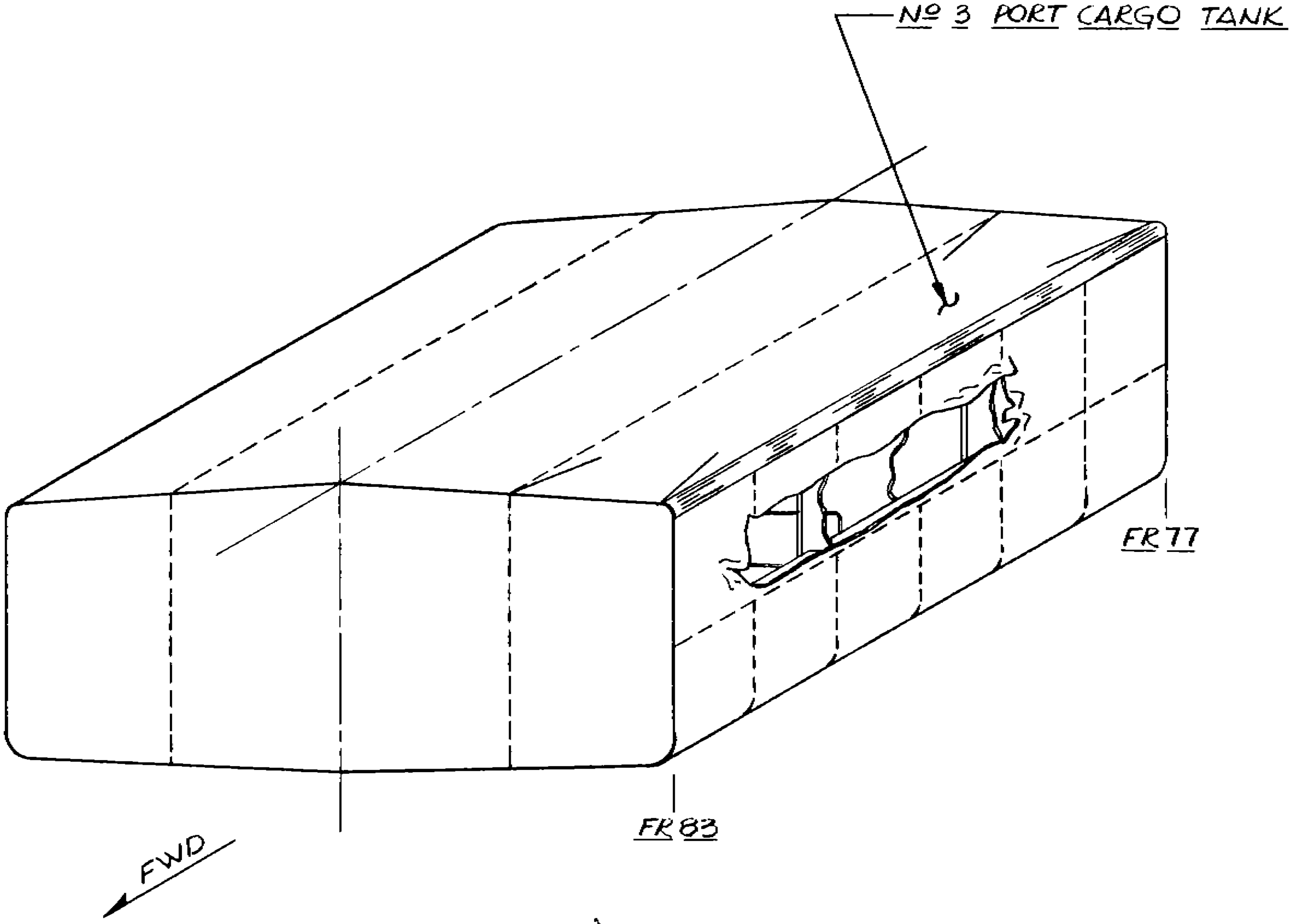


Figure 3-19 Cargo Hold Configuration of Tanker Showing Relative Location of Fracture

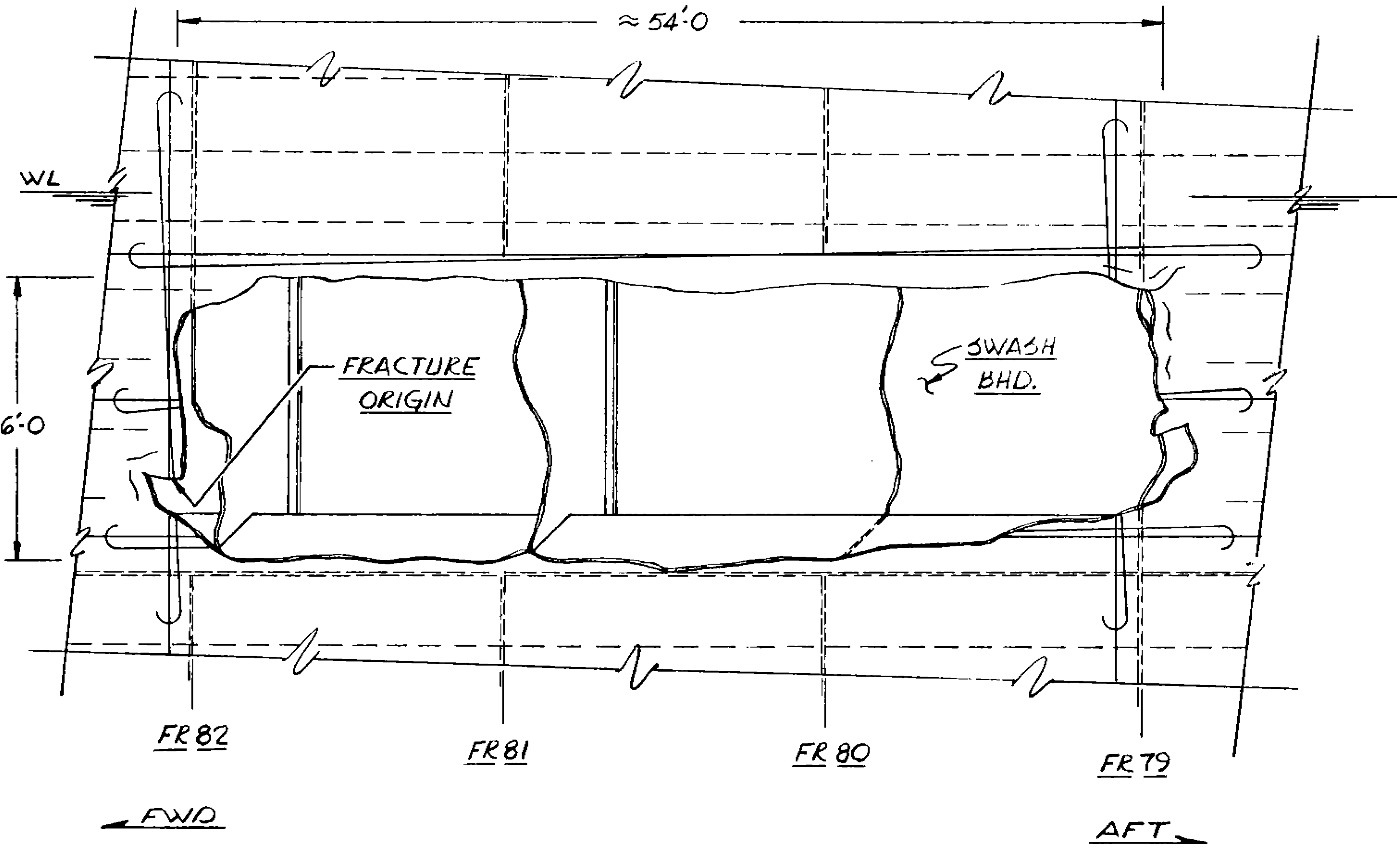


Figure 3-20 Configuration of fracture and loss of port side shell plating on the tanker

Analysis of the Fracture:

The analysis was limited to visual inspection by the ship owner's representative as described above.

Factors that Contributed Fracture Initiation:

The fracture of the side shell originated at a structural detail which had a history of failure at the waterline location. The fracture occurred near the neutral axis of the ship's hull girder and in an area which is subjected to local loading from internal cargo and external wave loading. Shear loading from hull girder bending in this area would be quite high. A contributing factor probably preceding the shell failure was the failure of the welded joint between the transverse webb frame stiffener and the side shell longitudinal allowing the longitudinal to flex relative to the web. The web/shell weld then fatigued under cyclic loading and eventually propagated via brittle fracture and finally ductile tearing until a large section of the side shell was lost.

3.4 TANK BARGE HULL FRACTURE

Description of Vessel:

In 1972, a tank barge fractured in two after being in service less than a year, as reported in References 3-4 and 3-5. The barge was part of an integrated tug-barge system. The particulars of the vessel are:

Length over all	583.75 ft
Length between perpendiculars	532.0 ft
Breadth (molded):	87.0 ft
Depth (molded):	46.4 ft
Gross tons:	15,579
Year built:	1971

The hull of the tank barge was ABS Grades B and C steel. In the tank barge, the radiused shear and bilge strakes of Grade C steel were intended to serve as crack arrestors.

Description of Circumstances at the Time of Fracture:

At the time of fracture the barge was dockside in a ballast condition having completed discharge of all cargo. The fracture occurred in January 1972. The reported air temperature was 40°F.

Description of the Fracture:

The fracture of the barge was generally in the vicinity of Frame 49, which is 42'-6" aft of the midpoint of the barge. The fracture extended completely across the main deck, down the side shell port and starboard, and across approximately 46 percent of the bottom plating. The configuration of the fracture path across the main deck is shown in Figure 3-21. The fracture originated at the base of a king post on the deck above the port longitudinal bulkhead. The king post was welded to a base plate doubler ring which was centered directly over the intersection of the transverse swash bulkhead at Frame 49

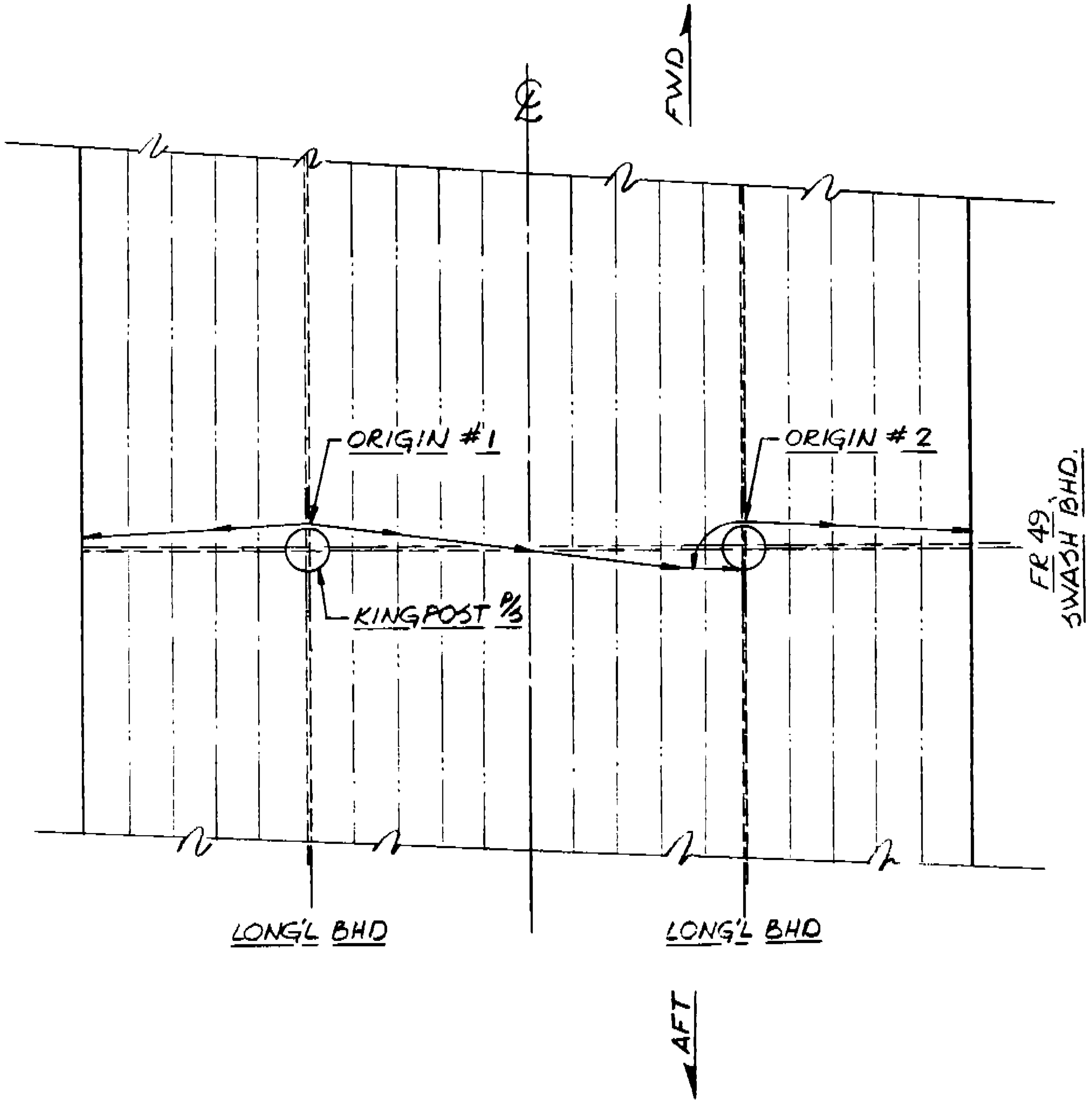


Figure 3-21 Fracture Path on the Main Deck of the Tank Barge

and the longitudinal oil tight bulkhead. The 1-inch deck plating was attached to the intersecting bulkheads by double, continuous fillet welds. The 3/4" thick base doubler ring was attached to the deck by 3/4" fillet welds on both the inside and outside diameters. As shown in Figure 3-22, four triangular, flanged brackets were symmetrically located around each king post. No preexisting flaw was observed on a microscopic scale at the point of the fracture origin as shown in Figure 3-23, though chevron markings point to the origin. A severe geometrical hard spot, or notch, was created by the design of this detail at the base of the doubler ring and support brackets. The fracture progressed in a brittle mode for the entire length of the fracture. The chevron pattern was observed throughout the fracture surface. The chevron pattern from about 4 feet either side of the port king post did have a small shear lip not more than a tenth of an inch deep and was very sharp. Directly forward of the port king post in the deck, the fracture surface showed a granulated area with no chevron pattern.

Analysis of the Fracture:

A finite element stress analysis conducted for the USCG as part of the casualty investigation verified that the local stress level was 2.5 times allowable or 23,515 psi. Because the barge was in calm water in a ballast condition, the loading conditions were essentially constant. Material tests were conducted on steel samples from the barge.

Although Grade B and C steels are not required by ABS rules to be tested for any specific transition temperatures, data derived from various samples manufactured to ABS specifications have shown that Grade B steel can be expected to have 15 foot-pound Charpy-V notch "transition" temperatures from -35°F to +30°F, a range of 65°F. ABS conducted tests on Grade B samples from the barge's fractured plating, which indicated 15 foot-pound Charpy-V notch values from -28°F to +30°F within the range expected from the ABS manufacturing specification. ABS determined that the nil ductility temperature (NDT) of the fractured Grade B steel was -10°F to +10°F. The Naval Research Laboratory conducted a dynamic tear test on Grade B specimens from the barge. The tests indicated NDT of +10°F and +20°F. ABS data concerning Grade C steel showed 15-foot-pound Charpy-V notch values from -40°F to +7°F, whereas ABS tests of the fractured barge Grade C steel indicated values of -30°F to +8°F. Corresponding NDT values on the barge's fractured Grade C steel as determined by ABS were 0°F and +10°F, and as determined by the Naval Research Laboratory were +20°F and +30°F using the more severe dynamic tear tests. In other words, the notch toughness of the Grade B and C steels in the tank barge exceeded expected values.

Factors Contributing to Fracture Initiation:

An unusual ballasting condition created a large stillwater bending moment with a resulting nominal stress off 23,515 psi in the deck, [3-4]. The combined effects of physical constraint, residual welding-induced stress and the nominal stress in the deck resulted in local stress sufficiently high to initiate a brittle fracture at the notch in the base of the king post.

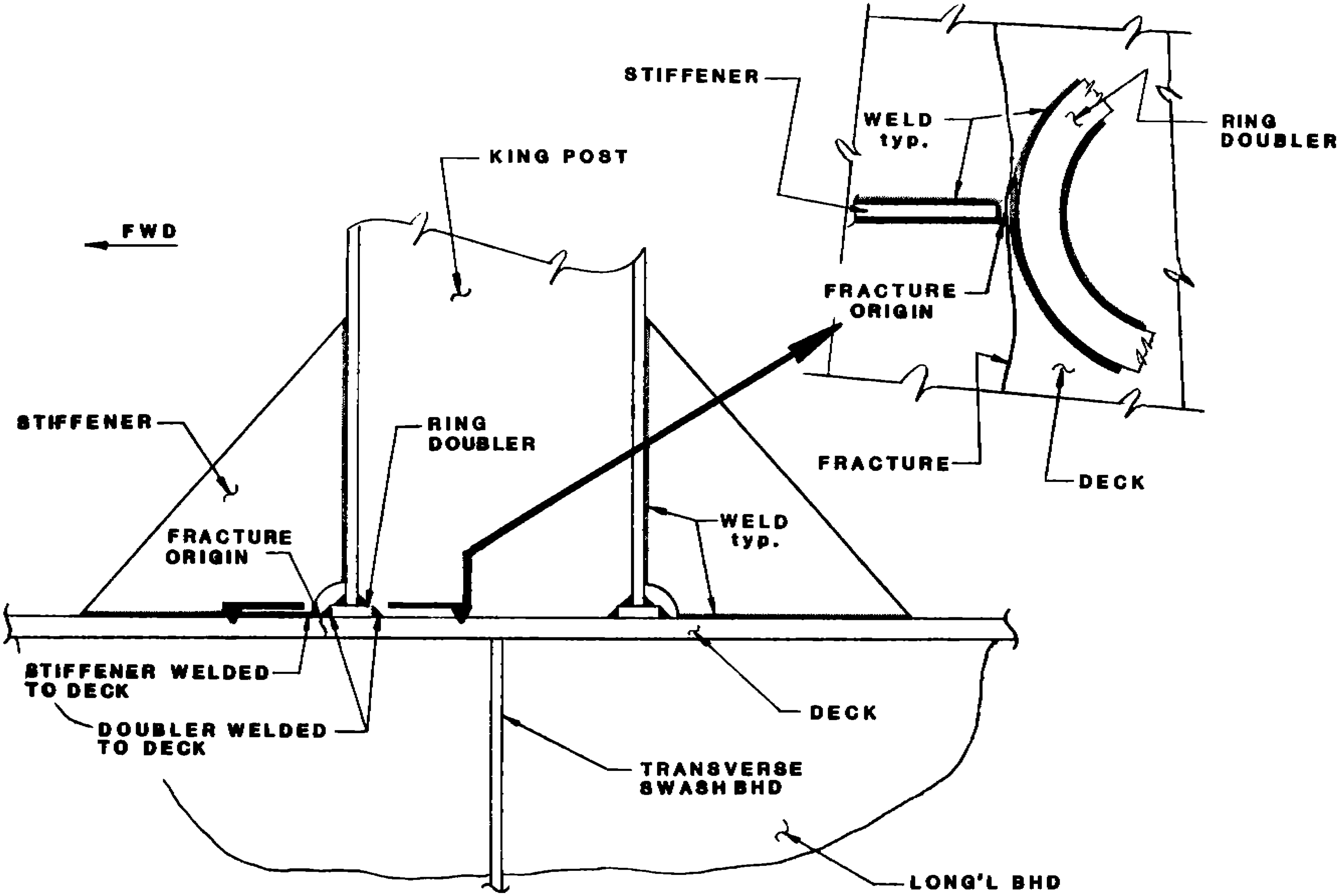


Figure 3-22 Structural Detail at the Fracture Origin on the Tank Barge

Figure 3-23 Origin of Fracture on the Tank Barge (Ring Stiffner Above Deck Plate and Longitudinal Bulkhead Below)

Factors Contributing to Fracture Arrest:

ABS "Rules for Building and Classing Steel Vessels" allow the use of special material on ships in place of riveted crack arrestors. At the time of this fracture, ABS Grade C steel served as "special material" only in thickness from 0.63 inches to .89 inches, yet in this barge 1-inch Grade C was used. To qualify as special material the 1-inch thickness Grade C steel should have been normalized. However, these rules did not apply to the construction of oceangoing barges. At the time the barge was built the ABS rules for offshore barges were silent on the installation of special material to act as crack arrestors. The year following the barge fracture, these rules were modified to include special material strakes.

3.5 OCEAN BULK CARRIER MAIN DECK AND SIDE SHELL FRACTURE

Description of Vessel:

A fracture occurred in the main deck and side shell of an ocean-going bulk carrier reported by Akita, [3-7]. The vessel was foreign built and classed.

Description of Circumstances at Time of Fracture:

None given.

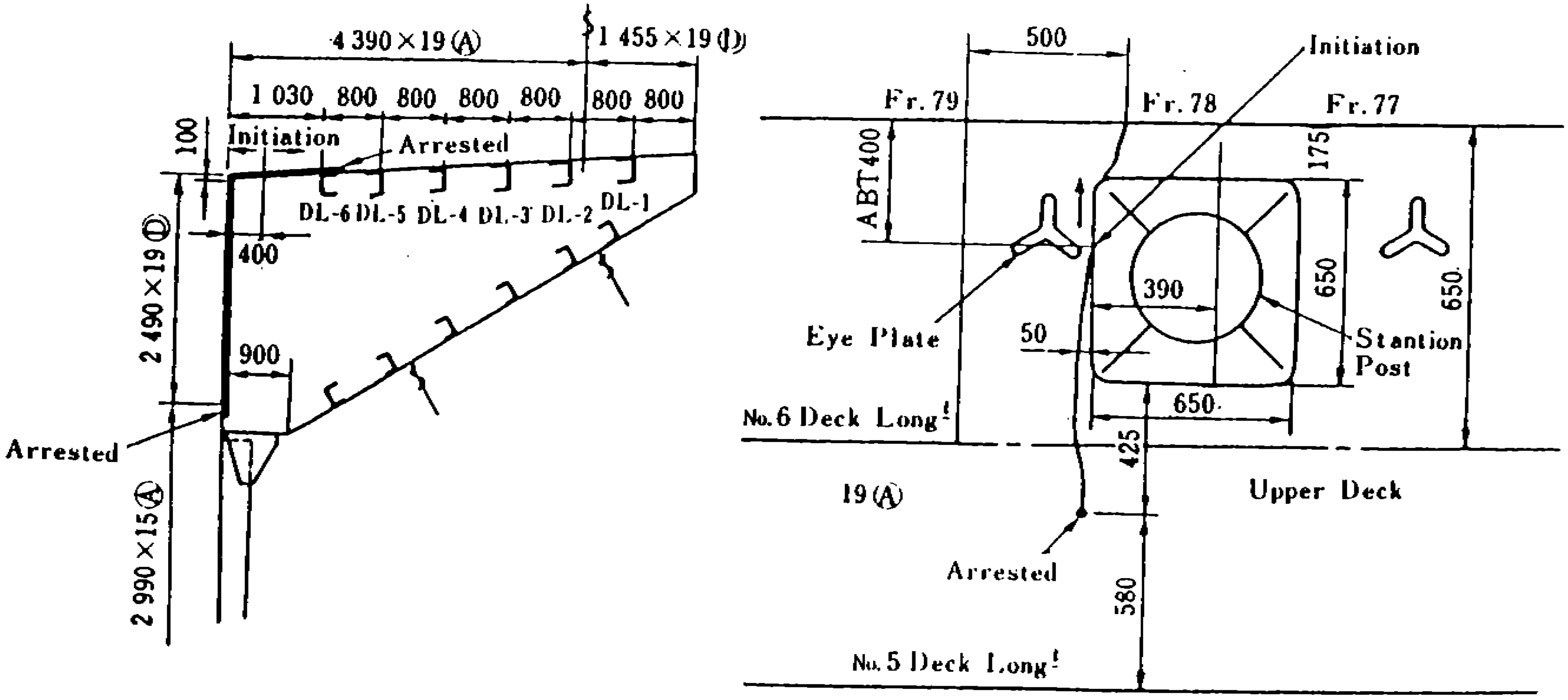
Description of Fracture:

A 3.7 meter fracture occurred in the upper deck and side shell of the bulk carrier. The configuration of the structure material thickness, steel grades and the fracture are shown in Figure 3-24. The fracture initiated in the main deck at a narrow zone between a fillet weld of a doubler for a stanchion base on the upper deck and a fillet weld of an eye plate. During investigation of the fracture, it was found that a fatigue fracture 200mm long existed at the point of origin prior to the occurrence of the brittle fracture that extended away from the origin in both directions until it was arrested.

Analysis Conducted:

The analysis reported by Alkeita [3-7] of this fracture concentrated primarily on the arrest characteristics of the brittle fracture. Stress intensities for were estimated. The effective stress intensity K is modified from a K-value in a static calculation by a K_{eff} concept (originated by the Japanese and described in SSC-265). The stress intensity in the deck increased going inboard, then decreased at the DL-6 longitudinal. The fracture was arrested somewhat beyond DL-6 where the stress intensity reached approximately the same level of the arrest toughness stress intensity K_{ca} of the Grade A steel obtained from the damaged plate.

The brittle fracture propagated into the Grade D shear strake before it was arrested near the lower edge. The estimated stress intensity decreased as the lower edge of the shear strake was approached, due in part to the sloping bulkhead of the upper wing tank. Arrest was predicted where the stress intensity reached a value of K_{ca}. Actual arrest occurred at the edge of the shear strake.



SECTION

PLAN

dimensions in mm

Figure 3-24 Brittle Crack on Upper Deck of a Bulk Carrier

Factors Contributing to Fracture Initiation:

This brittle fracture originated at a weld detail where stress concentration was high due to the close proximity of two highly restrained structural details. Fatigue was the cause of the initial crack. Placement of the eye plates further away from the stanchion base would have probably prevented the fracture. The mixed fracture modes that occurred in this case substantiate the concern that fatigue cracks can increase to a size that can contribute to the initiation of a major brittle fracture.

Factors Contributing to the Fracture Arrest:

The factor that contributed most to fracture arrest is the redundant structure in the opposite side of the ship. The hatch configuration minimized stress magnitude in the fractured side of the main deck. Therefore, the fracture propagated into areas of reduced stress.

3.6 CONVERTED CONTAINERSHIPS BOTTOM SHELL CRACKING

Description of Vessel:

A class of containerships* converted from Mariner Class general cargo ships [3-8] have experienced various chronic cracking problems which eventually resulted in their removal from service. Typical midship sections are shown in Figure 3-25 for the original transversely framed ship and the conversion. The conversions to containerships took place in the late 1960s and was performed at several U.S. shipyards. The conversions included lengthening each vessel by the addition of a new 97'-6" midbody, removal of 'tween decks, enlarging hatches, and other modifications necessary to carry containers. The particulars of the converted vessels are:

Length Overall:	661.1 ft
Length Between Perpendiculars:	625.5 ft
Breadth (Molded):	76.0 ft
Depth (Molded):	44.5 ft
Summer Draft:	29.55 ft
Displacement at Summer Draft (S.W.):	26,942 LT
Type of Machinery (Midship):	Geared Steam Turbine
Shaft Horsepower Maximum:	19,250
Designed Sea Speed:	20 knots
Year built (lengthened):	1952 (1969).

Just before actual conversion work began it was agreed by the owners and classification society that the bottom plating of the new midbody would be Grade A plate, .8125 inch thick, the same thickness as the bottom plating of the original ship. The increase in section modulus required by the lengthening was achieved by the addition of doubler straps welded to the bottom, main deck and shear strake throughout the .4 length of the hull girder.

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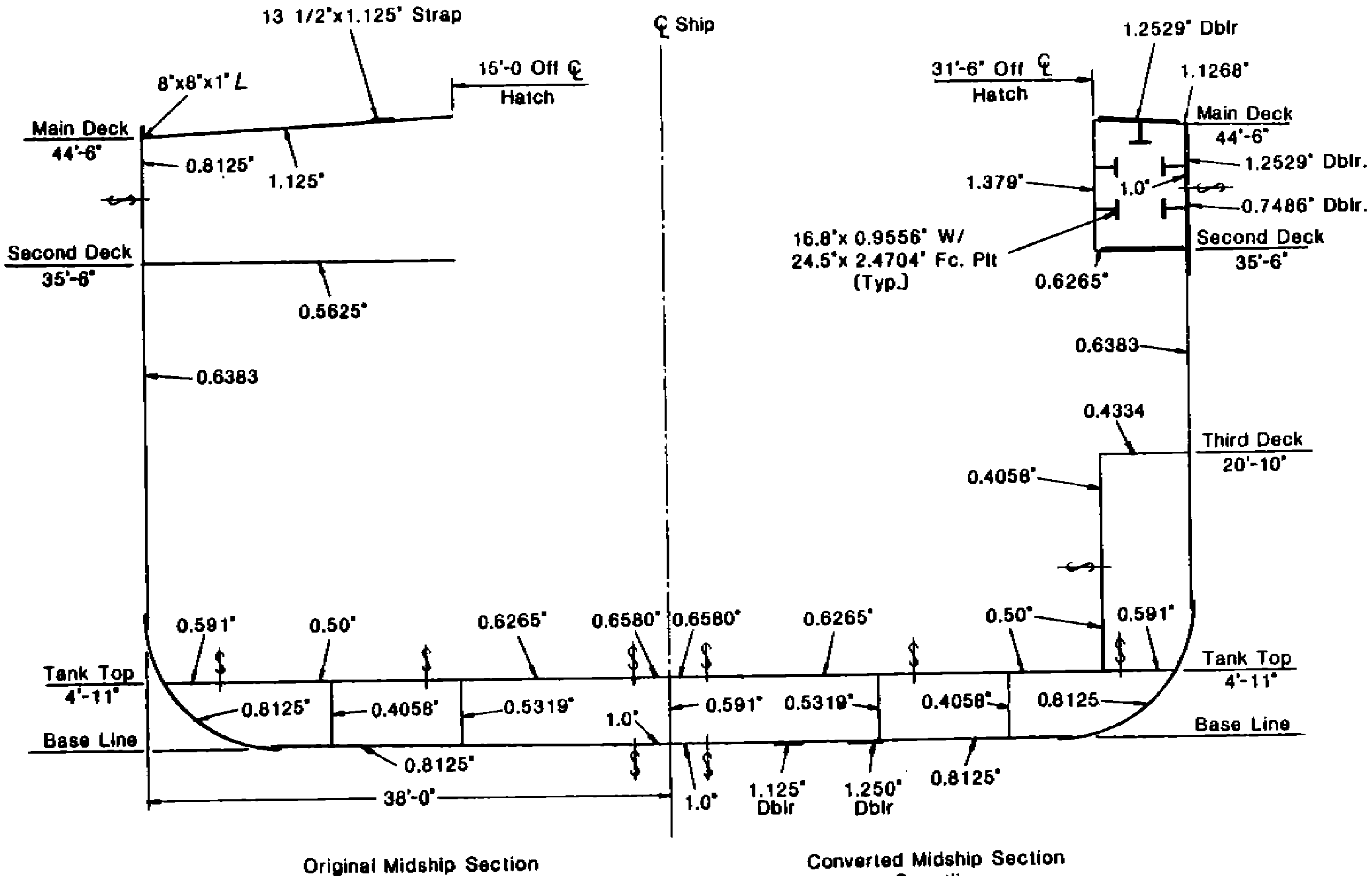
* The source of information is not identified due to proprietary considerations.



Original Midship Section Scantlings

Converted Midship Section Scantlings

Figure 3-25 Midship Section of the Original Mariner Class and the Containership Conversion

As part of the conversion, a significant amount of permanent ballast was added for stability considerations. Most of this ballast was placed in the ends of the vessel, which resulted in a large lightship still water hogging moment. At the time of the conversion there were no requirements for loading manuals on containerships to provide a means for determining bending moments.

Description of Circumstances at the Time of Fracture:

After conversion, these vessels operated in the North Atlantic. Reports of cracks in the primary structure began in 1972, and by 1978 the extent of cracking in numbers of cracks, location and size had become a serious problem. In an effort to reduce the hogging moment much of the permanent ballast was redistributed into the midship region. Loading computers were also placed on board the ship to assist the crew in controlling the still water bending moment. The early cracks were discovered during normal drydockings. As more cracks were reported the frequency of drydocking was increased. Bottom fractures were often first discovered when the crew was not able to empty a ballast tank. Such incidents required numerous non-scheduled drydockings.

Description of the Fracture:

The most prevalent type of crack initiation site on this class of ships is a transverse butt weld such as the one shown in Figure 3-26. There are three features of the weld, heat affected zone and plate material that can be observed in this bottom butt weld. These three features are the uneven surface geometry of the weld crown, steep angles at the weld edges (which produce areas of stress concentration), and the crack initiation sites. The quality of the weld is poor and includes porosity and slag.

Analysis of the Fracture

Visual inspection by ship owners' representatives showed that both surfaces were extensively corroded, with the exterior surface being the most severely effected. Examination of metallurgraphic specimens revealed the cracks in the plate and welds to be transgranular, to contain corrosion product, and to be characteristic of progressive fatigue cracking under the influence of corrosion. Several small cracks were examined by fractographic analysis as shown in Figure 3-27 where crack tip blunting can be observed. These cracks did propagate via corrosion fatigue and in more than one instance grew to a size where brittle fracture occurred and chevron patterns were observed.

Extensive effort by the ship's owners and consultants was directed at determining the state of stress in the ship's hull girder, both on a global scale and locally, using various techniques including finite element analysis. The stress in the bottom due to still water and wave induced bending moments was determined to be below yield. No attempt was made to determine the stress resulting from unrestricted loading permitted during the early years of service. A fatigue analysis was conducted for the bottom plating using Munse's [3-9] method. However, no definitive conclusions could be presented because the reliability factors for ship structures are unknown quantities at this time.

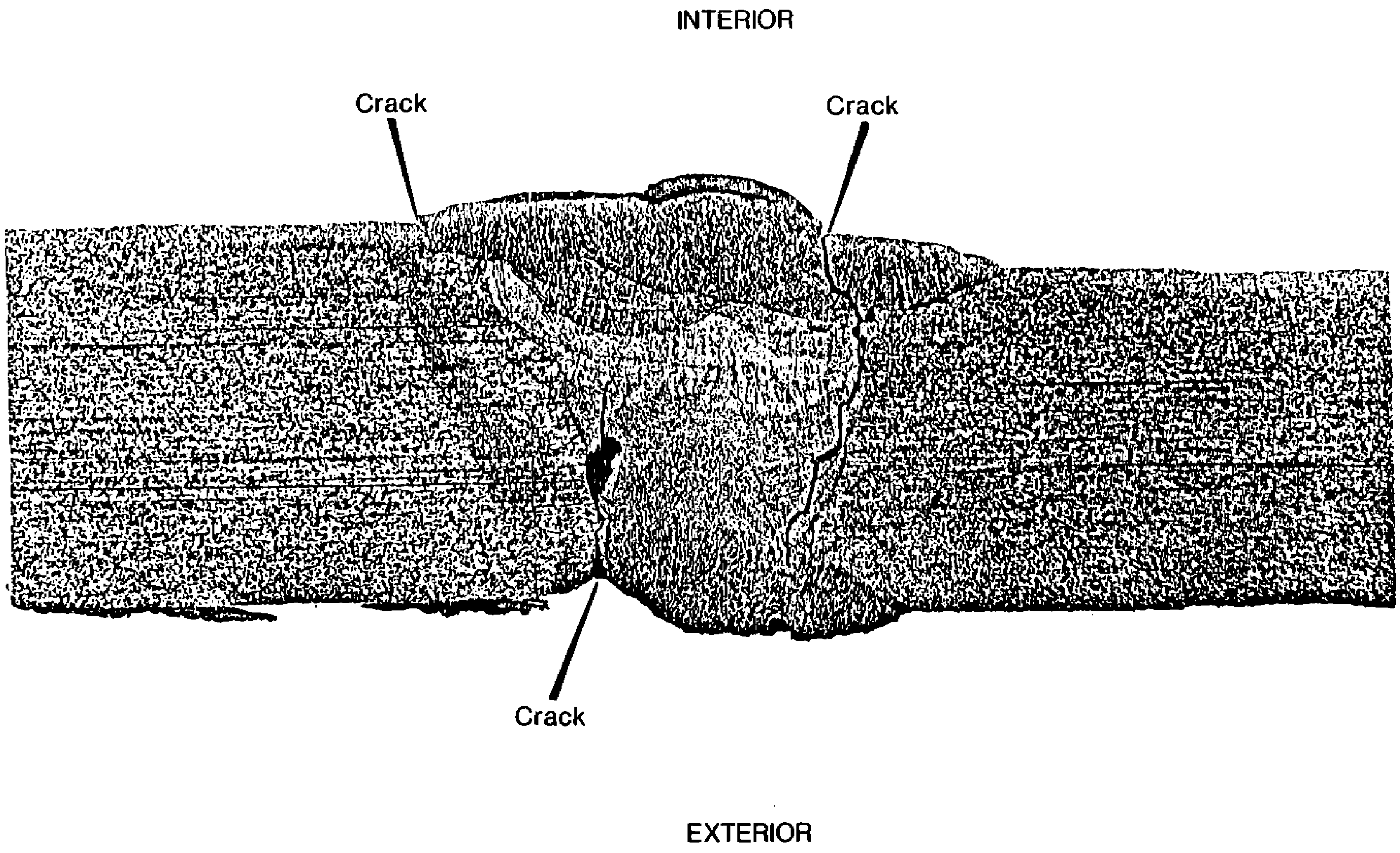
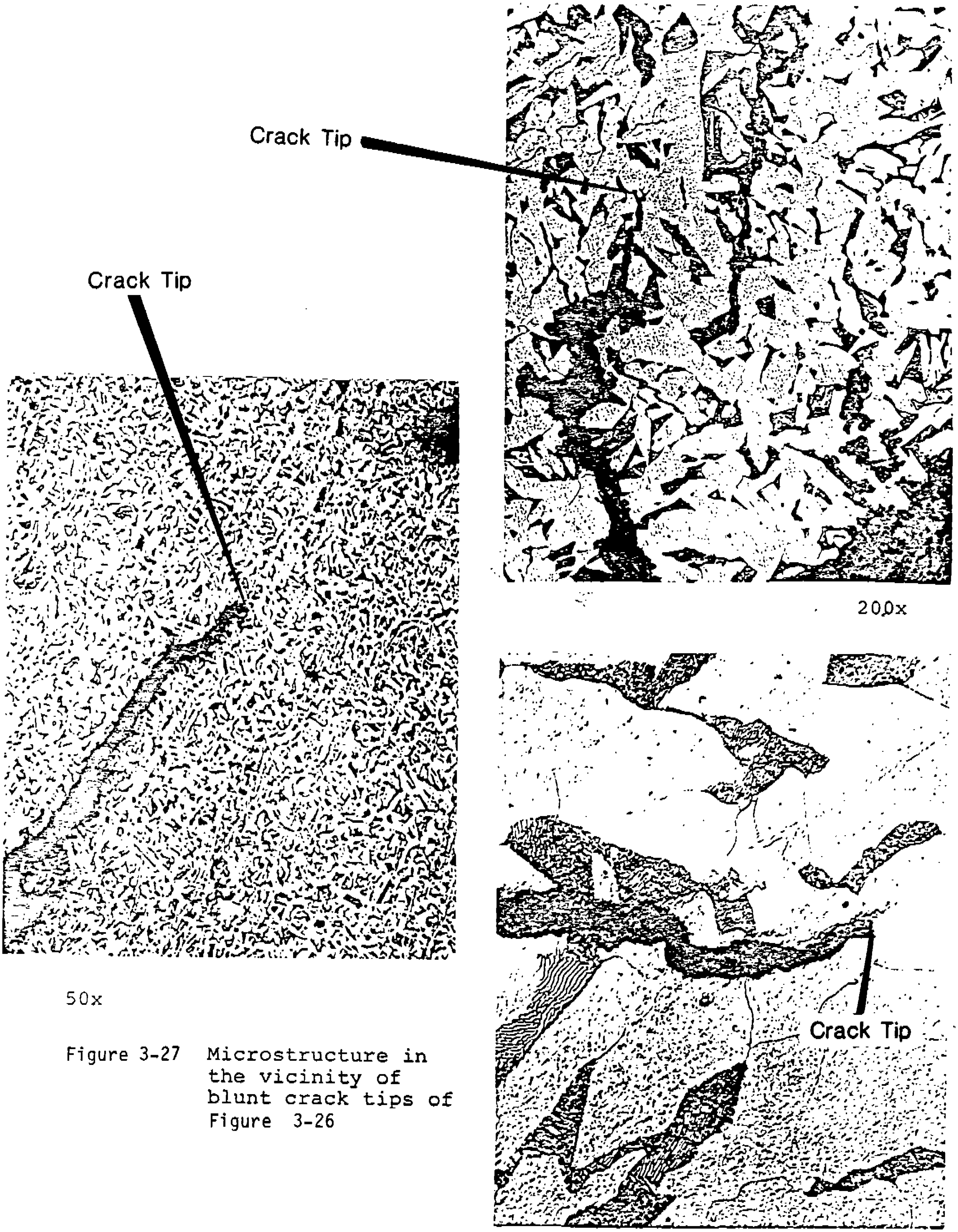


Figure 3-26 Weld Detail Used on the Converted Containership Showing Corrosion Fatigue Cracks



200x

50x

1000x

Figure 3-27 Microstructure in the vicinity of blunt crack tips of Figure 3-26

Factors Contributing to Fracture Initiation:

The investigators of this project believe that the primary cause of the cracking problems on these vessels can be related to the original design and conversion. The high still water hogging moments cause the bottom plating to be loaded in compression. This combined with the water pressure eventually led to upward deflection of the bottom plating between transverse floors, as shown in Figure 3-28. As the ship worked in a seaway, these buckles formed hinge points at the frames and over the years fatigue damage accumulated at the hinge points and other stress concentrations such as butt welds. The ship lengthening, placement of ballast in the ends, reduced scantlings allowed by the use of ineffective strapping, unrestricted loading, poor welds and corrosion all contributed to the problem. Fatigue cracks first appeared at the weakest points, e.g., poor quality welds, notches and defects, and then spread to base plating.

Factors that Contribute to Fracture Arrest:

The majority of these factures were detected and repaired. Other larger fractures were arrested at riveted seams.

3.7 TANKER (250,000 DWT) SIDE SHELL FRACTURE

Description of Vessel:

A major crack was discovered in the deck and down the side shell of a 250,000 DWT tanker built in 1967.* The particulars of the vessel are:

Length overall:	1143.0 ft
Beam:	170.0 ft
Depth:	65.5 ft
Draft:	44.0 ft
Deadweight:	250,000 LT
Year built:	1967 (foreign built and classed).

Circumstances at the Time of Fracture:

On a loaded voyage from the Persian Gulf this tanker encountered heavy seas with wind force 9/10 in the Bay of Biscay. A large wave struck the port forward quarter causing some damage to deck fittings. Repairs were made in Norway during discharge. There was no evidence suggesting hull damage.

This tanker finished discharging a cargo of Persian Gulf crude in Norway on December 4, 1972 and was proceeding to Teneriffe, Canary Islands, via the West Coast of Ireland. From December 5th through 10th the ship encountered heavy seas with vessel rolling up to 20°. The seas were hitting the ship from the starboard side. The sea and air temperatures were between 40°F and 50°F

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* The source of information is not identified due to proprietary considera-ations.

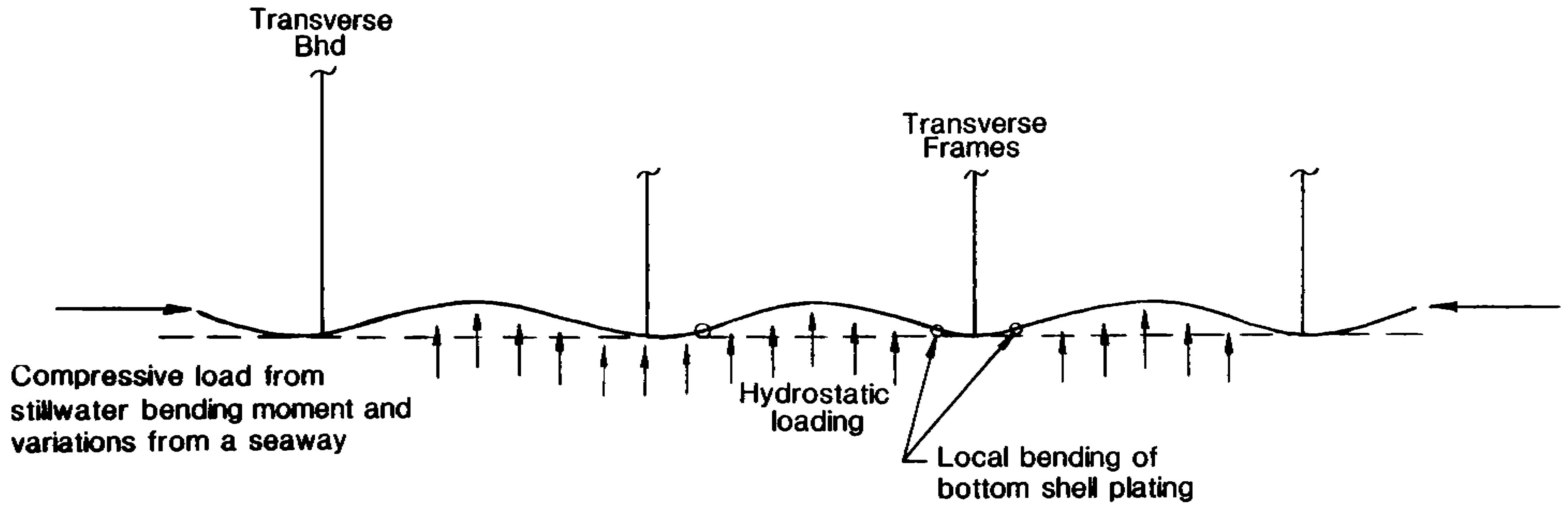


Figure 3-28 Illustration of Local Bending Associated With a Transversly Framed Ship

during the storm. On December 11th, after the storm subsided, a fracture was discovered in the main deck and side shell. During tank cleaning operations, the fracture was located in way of the empty No. 3 starboard wing tank.

Following discovery of the deck/side shell fracture, the ship proceeded to Teneriffe for assessment of damage and then to Lisbon for repairs.

Description of Fracture:

Figure 3-29 shows a sketch of the external appearance of the fracture which occurred in the shell and deck plating of No. 3 starboard wing tank. This failure appears to be three interconnected fractures plus one separate fracture. The main fracture extends from No. 1 side shell longitudinal to No. 18 side shell longitudinal. A second fracture is in the weld of the gunwale plate and connects to the main fracture in "S" strake. The third fracture in the deck (J-strake) connects to the fracture in the gunwale plate. An independent fracture was found across the weld between "P and "O" strakes. This fracture was directed towards, but not connected to, the main fracture.

Figure 3-30 is a sketch of the fracture as viewed from inside the tank. The relationship of the fracture to the erection butt welds in the longitudinals, and the fracturing of these butt welds are related to the sequence of fracturing and locating the origin of the fracture and will be discussed later.

Analysis is the Fracture:

The analysis consisted of visual examination by ship owners' representatives and material property determination tests. Visual examination of this main side shell fracture showed the majority of the surfaces to be fibrous with chevrons clearly evident. These chevrons "point" to the origin of the fracture. In this case the origin was in the fillet weld of No. 5 longitudinal in line with the erection butt weld made in this longitudinal. This fracture surface is shown in Figure 3-31 with the initiating point shown in more detail in Figure 3-32.

As shown in Figures 3-29, 3-30, 3-33, and 3-34, the fracture through the gunwale was primarily in the weld metal. The connection to the main fracture was through Grade DH_2 deck plate and on the deck end the fracture ran through a Grade EH_2 plate to what was probably a defect in the gunwale to deck plate weld. The only section of this fracture face available for examination is shown in Figure 3-35. Although there may appear to be a chevron pattern present, fractography studies have shown the bulk of the surface to be typical of ductile fracture. The measured impact energy, although below the specified value, is considered to be sufficient to prevent the initiation of a brittle fracture. The manner in which this fracture joins the main fracture at right angles indicates that this fracture probably occurred after the main fracture. The fracture in the deck plating is shown in Figures 3-29, 3-36, and 3-37. The fracture face, Figure 3-37, shows no sign of chevrons and is about 45° to the plate surface. This indicates that this was a ductile fracture and resulted from overloading after the main fracture occurred.

The main fracture, as shown in Figure 3-30, extends from the gunwale down to the "N" strake. Figure 3-38 shows the end of the fracture in the gunwale plate. The dimple at the end indicates that the energy at the crack tip was being absorbed by plastic deformation of the steel. Figure 3-39 is a photo-

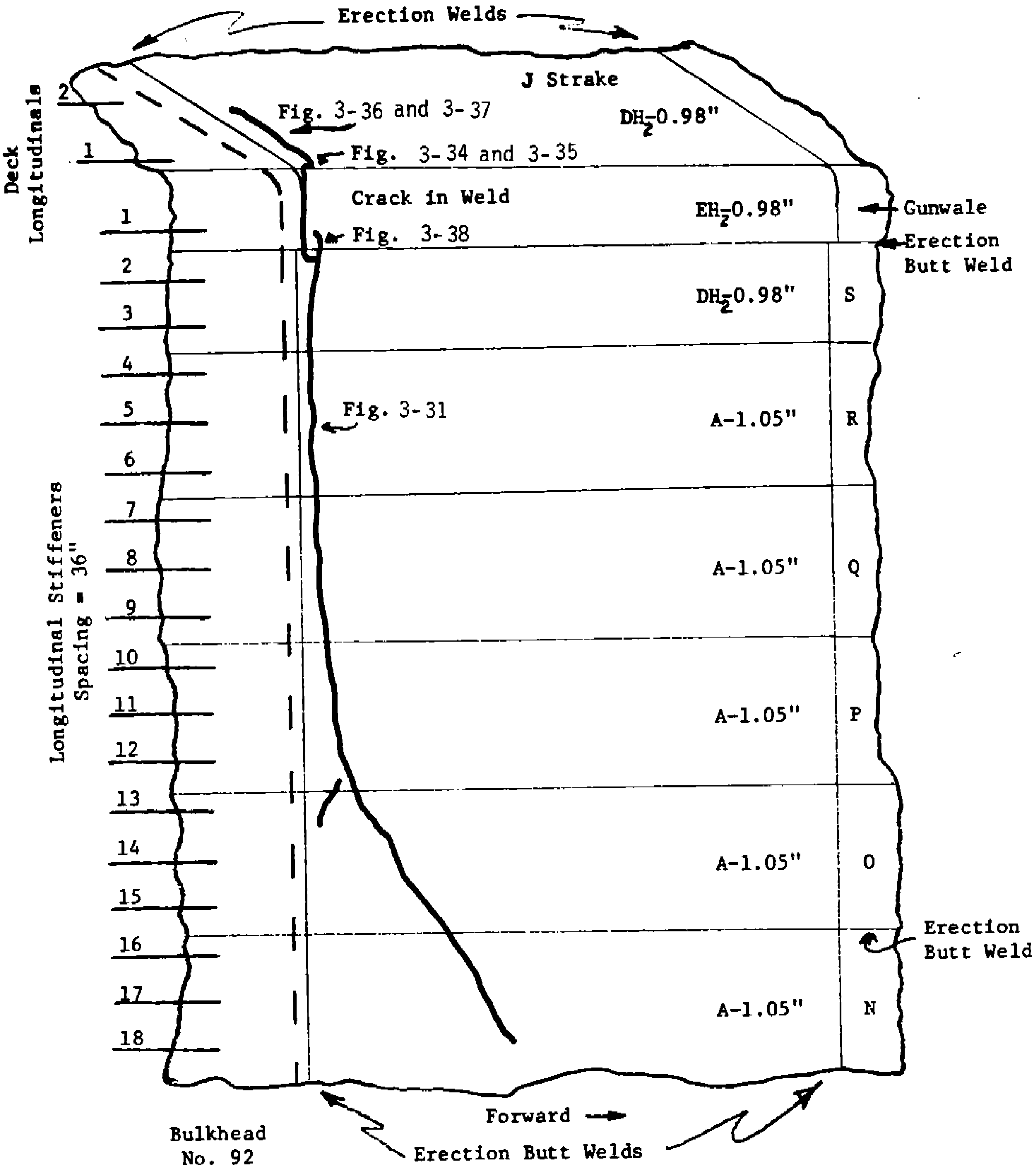


Figure 3-29 General View of Shell Fracture No. 3 Wing Tank Starboard

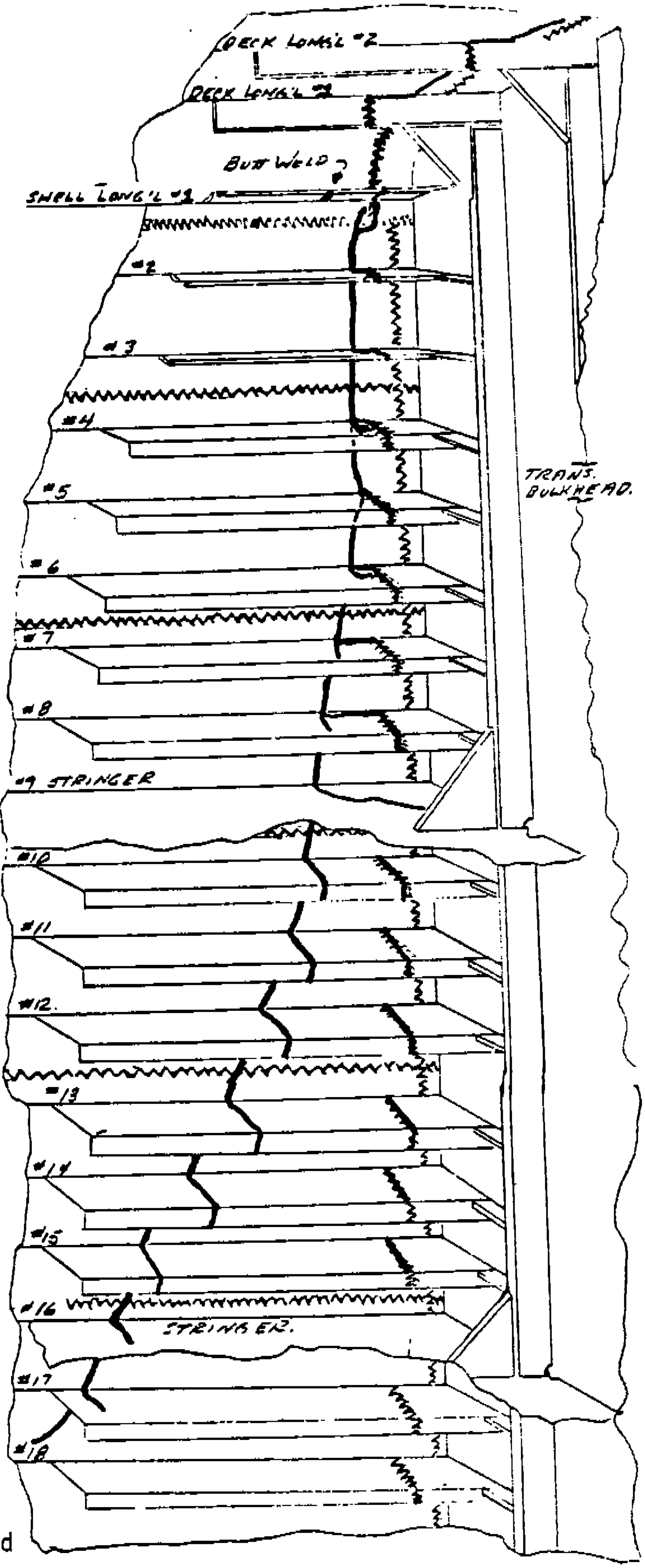


Figure 3-30 Location of shell Fracture From Inside No. 3 Starboard Tank. Fractures Found in the Longitudinals also Shown

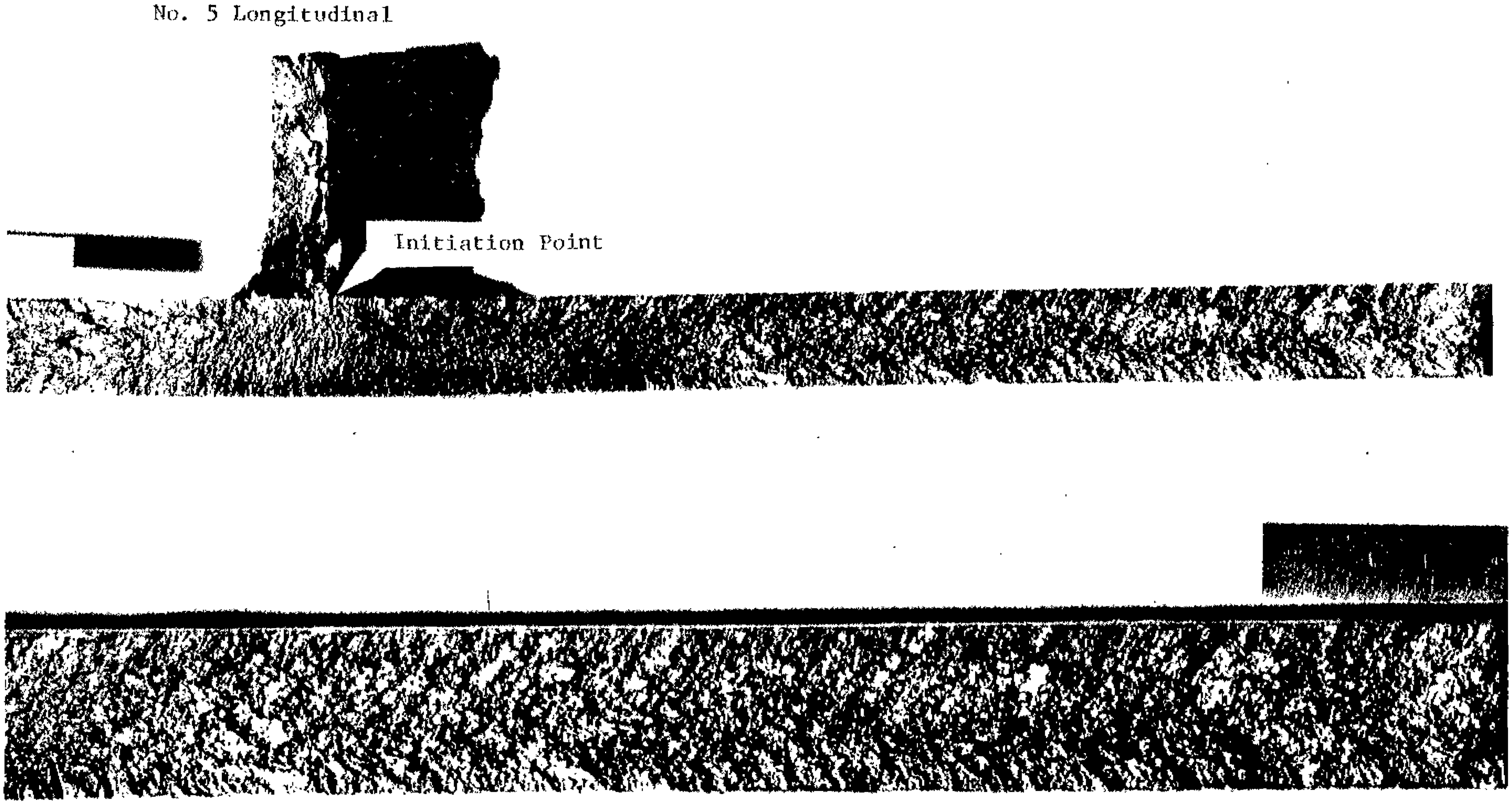


Figure 3-31 - Surface of main shell fracture showing chevron pattern typical of brittle fracture. Chevrons point to the fillet weld of No. 5 longitudinal as the initiating point. Specimen No. 3908; Magn. 0.6x and 1.1x.

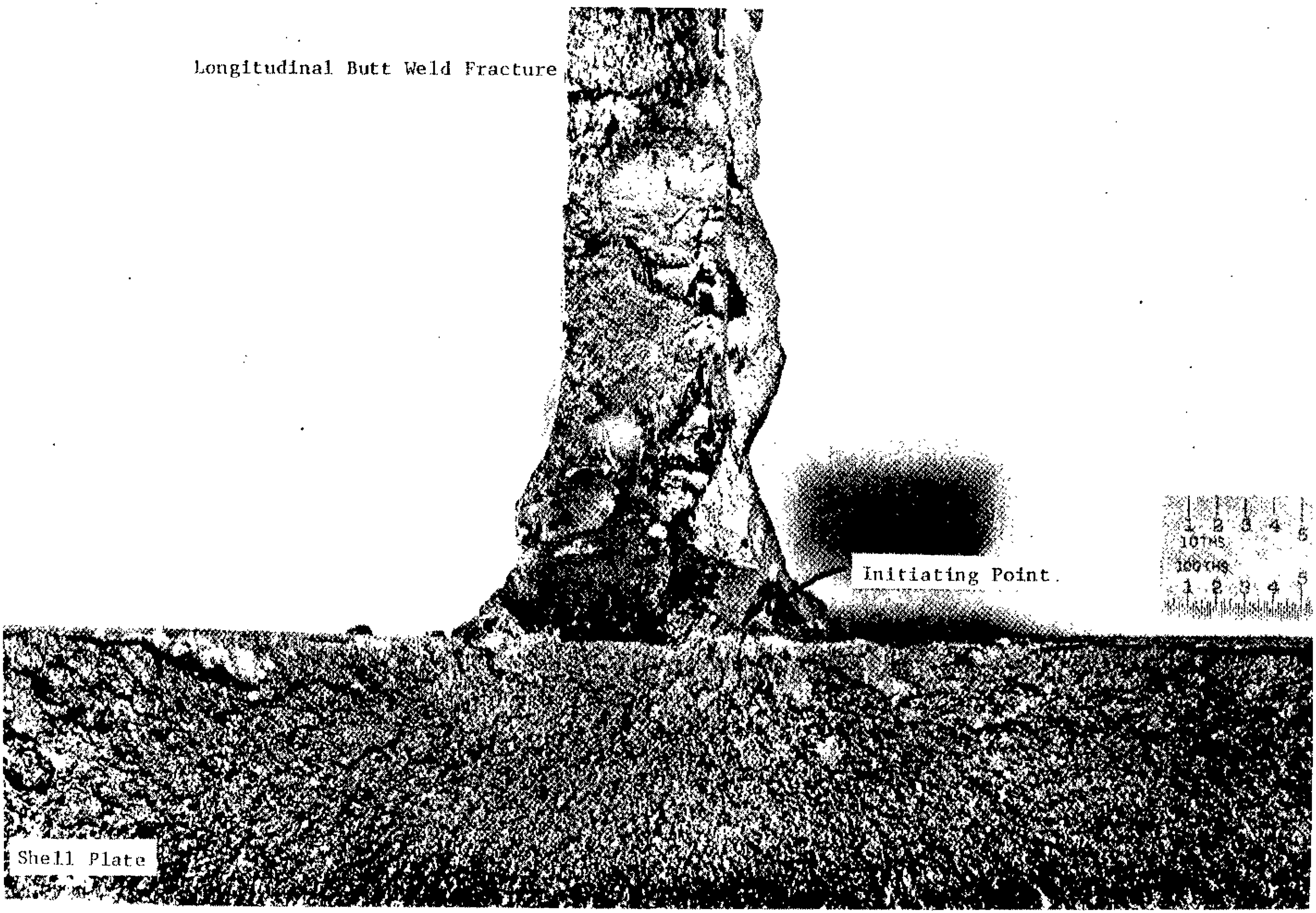


Figure 3-32 - Initiating point of brittle fracture in fillet weld joining No. 5 longitudinal to the shell plate. Specimen No. 3908; Magn. 2x.

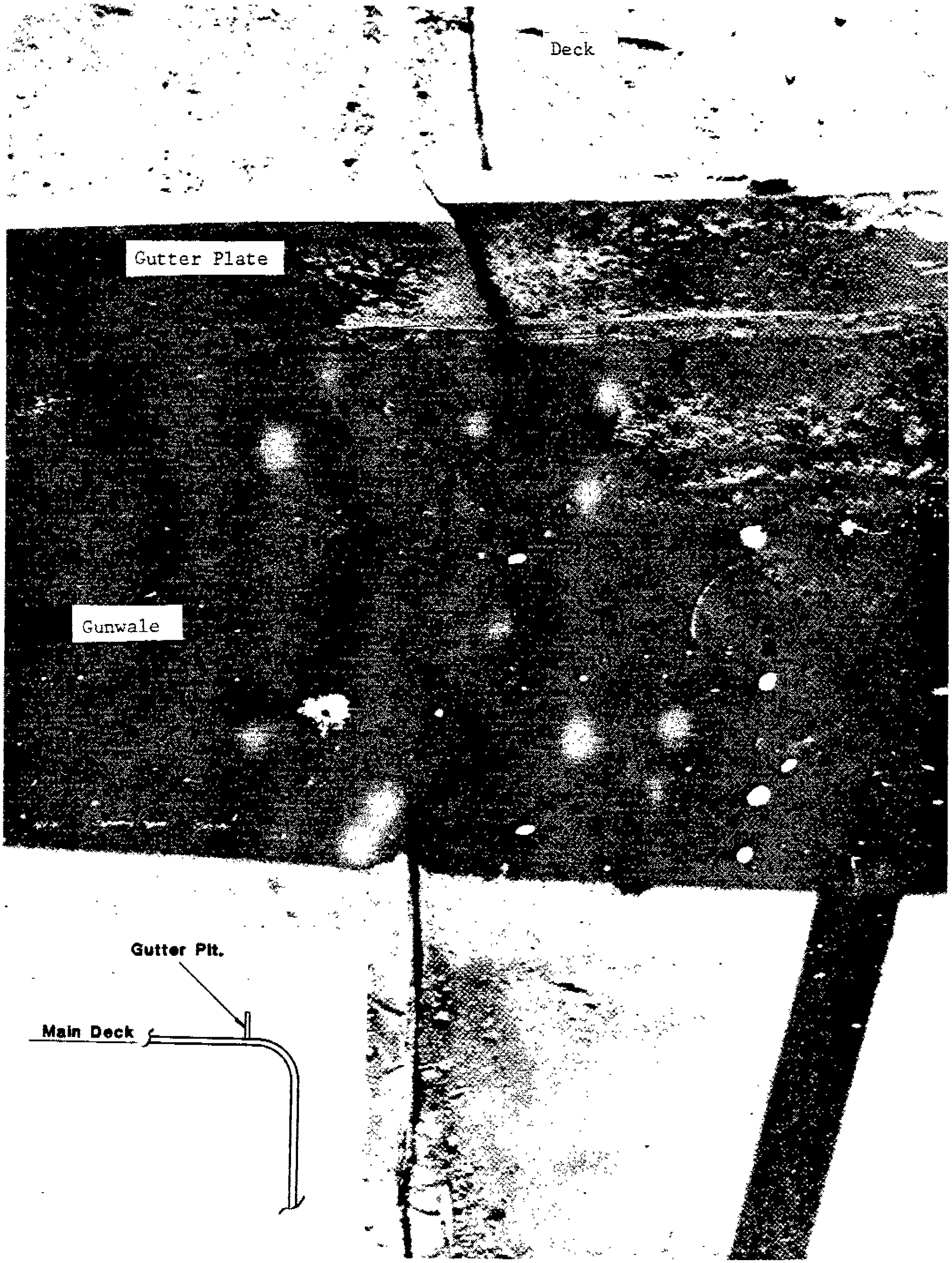


Figure 3-33 - Fracture as it passes from the gunwale plate onto the deck. Note path of fracture leaves the weld in the gunwale plate and runs parallel to the gunwale/deck weld.

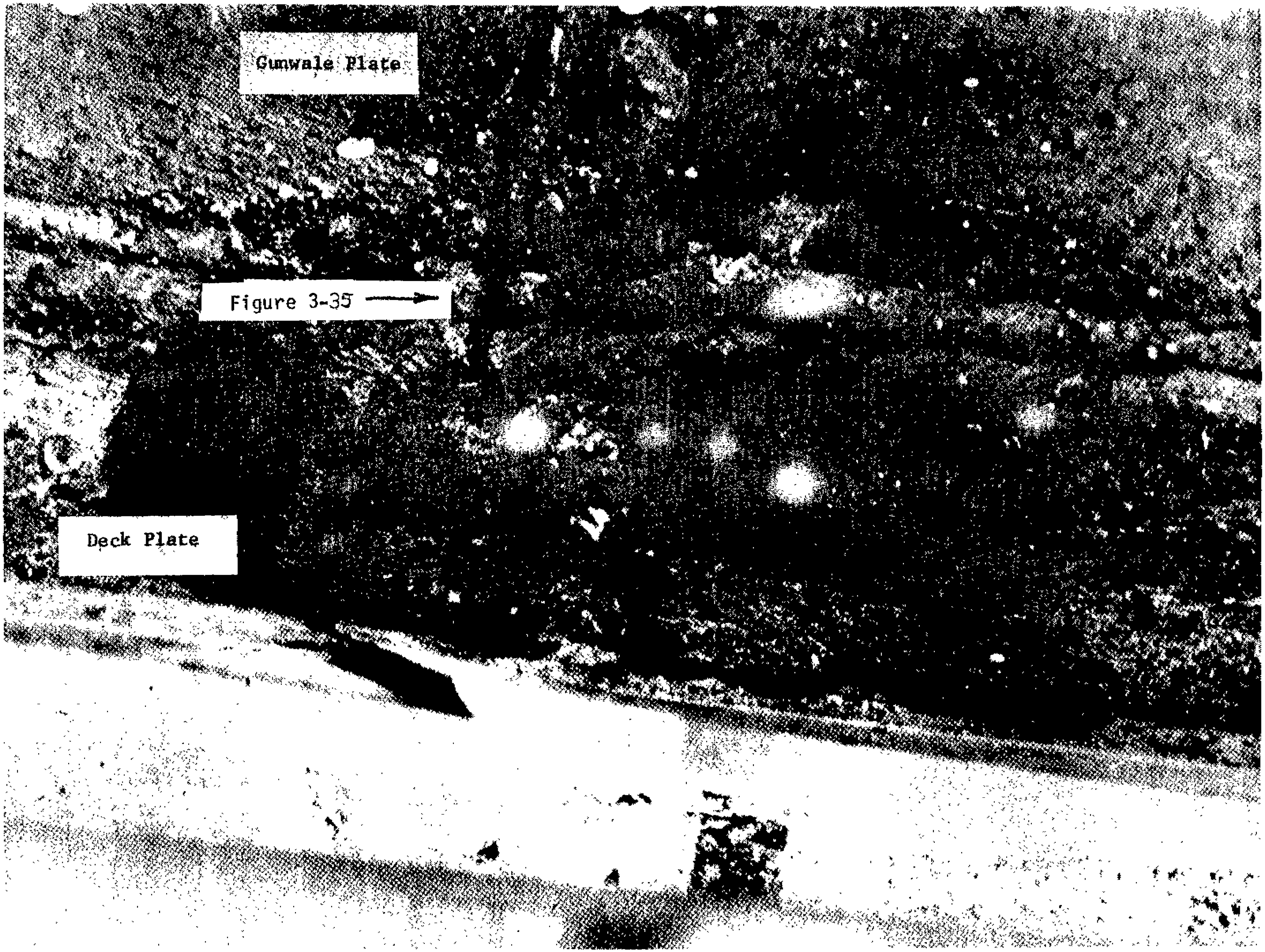


Figure 3-34 - Juncture of deck fracture with gunwale plate fracture.

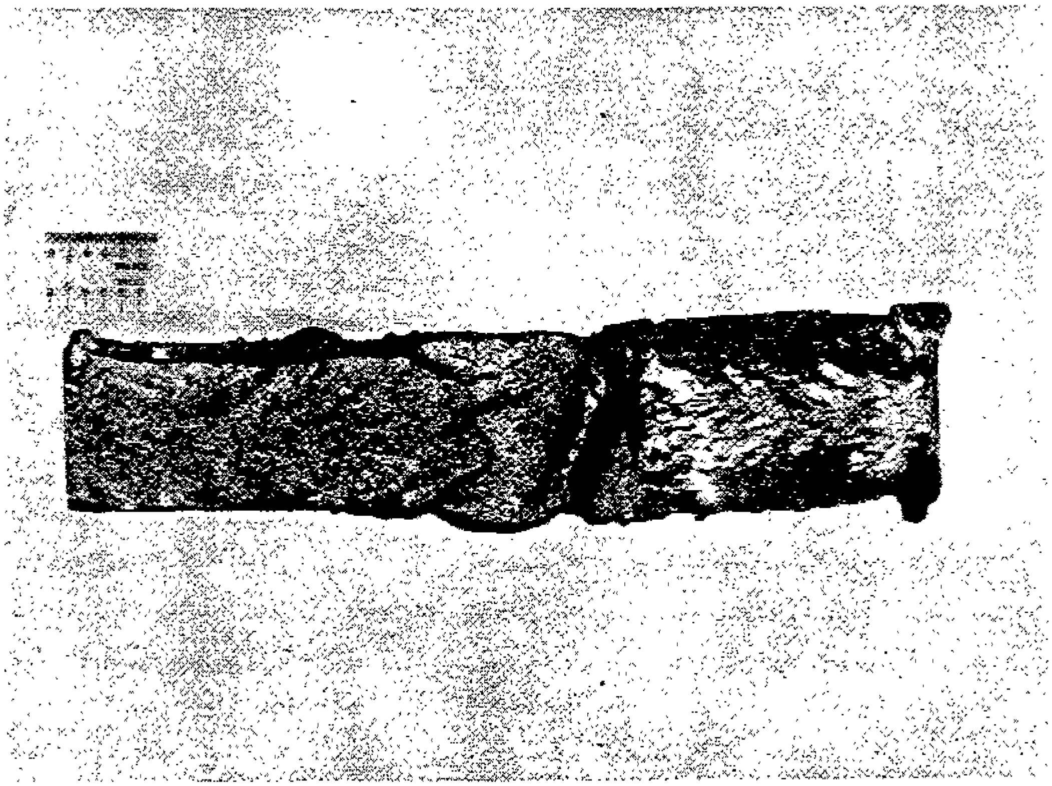


Figure 3-35 - Fracture face at weld joining gunwale plate (Grade EH_2) to deck plate (Grade DH_2). See Figure 3-34 for location. Note apparent chevron pattern in the gunwale plate.

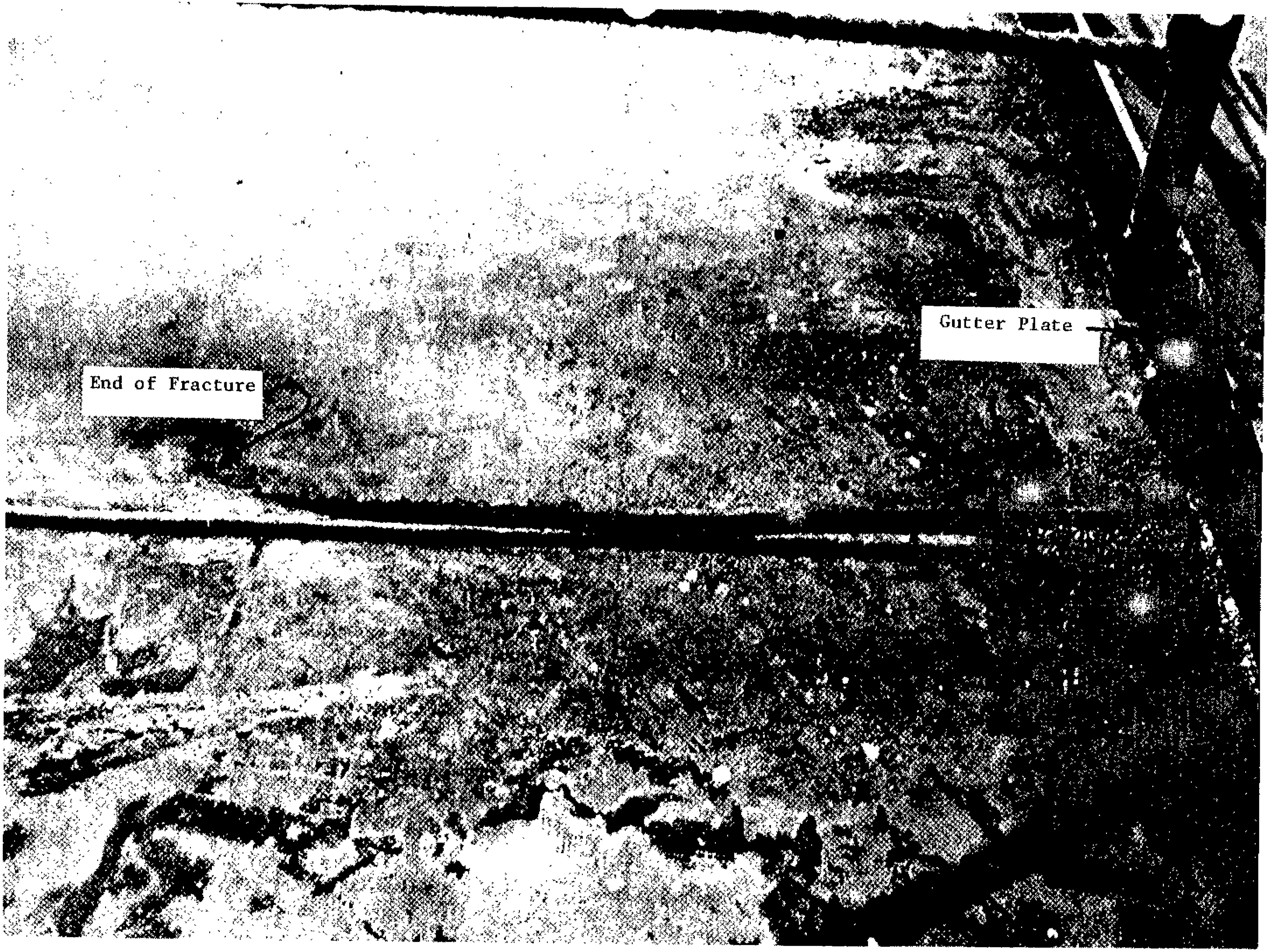


Figure 3-36 Fracture across the deck. Fracture was entirely in the plate with the fracture surface about 45° to the plate surface.

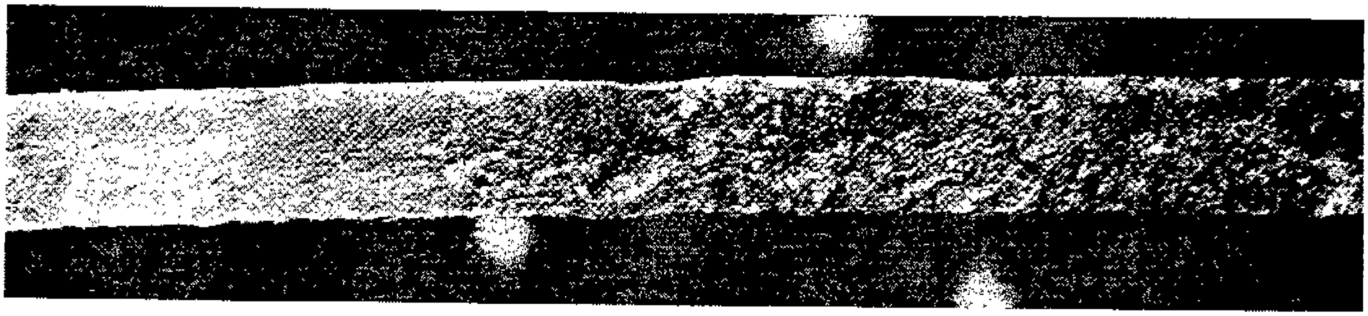


Figure 3-37 Fracture face of deck plate. This is typical of ductile type fracture.

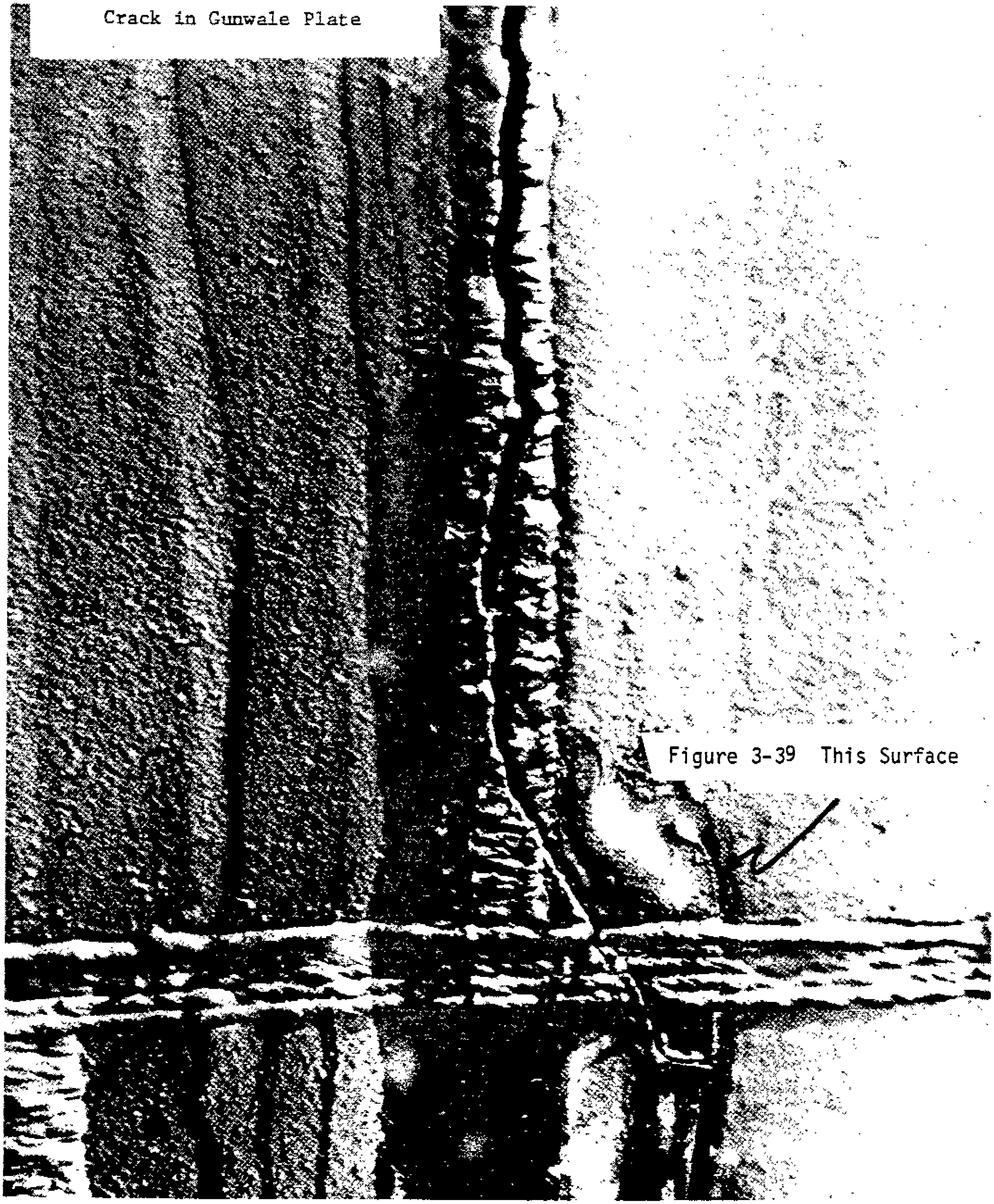


Figure 3-38 - Junction of main side shell fracture with the fracture through the weld of the gunwale plate.

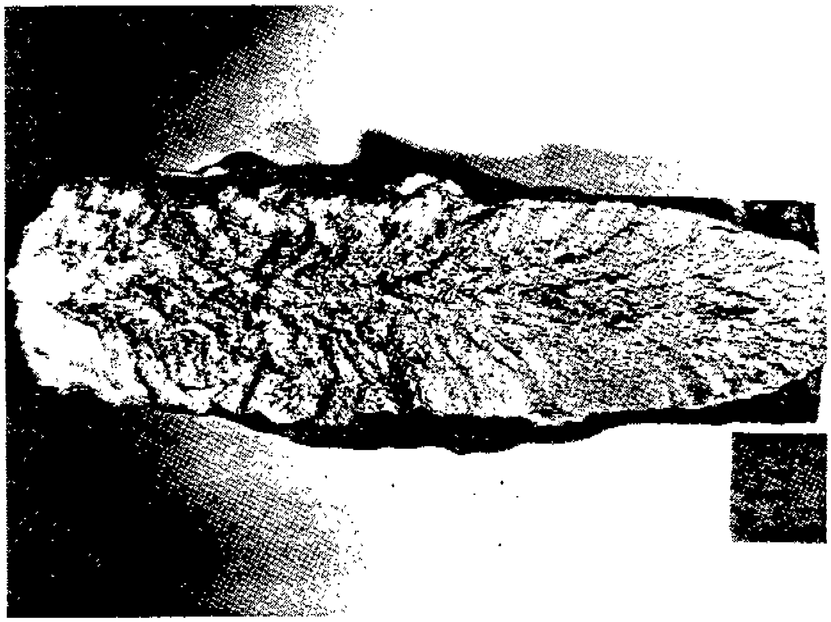


Figure 3-39 Fracture Face at End of Main Shell Fracture, see Figure 3-38. Note Chevron pattern and apparent "necking down" associated with fracture arrest. Specimen 3908, Magn. 1.2X.

graph of the fracture face in this area showing the apparent "necking down" of the brittle fracture surface. No "dimpling" (indicative of ductile fracture) was noted in this area and it is concluded that the fracture stopped when it ran into an area with stress too low for propagation.

An inspection of the internals by the ship owners' representatives near the main side fracture disclosed a definite pattern of brittle fracture in the side shell longitudinals. This pattern is shown in Figure 3-30. There are two sets of fractures in these longitudinals, one associated with the shell fracture and the other in the erection butt welds in the longitudinals. Where the shell fracture is near the fractured longitudinal butt welds it connects to the fractured butt weld through the fillet weld joining the longitudinal to the shell. In some cases, the fracture ran through the web of the longitudinal to join a fractured butt weld. Only at No. 5 longitudinal, the fracture origin, was the shell fracture about in line with a butt weld. In all other cases, the shell fracture was a measurable distance from the longitudinal butt weld.

Below No. 9 Stringer, there was no causal relationship between the fractures in the longitudinals in line with the shell fracture and the longitudinal butt welds fractures. This indicates that the butt welds failed before the shell fracture. This conclusion is based on the fact that once the longitudinals fractured in line with the shell fracture, there would no longer be enough loading on the longitudinals to cause fracture of the butt welds. The sequence of fracture is as follows:

1. The butt welds in the longitudinals failed first.
2. The side shell plating and adjacent longitudinals failed second because the longitudinals were no longer effective.

A detailed examination of the butt weld in No. 5 longitudinal showed that the weld was poorly made. Figure 3-40 is a sketch of how the weld attaching the longitudinals to the shell plate at the butt weld was supposed to be made. The butt welds in the web and face flange of longitudinal No. 5 are shown in Figure 3-41. The soundness of the web weld is good but it is obvious that the root was not back-chipped before back welding. The weld in the flange is extremely poor with effective fusion for less than half the depth. The lines "A", "B" and "C" indicate the angle of joint preparation. These welds obviously were not of the quality desired nor did they conform to the design joint of Figure 3-40.

The fillet weld joining the longitudinals to the shell plate was not made in the correct sequence in addition to being of poor quality. The actual weld detail is shown in Figures 3-32, 3-42, and 3-43. In Figures 3-37 and 3-42 it is obvious that the back welding of the butt weld has been laid on top of the fillet weld. On Figure 3-42 the same can be seen for the V'd side of the butt weld. To illustrate this more clearly a section was taken through line A-B in Figure 3-43. This is shown on Figure 3-44. The grain structure clearly illustrates that the butt weld was made over, and hence after, the fillet weld. Also note the almost total lack of fusion of the fillet welds.The effect of this welding sequence is to promote cracking of the butt weld. By

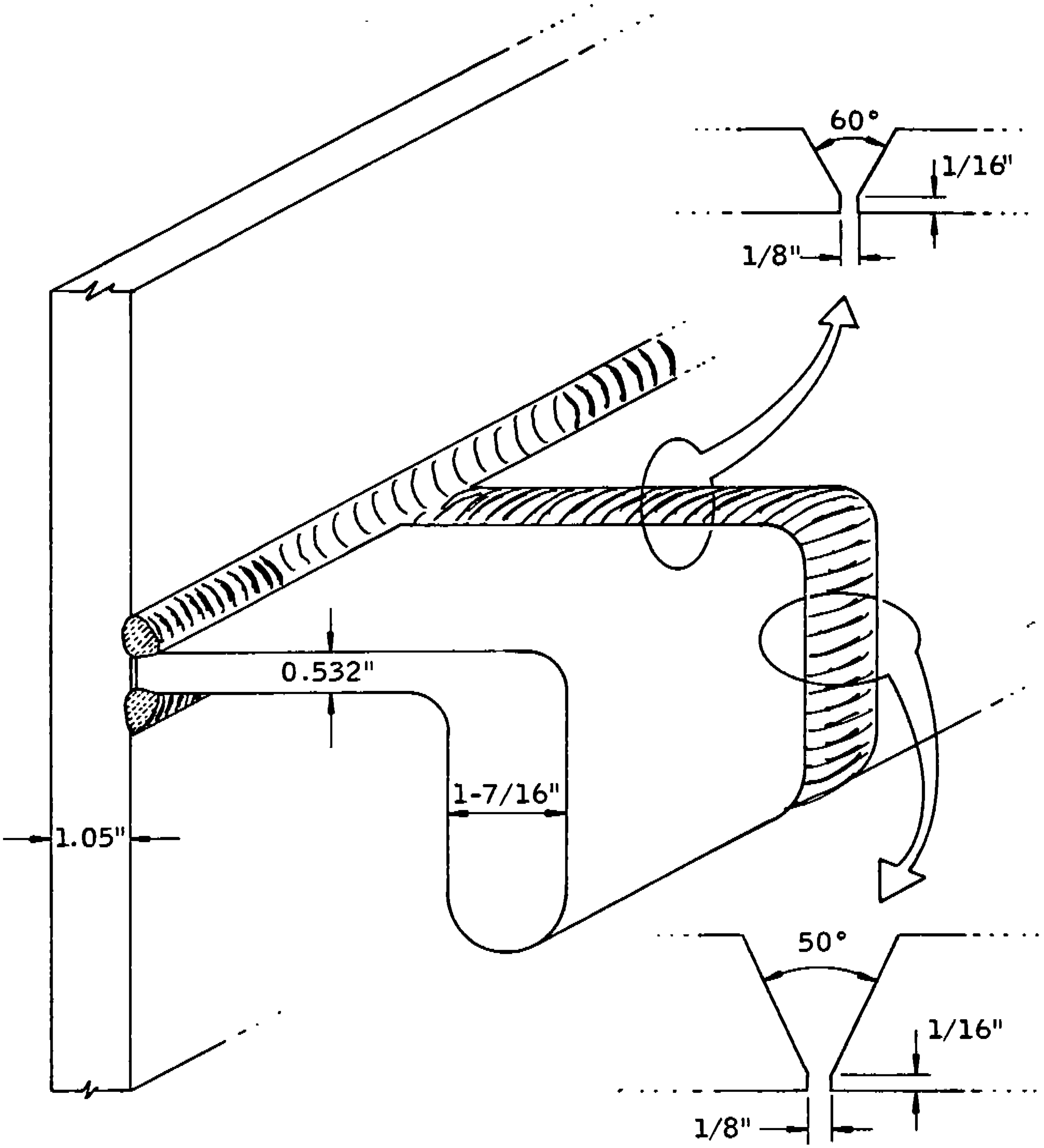
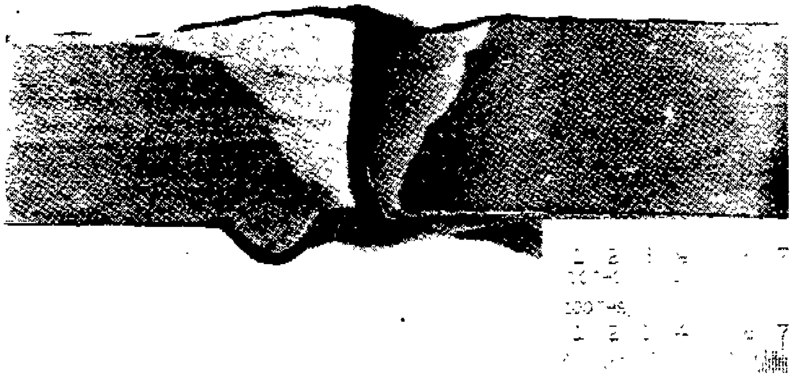
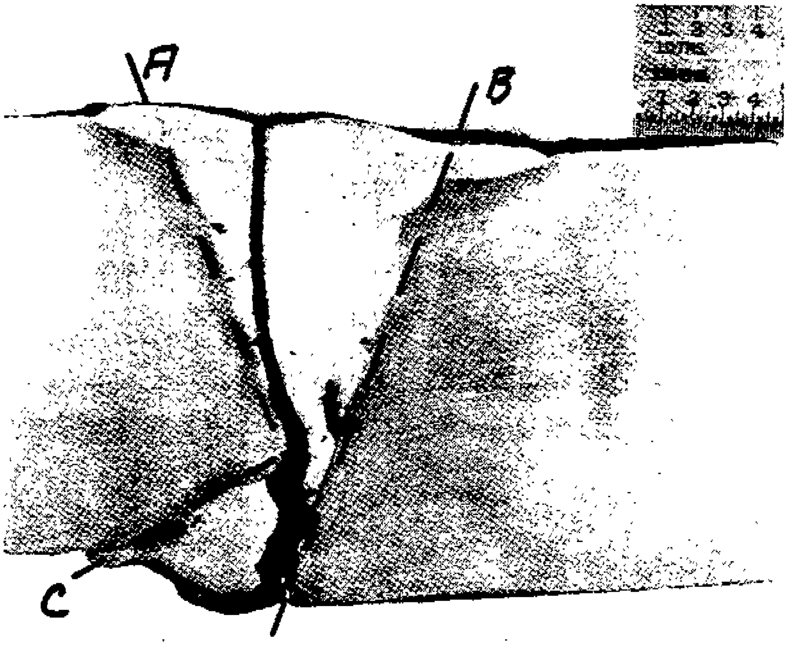


Figure 3-40 Weld details as reported by the builder for butt and fillet welds on the longitudinals. Fillet weld is stopped short of butt. V'd side is welded complete, starting at shell plate and welding around to toe of flange. Opposite side is back-chipped and welded. Fillet weld to the shell is then completed.



Web Butt Weld



Face Flange Butt Weld

Figure 3-41 Cross sections through the butt welds in No. 5 longitudinal. Lines A, B and C indicate edge preparation prior to welding. The small beads were made from the underside or backside. Note wide cover pass. Specimen No. 3908; Etch, 4% Nital; Magn. 1.5x.

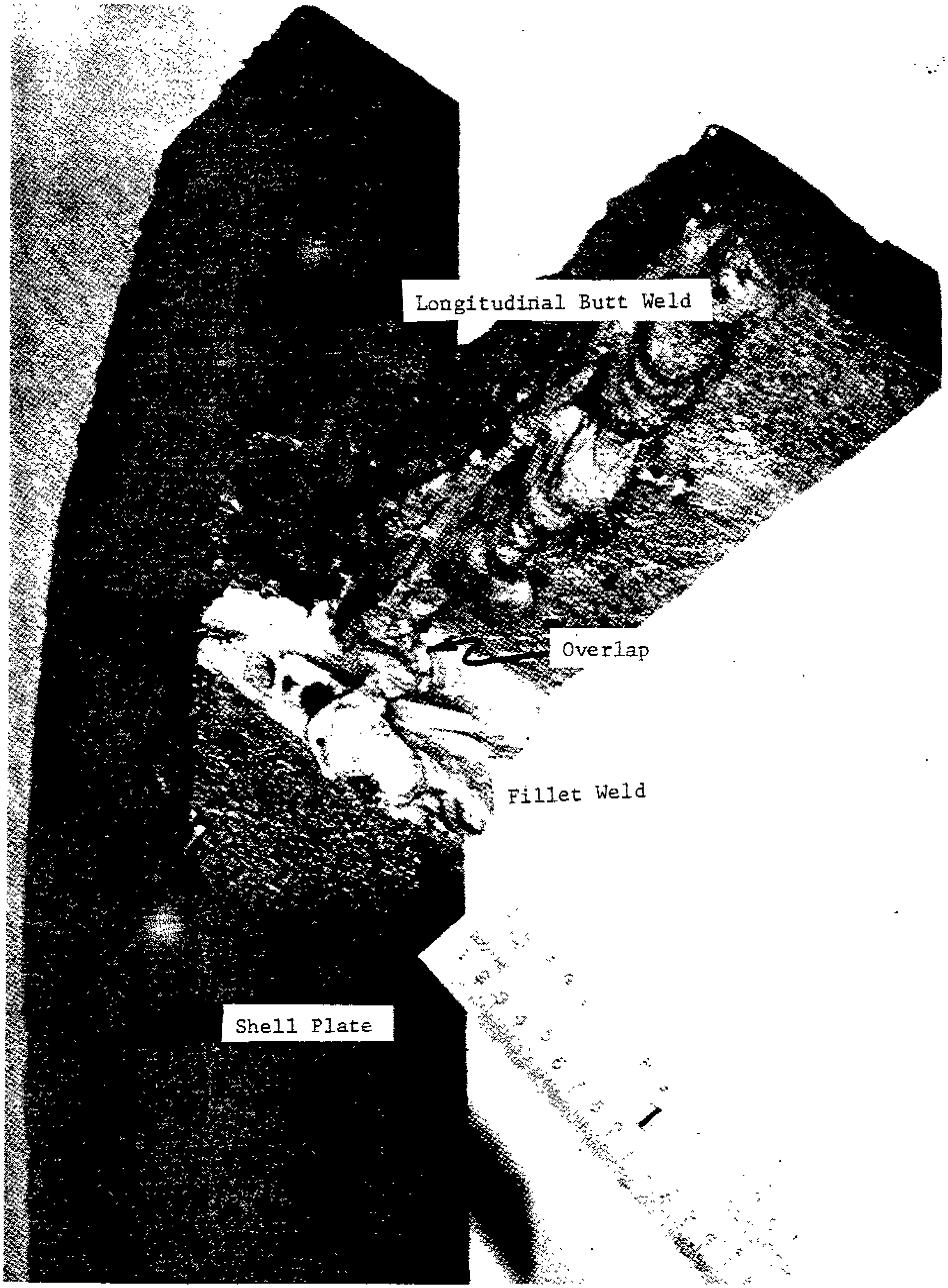


Figure 3-42 Weld joint of longitudinal to shell plate looking at underside of the longitudinal butt weld. Note overlap of butt weld onto fillet weld. Specimen No. 3908; Magn. 1.9x.

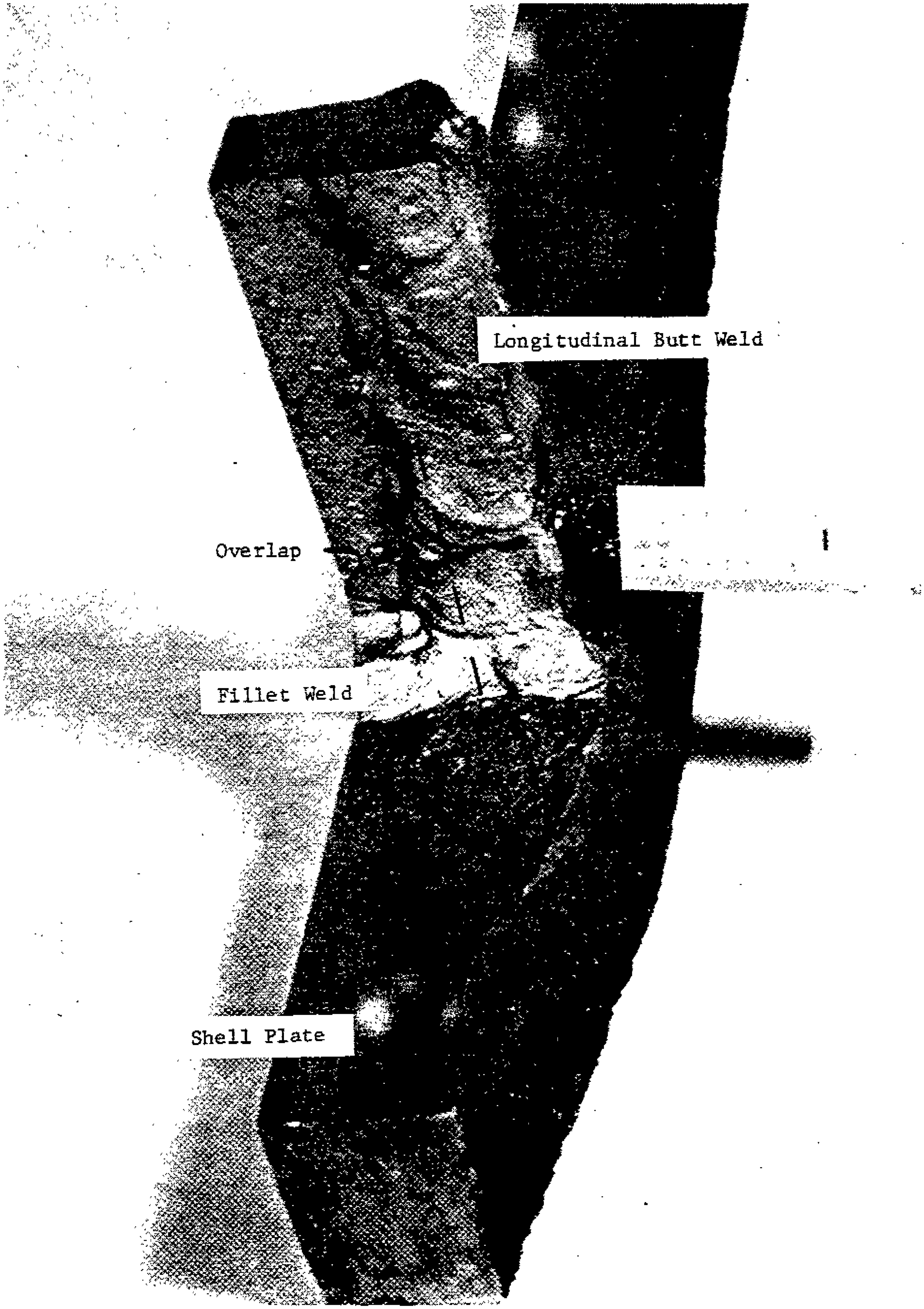


Figure 3-43 Weld Joint of Longitudinal to Shell Plate Looking at Upper Surface of the Longitudinal Butt Weld. Section through line A-B shown in Figure 3-44. Specimen No. 3908; Magn: 1.9X.

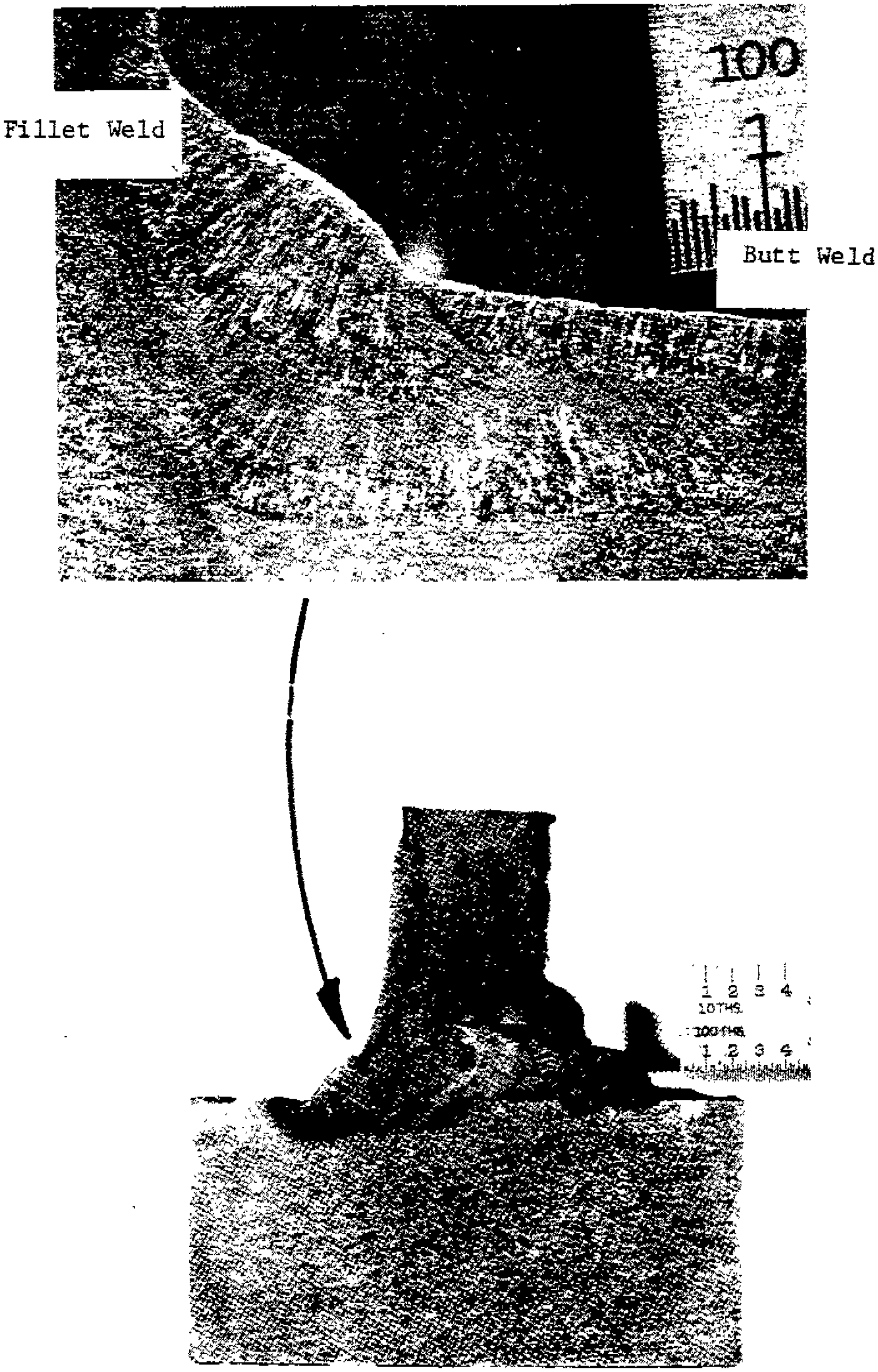


Figure 3-44 Juncture of Fillet and Butt Welds at Line A-B of Figure 3-43. Detail shows that butt weld was made over the fillet weld. Specimen No. 3908; Etch: Ammonium Persulfate; Magn. 1.5x & 5.7x.

attaching the longitudinals to the shell with the fillet weld first, the ability of the longitudinals to absorb the shrinkage stress associated with the butt welding is greatly reduced. This will lead to cracking of the butt weld as has been experiencd frequently in shipyards that use this welding sequence.

The proposed weld joint configuration shown in Figure 3-40 does not compare with the actual flange face weld in Figure 3-41. The actual weld joint appears to combine a double Vee joint with a single Vee joint. Since the builder reports that the weld was a single Vee type, we can assume the weld edge represented by the line "B" was a shop preparation. The line "B" is 25° to a line perpendicular to the plate surface. By measurement line "A" is also found to be 25° to the perpendicular. This suggests that these two plate edges were originally prepared for the 50° bevel specified. Line "C" was subsequently cut and would have the effect of shortening the longitudinals as may be necessary for adjustments in the gap at the erection joint between preassembled sections.

In Figure 3-29 the location of field erection welds delineate an erection unit which included the shell and longitudinals 2 through 15. In Figure 3-30, it can be seen that the butt welds in longitudinals 2 through 15 were fractured. Those in No. 17 and on down the side were intact. This further suggests that trimming of the longitudinals for fit-up of this erection butt is the reason for the unusual joint preparation, subsequent poor weld quality, and the fracture.

The design of the ship included DH_2 and EH_2 Grades of steel in the area of the gunwales shown in Figure 3-29 to arrest a running brittle crack should it initiate in the Grade A steel. The specified properties of these steels are given in Table 3-1. The impact values measured on plate samples from the ship are shown in Table 3-2. With an Charpy-V notch impact energy at the temperature conditions at the time of failure of less than 14 ft-lbs it could not be expected that the Grade A plate could stop a brittle fracture. A full mechanical and chemical analysis of the Grade A plate sample showed it was within the classification society specification.

As shown in Table 3-2, the limited sample of Grade EH_2 steel and its weld did not actually meet the minimum impact energy requirement of the specification. Since each plate of Grade EH_2 steel is tested prior to use, these low values are surprising. However, the Grade EH_2 plate did demonstrate sufficient toughness to contribute to the arrest of the fracture.

Factors Contributed to the Fracture Initiation:

The factors necessary to trigger and maintain the brittle fracture were the result of weld failures on the side shell longitudinals combined with the heavy sea conditions experienced in the storm. Examination of butt welds disclosed poor joint preparation which resulted in incomplete fusion and incorrect welding sequence resulting in high locked-in residual stresses. It is believed that approximately fifteen such welds (one erection panel) had failed sometime prior to the shell fracture. This transferred additional stress into the shell plating. Furthermore, stiffness was lost, allowing a heavy sea to flex the shell plating. Thus the necessary prerequisites to trigger a running brittle fracture were present:

TABLE 3-1
TANKER (250,000 DWT)
SPECIFICATIONS OF MATERIALS*

Grade	A	DH_2	EH_2
Analysis (%)			
Carbon	N.S.	0.18% max.	0.18% max.
Manganese	Min. 2.5 x C	1.40% max.	1.40% max.
Silicon	N.S.	0.50% max.	0.50% max.
Sulfur	0.05 max.	0.05% max.	0.05% max.
Phosphorous	0.05 max.	0.05% max.	0.05% max.
Niobium	--	0.10% max.	0.10% max.

For DH_2 & EH_2
Carbon equivalent ... $C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} = 0.41\%$ max.

Grade	A	DH_2	EH_2
Tensile Strength	58-70 K psi	71-88 K psi	71-88 K psi
Yield Strength	N.S.	50 K psi min.	50 K psi min.
Elongation (%) in 8 in.	21%	20%	20%
Impact Test	N.S.	40 ft-lbs @ 32°F	51 ft-lbs @ 14°F
Bend Test	180°	20%	20%
Heat Treatment	N.S.	Normalized	Normalized
Deoxidation	N.S.	Killed, fine grain practice	Killed, fine grain practice

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N.S. = Not Specified

* December 1, 1967

TABLE 3-2
TANKER (250,000 DWT)
IMPACT TEST* RESULTS FROM PLATE SAMPLES

Sample Location	Temperature °F				
	14° ft-lbs	32° ft-lbs	40° ft-lbs	50° ft-lbs	75° ft-lbs
Grade A Specification = None					
By Long. #5	-	10-10- 9	8-10-13	13-15-19	28-31-37
By R-S Strake Weld (1)			12-11- 9	9-14-13	
(2)			5- 7- 9	12- 9- 8	
Grade DH_2 Specification		40			
Strake 5		57-50-41	44-52-49	62-53-52	73-71-74
Strake J (Deck Plate)		59-60-65			
Grade EH_2 Specification	50				
Gunwale Forward of Fracture	52-47				
Gunwale Aft of Fracture	92-46				
Welds					
EH_2 Gunwale Plate Weld	43				
R-S Strake Weld			31-33	59-72	

* Charpy Vee notch per ASTM E23

(1) See Figure 3-31 for location of strakes.

(2) Notch located through thickness of plate. All others with notch in direction of fracture propagation.

- A stress concentration such as the defect in the weld of No. 5 longitudinal
- A source of stress or impact loading - the impact of the heavy sea on the insufficiently stiffened shell plate.
- The fracture of the longitudinal stiffeners, which also transferred additional stress to the shell plating.
- A low toughness plate - the grade A steel had 10 ft-lbs Charpy V-notch at failure temperature.

Factors Contributing to the Fracture Arrest

Because the loading that produced the fracture was a local load, the fracture propogated into an area of lower stress and into plating of increased material toughness. The fracture switched from brittle to ductile and arrested in 1" DH plating.

3.8 TANKER (70,000 DWT) BOTTOM CRACKING

Description of Vessel:

During January of 1985 a fracture was discovered in the bottom of a tanker.* The tanker was a 70,000 DWT products carrier with a new forebody built in 1981. The particulars of the vessel are:

Length overall:	810 ft
Beam (molded):	105 ft
Depth:	57 ft
Draft:	65.5 ft
Deadweight:	70,000 LT
Year built:	1981.

Circumstances at the Time of Fracture:

The fracture was discovered while loading oil in Valdez, Alaska where oil was noticed leaking up from the bottom of the starboard side. A diver sent to investigate the leakage found a crack in a bleeder/docking plug insert plate in #3 starboard wing tank. The crack extended from the plug to the outside circumference weld of the insert plate and did not extend into the bottom plating. At a subsequent drydocking, the details associated with the fracture were examined.

Description of Fracture:

The fracture was examined by the project investigators. The bleeder/docking plug is used for draining tank liquids in dry dock. There are usually one or two plugs per tank. These plugs are often located in insert plates as shown in Figure 3-45. These insert plates are thicker than the base shell plate to receive a threaded plug, and are often grooved to facilitate drainage. The

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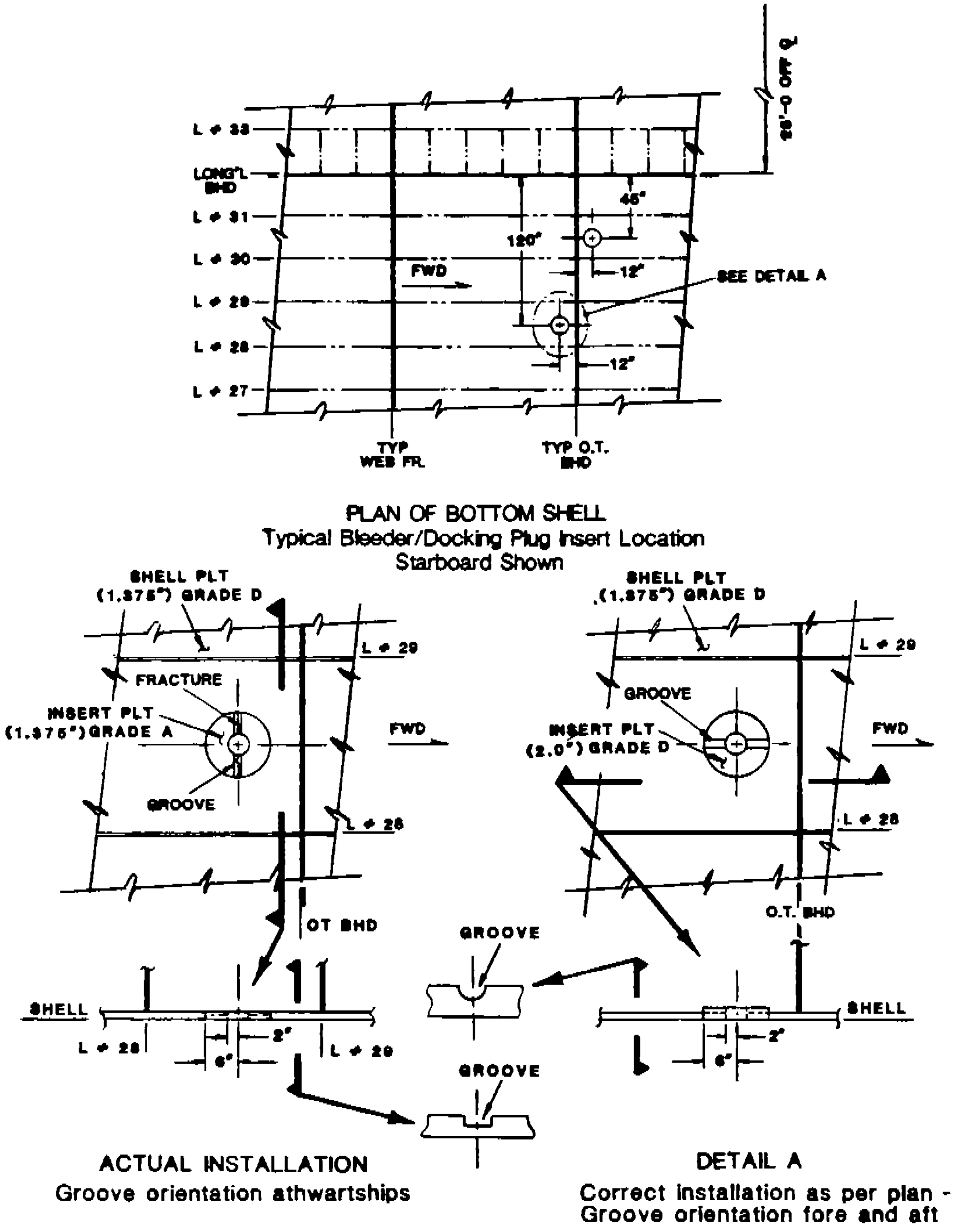
* The source of information is not identified due to proprietary considerations.



PLAN OF BOTTOM SHELL
Typical Bleeder/Docking Plug Insert Location
Starboard Shown

ACTUAL INSTALLATION
Groove orientation athwartships

DETAIL A
Correct installation as per plan - Groove orientation fore and aft

Figure 3-45 Structural Detail of the Docking Plug on the 70,000 DWT Tanker plans for the new forebody note that the groove should run fore and aft. The grooves in the insert plates examined on the ship were installed athwartship as shown in Figure 3-45. This tanker had two plugs per tank, all of which had grooves running athwartship. In all, four insert plates were fractured at these grooves.

This orientation put the drain groove perpendicular to the direction of primary hull girder stress, making it susceptible to fatigue cracking in normal service. The correct installation shown on the ship plans would put the bleeder plug insert plate drain in the fore and aft orientation. The type of steel used for the insert plate is Grade A. The bottom shell was 1-3/8" Grade D steel.

Analysis of the Fracture

Fracture samples were removed from the ship and examined in the laboratory at Lehigh University. To examine the fracture surface of the bleeder plug insert crack, the sample was loaded in a universal testing machine and the unbroken portion of the insert plate was fractured. The resulting fracture surfaces are shown in Figure 3-46 and 3-47.

The surfaces of the fractured pieces, while showing considerable corrosion, indicate failure by fatigue. The surface closest to the unfractured area broken open in the laboratory, seen in Figures 3-46 and 3-47, has much less corrosion, and has the smooth surface and "clam shell" markings characteristic of fatigue fracture. The same markings are seen on other parts of the fracture but not as clearly. The surface markings clearly show that the cracking started at the bottom of the groove next to the threaded plug hole and proceeded in both directions away from the hole and toward the edges of the insert plate. There is no evidence of brittle fracture or ductile tearing on the surfaces.

The groove in the insert plate is square and there appears to be a second fatigue crack starting from the other side of the groove at the threaded hole. This crack apparently terminated when the first crack became larger and continued to grow.

Factors Contributing to Fracture Initiation:

The cracking in the insert plate was caused by fatigue, starting where the square drain groove intersected with the threaded drain plug hole in the plate. The fatigue cracking was initiated by a high stress concentration resulting from improper orientation of the square cut drain groove in the insert plate.

Our investigation found:

- The plates were made of Grade A rather than Grade D steel as called for in the plans
- The insert plates were of equal thickness to the shall plating rather than twice the thickness
- The channel cut to facilitate drainage of the tank was cut in the reduced thickness plate, thereby locally reducing the shell thickness below acceptable tolerances

Figure 3-46 Fracture surface half, groove at top. Laboratory fracture at lower right, threads at left. Note clam shell marks at arrow.

Figure 3-47 Fracture surface half, groove at top. Threads at right. Note clam shell marks at arrow (not as evident in this picture as in Figure 3-46).

- The drain channel was cut with sharp, square rather than rounded corners as shown in the plans
- The channels were oriented arthwartship rather than fore and aft as shown in the plans.

Factors Contributing to Fracture Arrest:

The cargo oil leaked through the fatigue fracture. The crew saw oil on the water surface and subsequently the cracks were found by a diver. The cracks were detected and repaired before they reached the critical size needed to initiate a brittle fracture.

3.9 CONTAINERSHIP TRANSVERSE BULKHEAD CRACKING

Description of Vessel:

A fracture occurred in a containership* that operates in the North Pacific between the West Coast of the United States and the Orient. The particulars of the ship are:

Length between perpendiculars:	810.0 ft.
Breadth:	105.75 ft.
Depth:	66.0 ft.
Draft:	17.75 ft.
Deadweight:	29,963 LT
Design Speed:	24 knots
Year Built:	1982.

Description of Circumstances:

The cracking occurred over a period of time starting approximately two years after the ship began service. This fracture was examined on site during December of 1985 by the project investigators.

Description of the Fracture:

The crack is located in a transverse bulkhead where the longitudinal box girder intersects a transverse bulkhead. The transverse bulkhead is located at frame 65, 150 feet aft of the forward perpendicular. The crack is located on the port side of the ship in close proximity to the hatch corner cutout. The crack and local ship structure are shown in Figures 3-48, 3-49 and 3-50. The crack originated from a weld at the intersection of a lower sealing box, a transverse bulkhead and a longitudinal bulkhead of the box girder. The bulkhead is five-sixteenth of an inch thick and is attached to a longitudinal bulkhead that is one-half of an inch thick and heavily reinforced by longitudinals and deck structure.

The cracked bulkhead material is DH-36. The upper deck portion of the box girder is EH-36 and the longitudinals under the deck are AH-36.

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* The source of information is not identified due to proprietary considerations.

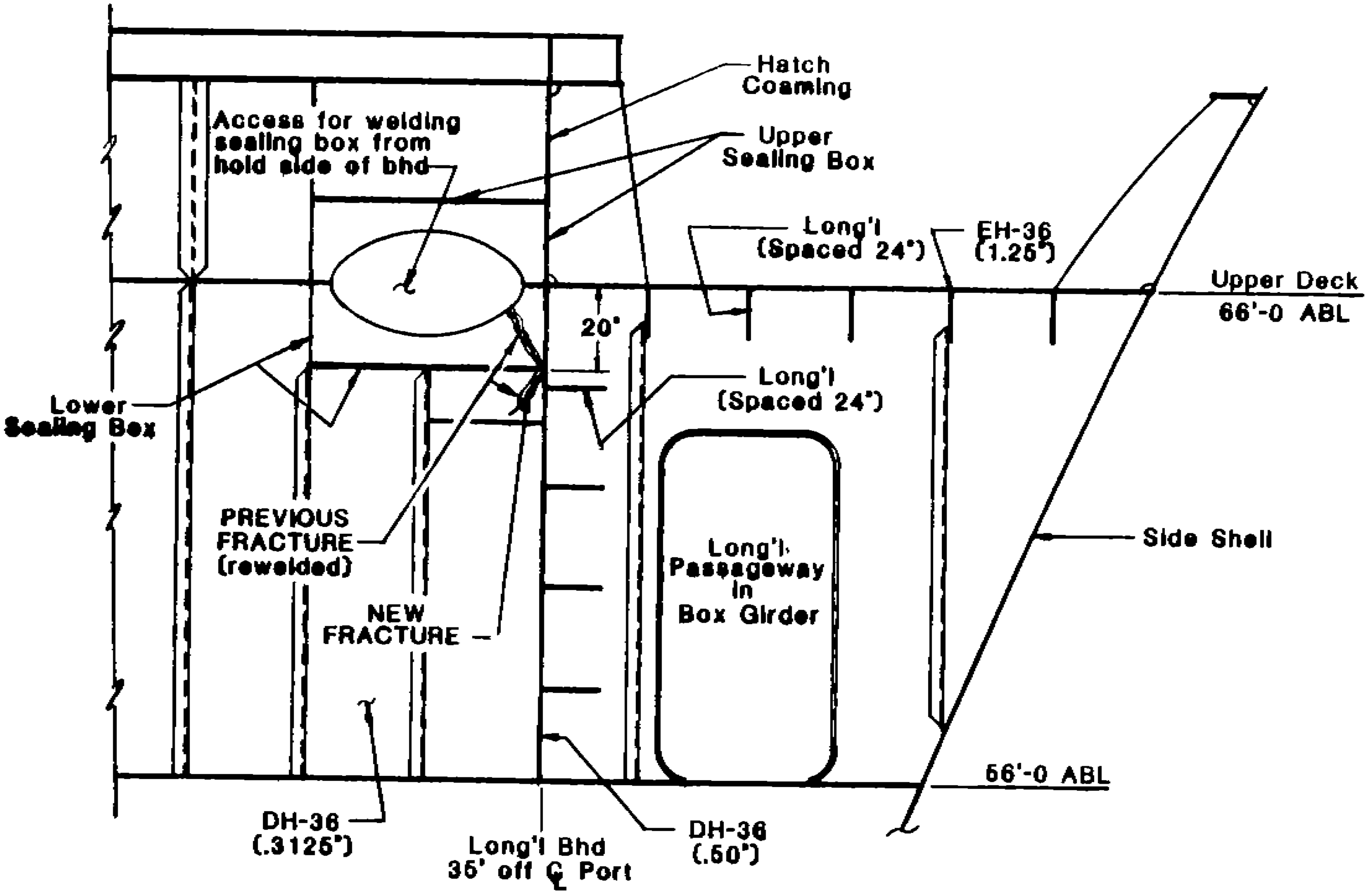

Figure 3-48 Fractured Transverse Bulkhead of a Containership

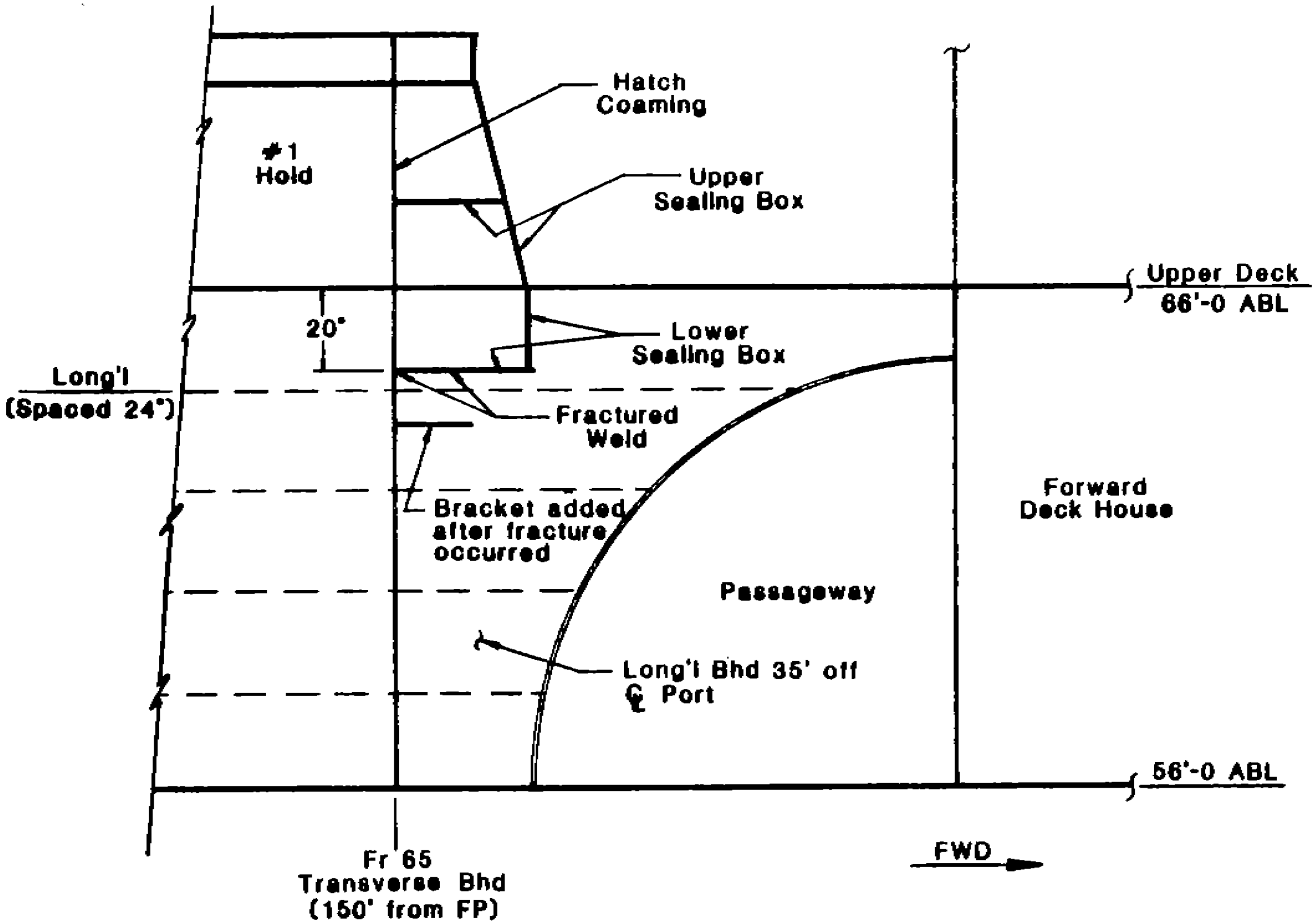

Figure 3-49 Longitudinal Bulkhead of the Containership With a Fractured Transverse Bulkhead

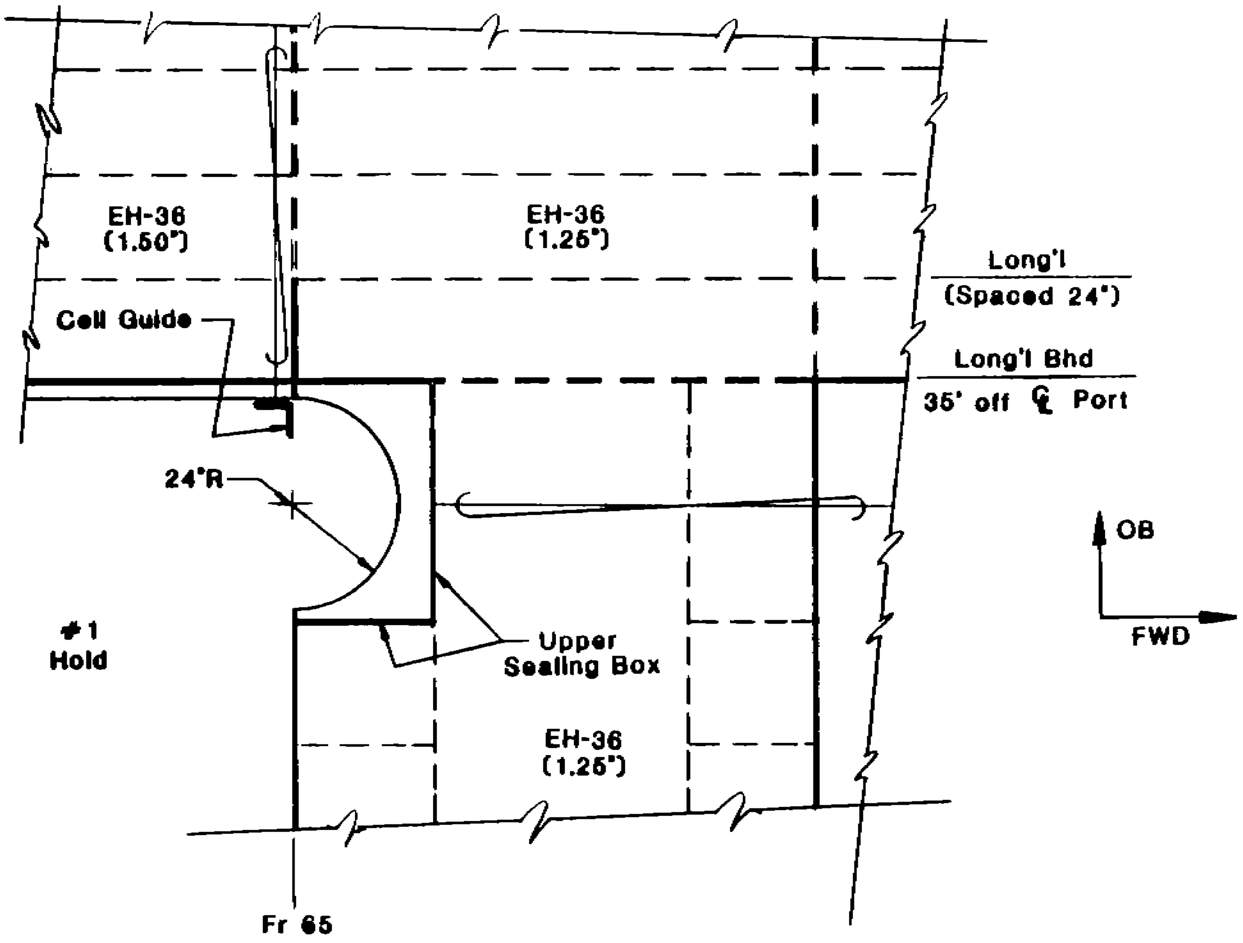

Figure 3-50 Hatch Cut-out of the Containership With a Fractured Transverse Bulkhead

Analysis of the Fracture

The crack was examined visually by the project investigators. The crack was closed and the surface was not visible. A ship operator's representative conducted dye penetrant tests to determine the length of the crack and to see if the crack extended beyond the visible crack tip; it did not. The crack was approximately 20" long and extended in two opposing directions (as shown in Figure 3-48) from the point of origin.

Factors Contributing To Fracture Initiation

The project investigators believe the area of the ship that fractured is a highly stressed area. The stress is caused by torsional hull girder loading in oblique seas. The structure and details at the location of the crack were not designed in a manner that distributes the stresses, and in fact produces areas of stress concentration in the vicinity of the hatch cutout sealing box. Because structural continuity is not maintained at the lower sealing box, the crack propagated from a weld into adjacent structure. This crack is probably due to fatigue.

Factors Contributing to Fracture Arrest

The crack was not repaired at the time of inspection and will continue to propagate via fatigue. The fatigue propagation is being monitored by the ship's operators, regulatory body inspectors and government inspectors. The crack is to be repaired during the ship's next scheduled drydocking. Other structural modifications are planned at that time.

3.10 CONTAINERSHIP BOW FLARE FRACTURE

Description of the Vessel

A fracture occurred in a containership [3-9] that was a first-generation containership launched in 1968, which was drydocked and modified in 1969 to increase its container capacity from 600 TEU to 819 TEU. During this drydocking, web frames 151a and 156a were installed in the bow flare area where previous bow flare damage had occurred. Cracking continued at frame 151a and lead to additional reinforcement during 1975. The structural modifications to frame 151a are shown in Figure 3-51. The principal characteristics are as follows:

Length between perpendiculars:	175.04 m	(574.1 ft)
Beam:	25.20 m	(81.9 ft)
Depth:	15.30 m	(50.2 ft)
Draft Full:	10.024 m	(32.9 ft)
Dead Weight:	16,796 tons	
Speed:	26.03 kts.	

A body plan of the containership is shown in Figure 3-52.

Description of Circumstances at the time of Fracture

On January 17, 1978 the containership departed from the Port of Oakland, California bound for Kobe, Japan, sailing westward at approximately 33°N latitude. The ship was loaded with 769 TEU of containers (9,221.8 tons). On January 24, the ship encountered a storm where significant wave heights were

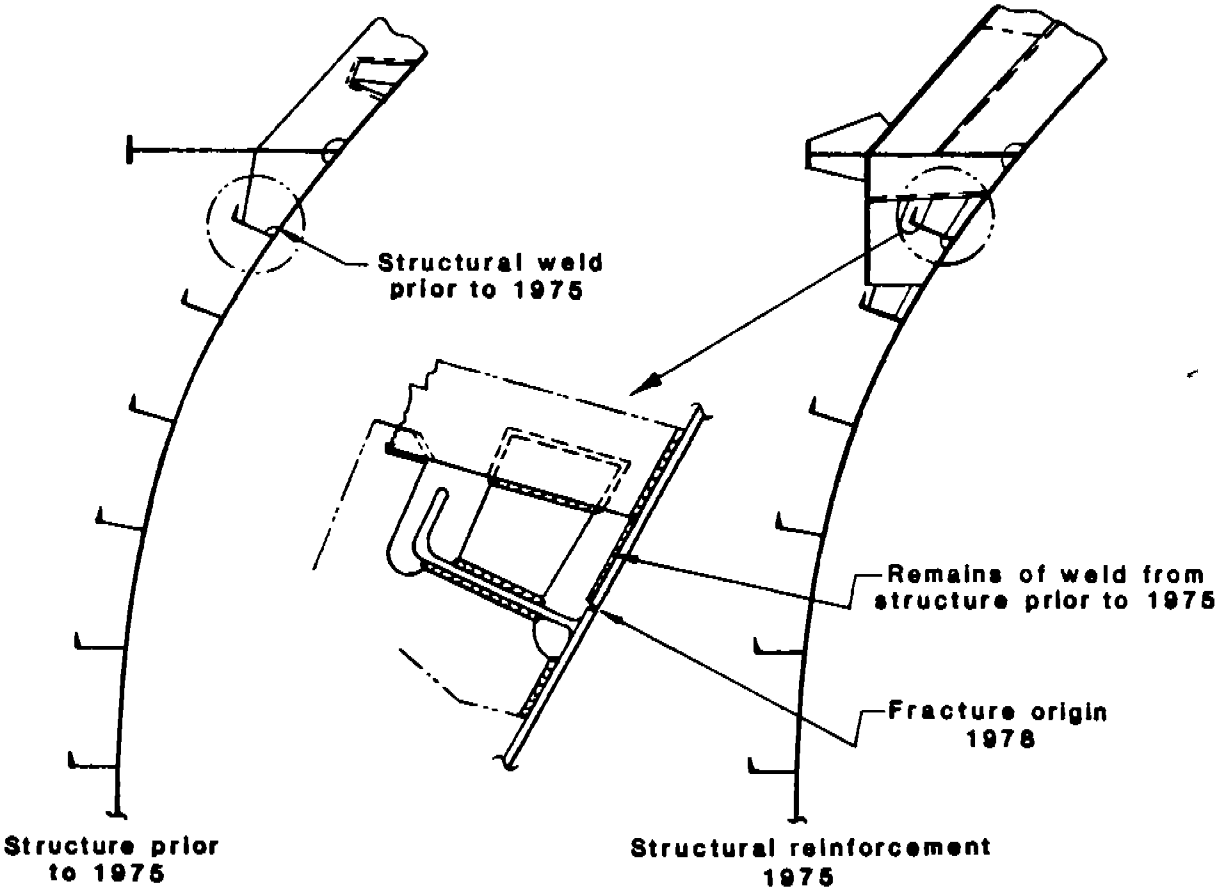

Figure 3-51 Structural Detail Associated With the Containership Bow Flare Fracture

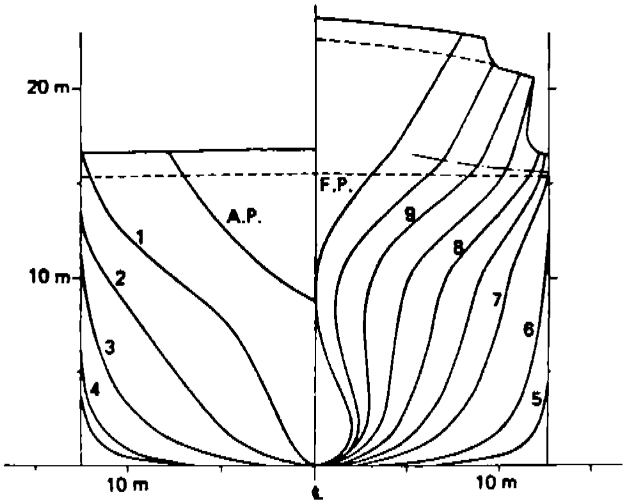

Figure 3-52 Body Plan of Containership

reported in excess of 9 m. As the storm front passed, the winds shifted from SW to NW and waves were encountered from the SW and NW, which resulted in confused seas. Waves were reported in excess of 20m. The crew reduced the ship speed to 7 knots and later increased the speed to 9 knots because the rudder steering gear malfunctioned. The ship experienced violent rolling and pitching motions in the confused seas. The fracture occurred when the ship encountered large waves, approximately three hours after the storm passed and the atmospheric pressure in the location of the ship had begun to rise. Following the storm. it was discovered that cargo-hold Number 1 and the forepeak tank contained sea water and the crew observed a fracture in the starboard side shell at the bow. Severe buckling of the deck and port side shell was also observed.

Description of the Fracture:

The fracture occurred in the starboard bow flare region just above the waterline. The fracture was approximately 10 m in length and is shown on the side shell expansion in Figure 3-53. Figures 3-53 and 3-54 show the observed buckling damage that also resulted from the storm. The fracture surface was examined and chevron markings observed, as shown in Figure 3-55, pointing to a fabrication flaw on a structural detail at frame 151a. The structural detail at the origin is shown in Figure 3-51.

Analysis Conducted:

Those investigating the fractures performed extensive analysis, including predicting seaway loads encountered by the ship in the observed wave conditions and fractographic analysis of the fracture origin.

Bow impact velocities were predicted by a computer program called TSLAM for the wave heights observed during the storm. The impact velocities were determined with respect to the center of the bow flare at frame 151a as shown in Figure 3-51. The mean pressure, Pm, in the side shell was estimated using Von Karman's formula:

$$Pm = \frac{1}{2} \rho \, V^2_\pi \, \mathrm{Cot}\, \beta$$

Where: ρ = density of seawater
V = impact velosity
β = impact angle.

Hoop stresses were derived from these pressures using a finite element computer model of the forebody structure. A plastic model was constructed of the bow and tested to verify the finite element analysis of the stress caused by the bow flare pressure. Results of the analysis indicated that the yield stress was exceeded in the shell plating for wave lengths less than 175m and wave headings (relative for the ship heading) of 22.5°.

Fractographic analysis showed a ring-like pattern, shown in Figure 3-56, at the assumed crack initiation point. This point is located 1.5mm below the plate surfaces in the proximity of a structural weld. The pattern is indicative of microstriations, cyclic growth of a circular shaped crack, caused by fatigue loading.

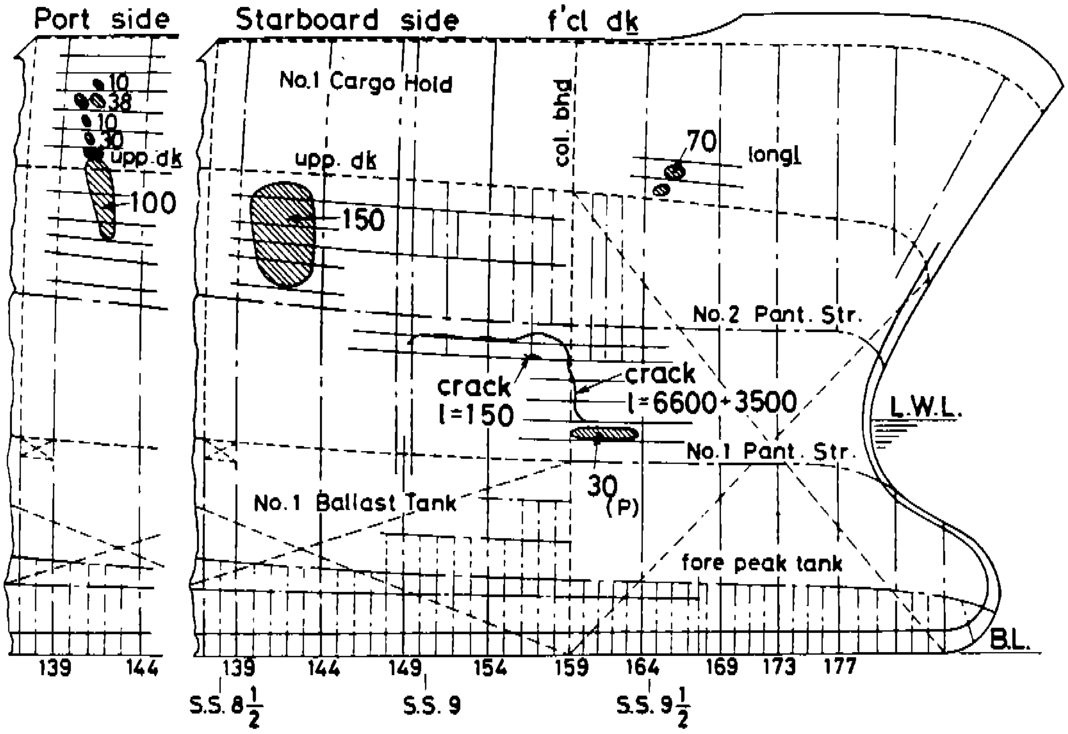

Figure 3-53 Shell Expansion and Fracture Location in the Containership Flare

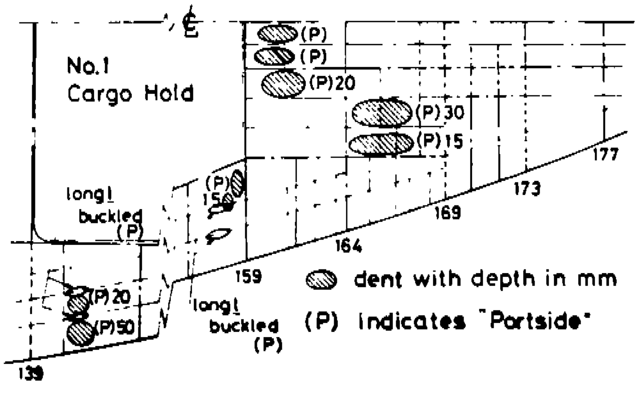

Figure 3-54 Deck Buckling in the Deck of the Containership Bow

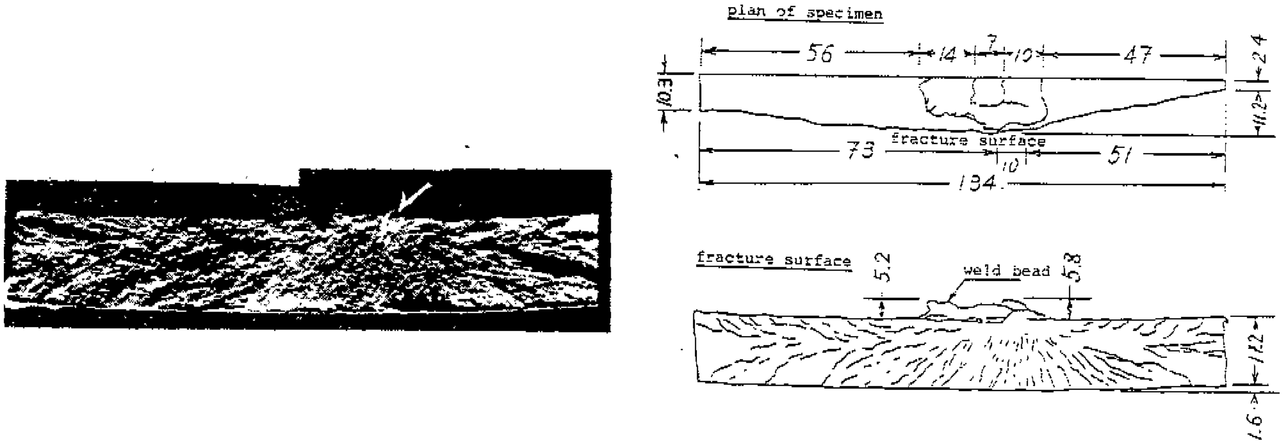

Figure 3-55 Location of the Fracture Origin of the Containership Bow Flare Fracture

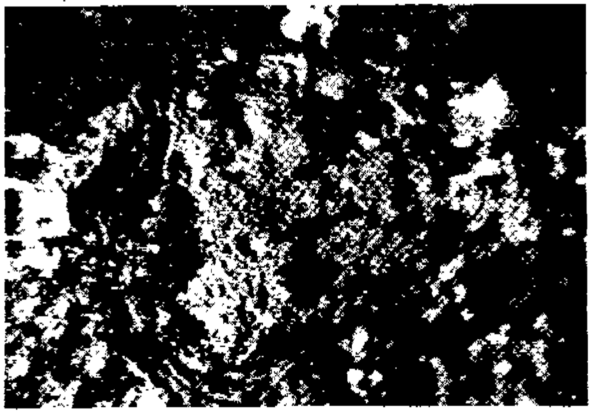

Figure 3-56 Ring Pattern at the Origin of the Fracture in the Containership Bow Flare

Factors Contributing to Fracture Initiation:

Severe wave impact loading initiated the fracture at a structural detail near a discontinuous transverse frame. This detail was the site of previous cracking and repairs which contributed to the initiation of the fracture.

Factors Contributing to Fracture Arrest:

The fracture occurred in an area of high local load but of very low global load; therefore, complete hull girder failure was not possible. The fracture propagated into areas of lower stress intensity and arrested.

3.11 TANKER (JUMBOIZED T-2) MAIN DECK FRACTURE

Description of the Vessel

The vessel is a T-2 tanker* built in 1943 and jumboized in 1961. The particulars of the vessel are:

Length:	575.0 ft
Beam:	68.0 ft
Depth:	39.75 ft
Draft:	11.67 ft.

Description of Circumstances at the Time of Fracture:

The fracture occurred February 1975. The tanker was dockside discharging cargo at the time the fracture occurred. The vessel had 9900 gallons of gasoline in Number #2 center tank and 9000 gallons of water in Number #8 center tank. The air temperature was 30°F and the water temperature was 36°F. The draft readings immediately before the fracture occurred were: 5'-8" fwd and 17'-8" aft. The tanker was discharging its cargo after its first voyage after drydocking. During drydocking, repairs were made to internal structure during which time a slot approximately 1 ft x 20 ft was cut in the deck to allow passage of materials.

Description of the Fracture:

The fracture was located between frame 62 and a transverse bulkhead as shown in Figure 3-57. The transverse structure is shown on Figure 3-58. The fracture was inspected visually. Chevron marks were observed and photographed pointing to the fracture origin. The fracture originated at a butt weld where the 1 ft x 20 ft access plate was reinstalled. The path of the fracture is shown by Figure 3-56. The entire fracture was approximately 19.6 ft long. The fracture ran inboard and terminated at at a kingpost and outboard where it terminated at the longitudinal butt weld of the access plate. The fracture reinitiated at a butt weld and arrested at a rivet hole, in the crack arrester seam, outboard of the longitudinal bulkhead.

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* The source of information is not identified due to proprietary considerations.

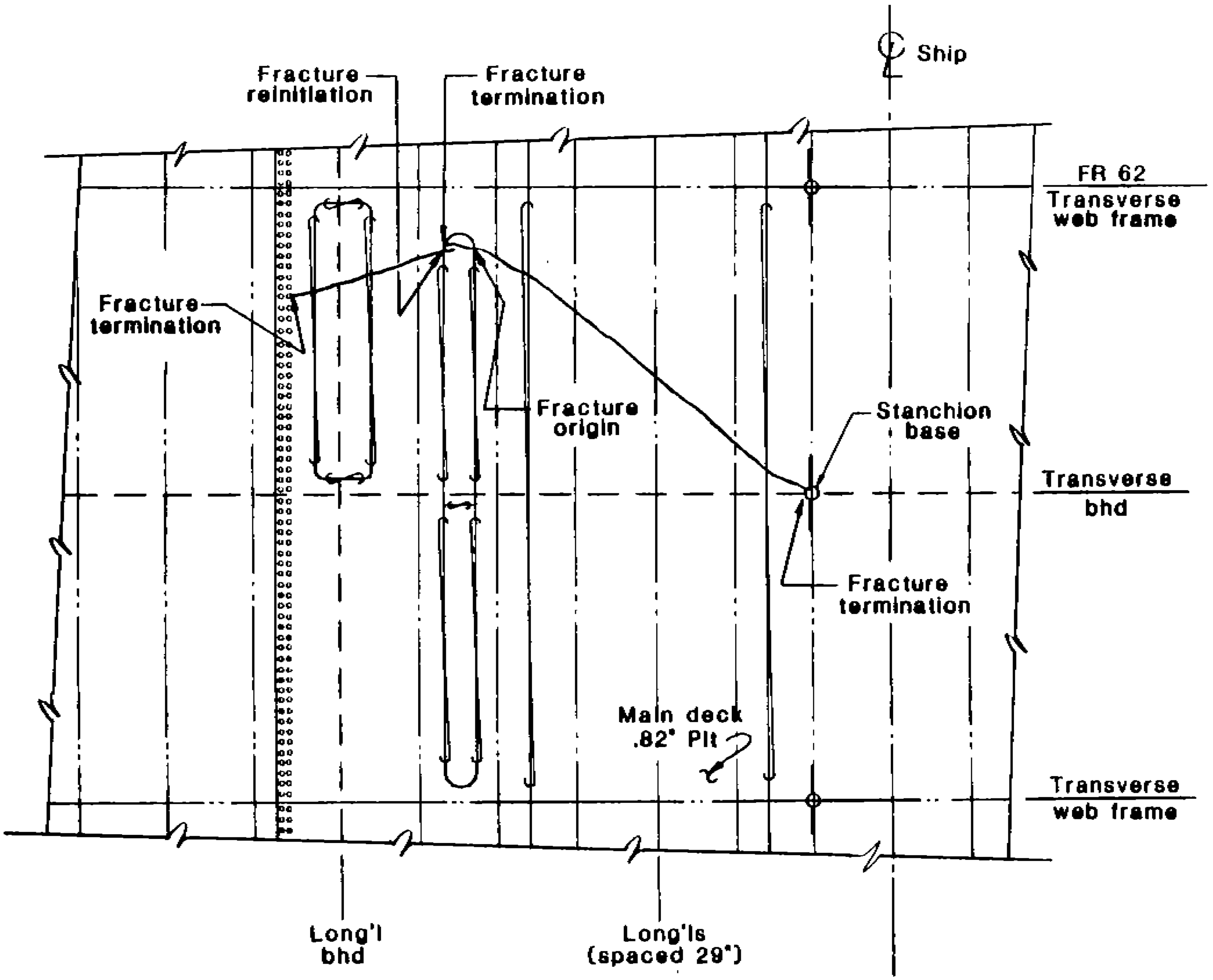

Figure 3-57 Fracture in the Deck of the Jumboized T-2 Tanker

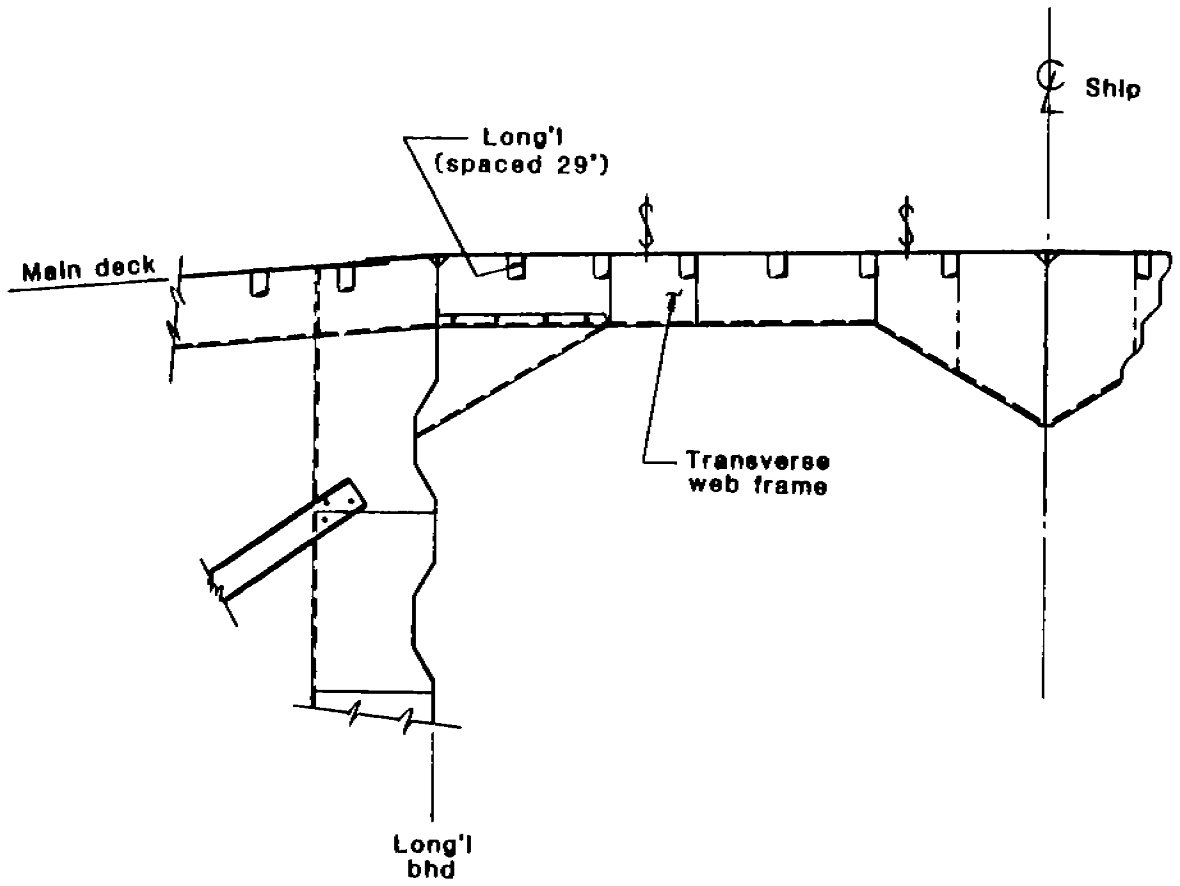

Figure 3-58 Structural Section of the Jumboized T-2 Tanker

Factors Contributing in Fracture Initiation:

The fracture initiated at a repair weld. The project investigators suspect that an internal flaw in the weld was the cause of the fracture.

Fractors Contributing to the Fracture Arrest:

The ship was built using riveted crack arresting seams and one of these seams did arrest the fracture.

3.12 TANKER (170,000 DWT) TRANSVERSE BULKHEAD CRACKS

Description of the Vessel:

A Fracture occurred in a tanker* that operates in the oil trade between Alaska and the U.S. West Coast. The particulars of the vessel are:

Length between perpendiculars:	906.0 ft
Beam	173.0 ft
Depth	75.0 ft
Draft	57.3 ft.
Dead Weight	170,000 DWT
Year Built	1977

Description of Circumstances at the Time of Fracture

A shean of oil was noticed in December, 1975 by the ship's engineer during discharge of ballast from the starboard segregated ballast tank. The oil leaked through a fracture from an adjacent oily waste tank. No other circumstances at the time of fracture are known. The fracture was examined on site by the project investigators.

Description of the Fracture:

The fracture is located in a transverse bulkhead at Frame 69. The bulkhead separates a segregated ballast tank from an oily waste tank. The fracture runs parallel to a weld connecting a vertical stiffener to the bulkhead on the ballast tank side. The bulkhead, surrounding structure, and approximate location of the fracture are illustrated in Figures 3-59 and 3-60. The bulkhead is 3/8" AH-36 steel.

The fracture originated at the heat affected zone adjacent to the weld between the bulkhead stiffener and bulkhead plate.

Analysis Conducted:

The fracture surface was examined at Lehigh University and is characteristic of fatigue cracking, as shown in Figure 3-61.

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* The source of information is not identified due to proprietary considerations.

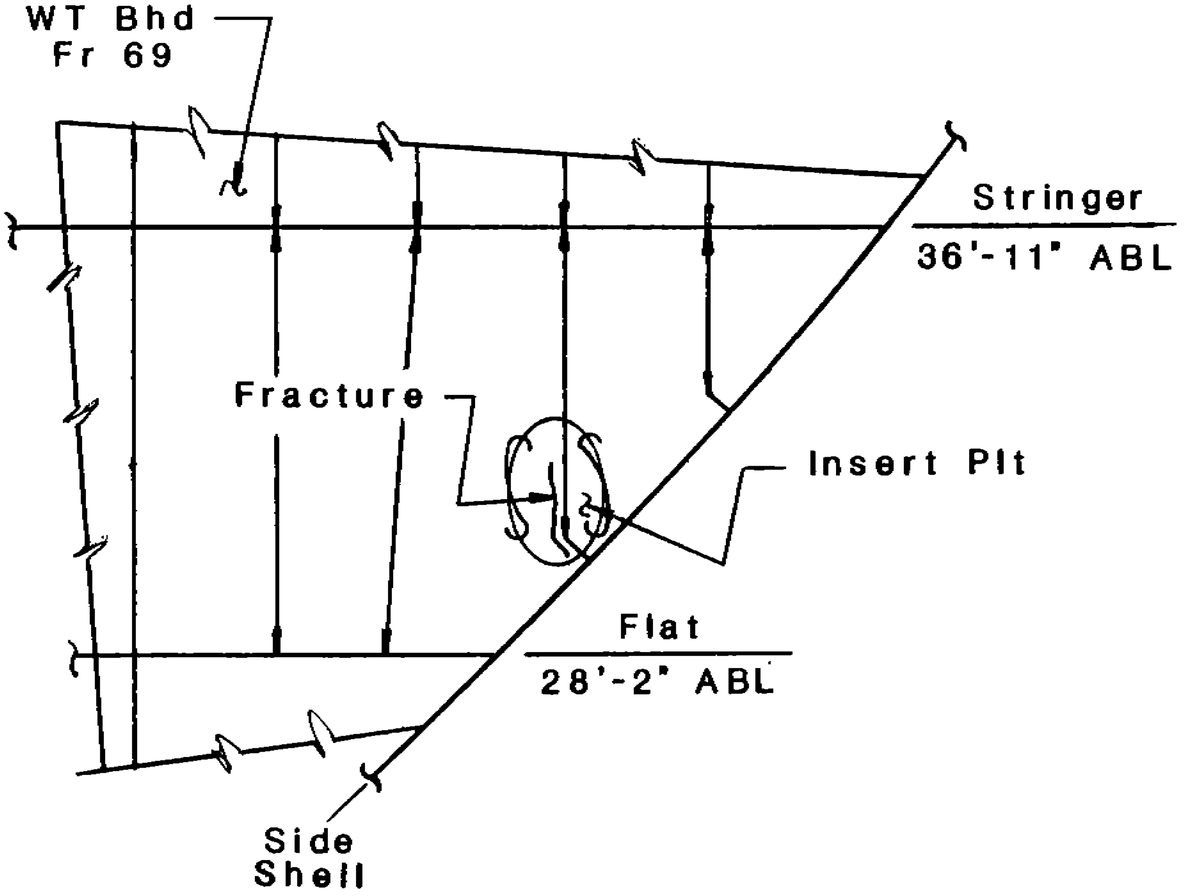

Figure 3-59 Fracture on the Transverse Bulkhead of a Tanker

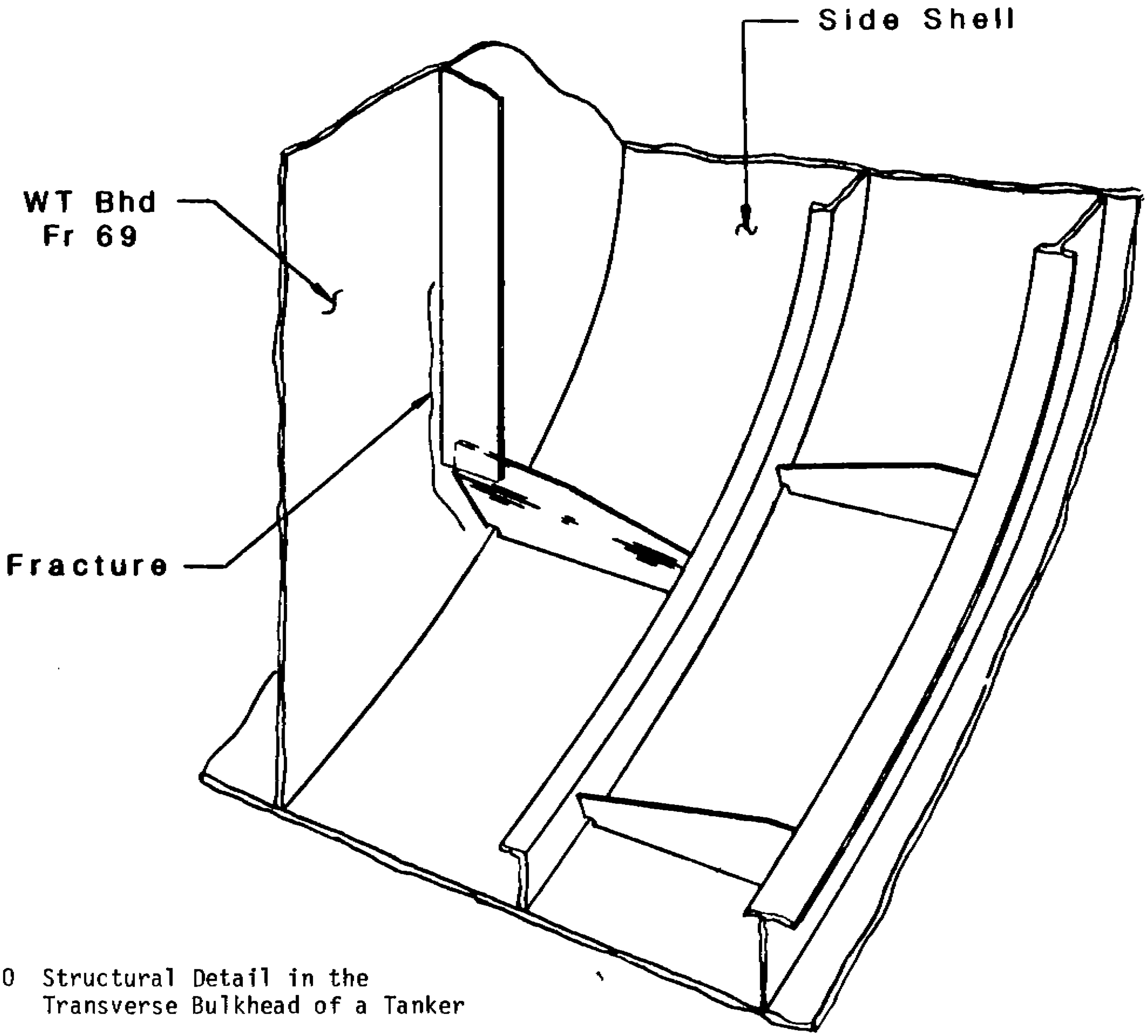

Figure 3-60 Structural Detail in the Transverse Bulkhead of a Tanker

Figure 3-61 Scanning Electron Micrograph of the Crack Surface in Bulkhead. 20X.

Factors Contributing to Fracture Initiation:

The fracture originated at a construction detail that was improperly designed to carry intended bulkhead loads. Fatigue cracking initiated and propagated.

Factors Contributing to the Fracture Arrest:

The fracture was detected and repaired.

3.13 GREAT LAKES BULKCARRIER MAIN DECK FRACTURE

Description of the Vessel:

The fracture occurred on a Great Lakes bulk carrier* that was built in 1963. The bulk carrier has an aft superstructure and machinery space. The particulars of the vessel are:

Length between perpendiculars:	712.0 ft
Breadth	75.0 ft
Depth	39.9 ft
Service Speed	14.5 knots.

A profile and typical section of the ship are shown in Figure 3-62.

Description of Circumstances at the Time of Fracture:

The vessel was loaded to the fully ballasted condition regularly adopted on return voyages. The fore peak tank was approximately 40% full, and the after peak tank and Nos. 1, 2, 3, 4, 5, and 6 upper wing ballast tanks (P&S) were full, providing a total of 10,050 tons of water ballast, which together with 595 tons of oil fuel and 60 tons of fresh water, resulted in a reported departure draft of 3.23m (10'-6") forward and 6.25m (20'-6") aft.

The vessel encountered a storm on a northwest bound passage in Lake Superior in late April of 1984. During the storm, the winds were from the northwest at 40-45 knots and the waves were reported to be 12 - 15 feet high. Ship speed was reduced to 7.5 knots. The air temperature was +3°C. The ship encountered an irregular head-sea condition which caused a severe shock impact. The shock was transmitted throughout the vessel and the crew reportedly felt the aft-end whip violently three times in rapid succession. Various unsecured items of equipment in the after accommodation area were dislodged and some crew members were nearly thrown off their feet by the sudden repetition of the shock effects. The engineer on watch in the engineering room reported water leaking into the wing ballast tank. A later inspected revealed a fracture in the starboard side of the main deck.

Description of the Fracture:

The fracture was located in the main deck and ran athwartship at the aft end of Hold No. 4. The fracture extended across the deck plate from the riveted gunwale bar at the side to the riveted deck seam just inboard of the hatch

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* The source of information is not identified due to proprietary considerations.

way. The main deck fracture was 12'-5" long and was located approximately 61'-0" aft of amidships. The main deck was .89" thick. A fracture was also discovered in the adjacent longitudinal bulkhead. Figure 3-62 shows the location of the fracture in a profile drawing and the transverse section of the structure in a detail drawing. An inspection of the main deck and longitudinal bulkhead fracture while afloat prior to drydocking revealed the following:

a. The main starboard side stringer plate and adjacent inboard strake, each 75.8 x 1.46 in thick, were fractured along their full width, immediately aft of Frame 103

b. Four main deck longitudinals, each 12.2 x 4.08 in channel bars were fractured vertically in a line

c. The main deck hatch cover lifting crane rail was fractured

d. The .4 in thick main deck plating inboard of the fracture was buckled and deck paint was disturbed

e. Four 1-1/8 in diameter rivets at the stringer plate to gunwale bar connection appeared to be have yielded, one of which was in line with the fracture and had acted as a crack arrestor at the outboard end

f. The inboard end of the deck fracture passed into and was arrested at the riveted seam inboard of the hatchways.

Sample pieces of the longitudinal bulkhead plating, deck longitudinals and crane rails were cut from the structure in way of the fracture. Inspection of the sample surface revealed flat fractures with no evidence of any reduction in thickness due to yielding, and negligible shear lips along the edges of the fracture faces. The fracture surfaces were all clean and bright. The surfaces of the fractures show the classic chevron pattern pointing toward the source of the brittle fracture. In this case the fracture was caused by a weld flaw in a longitudinal butt weld, shown in Figure 3-63. The flaw was discolored by rust, indicating that it had existed before the fracture occurred. The flaw was approximately 3/8" deep x 1/2" wide and 3/16" long.

Analysis of the Fracture:

The sample pieces were examined by those investigating the fracture. Summarized results of the tensile and impact testing, and spectrochemical analysis are given in Tables 3-3, 3-4 and 3-5 respectively. No records were available indicating the grade of steel used in the structure; however, spectrochemical analysis indicates that the main deck plating and longitudinals conform with Lloyds Grade D and ASTM A36 Grade steel. Laboratory testing of the samples from the main deck plating, welded seam material, and deck longitudinals show that the main deck steel plate exceeds Lloyds notch toughness requirements. The main deck longitudinals meet the specifications of ASTM A36 Grade steel, the notch toughness of which is lower than the deck plate to which it is attached, but similar to that of Lloyds Grade A. The deposited weld metal impact tests indicated that the deck butt weld seam was marginally below the specified minimum.

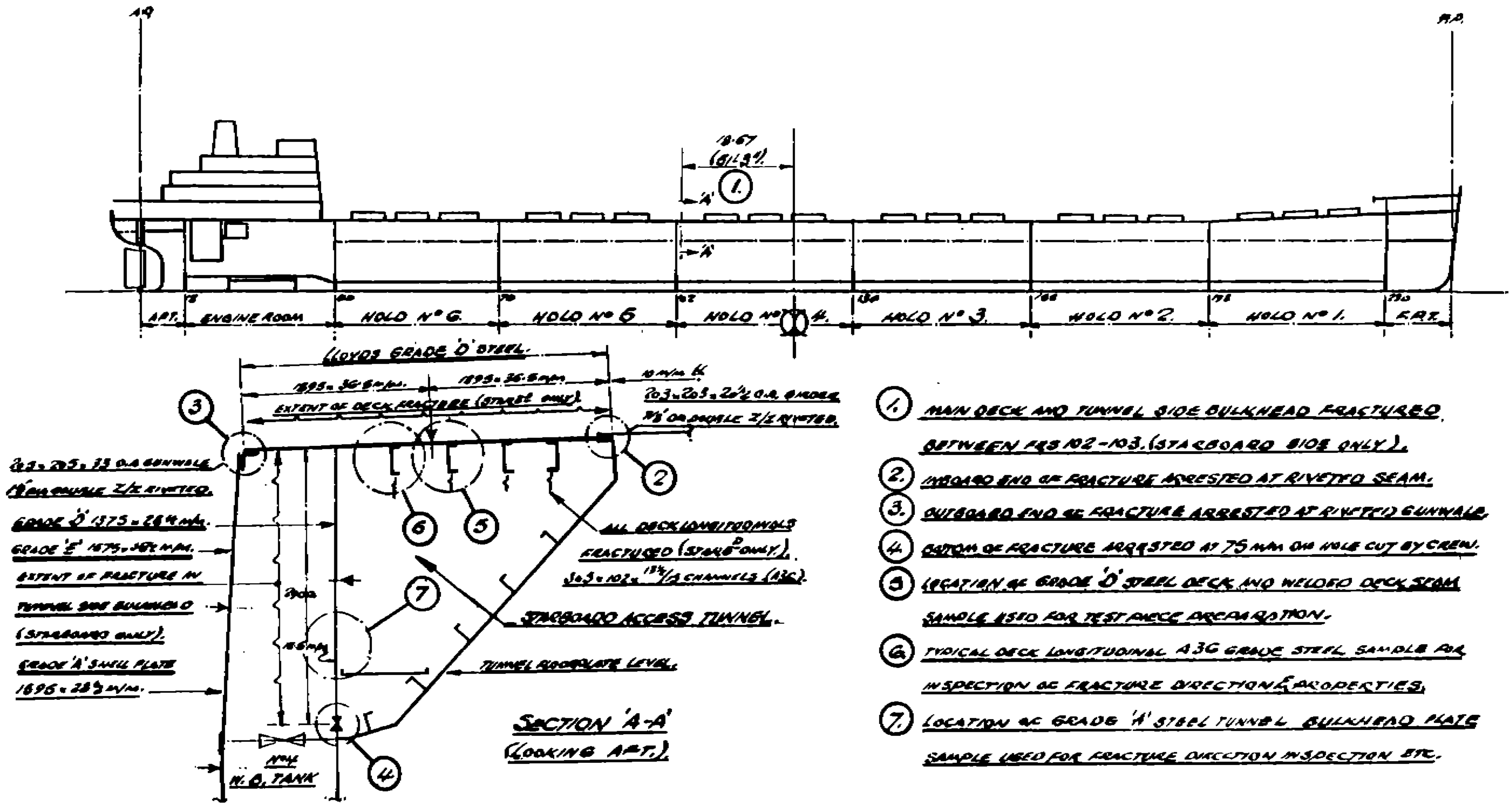

Figure 3-62 Profile and Structural Section of the Great Lakes Bulk Carrier Maindeck Fracture

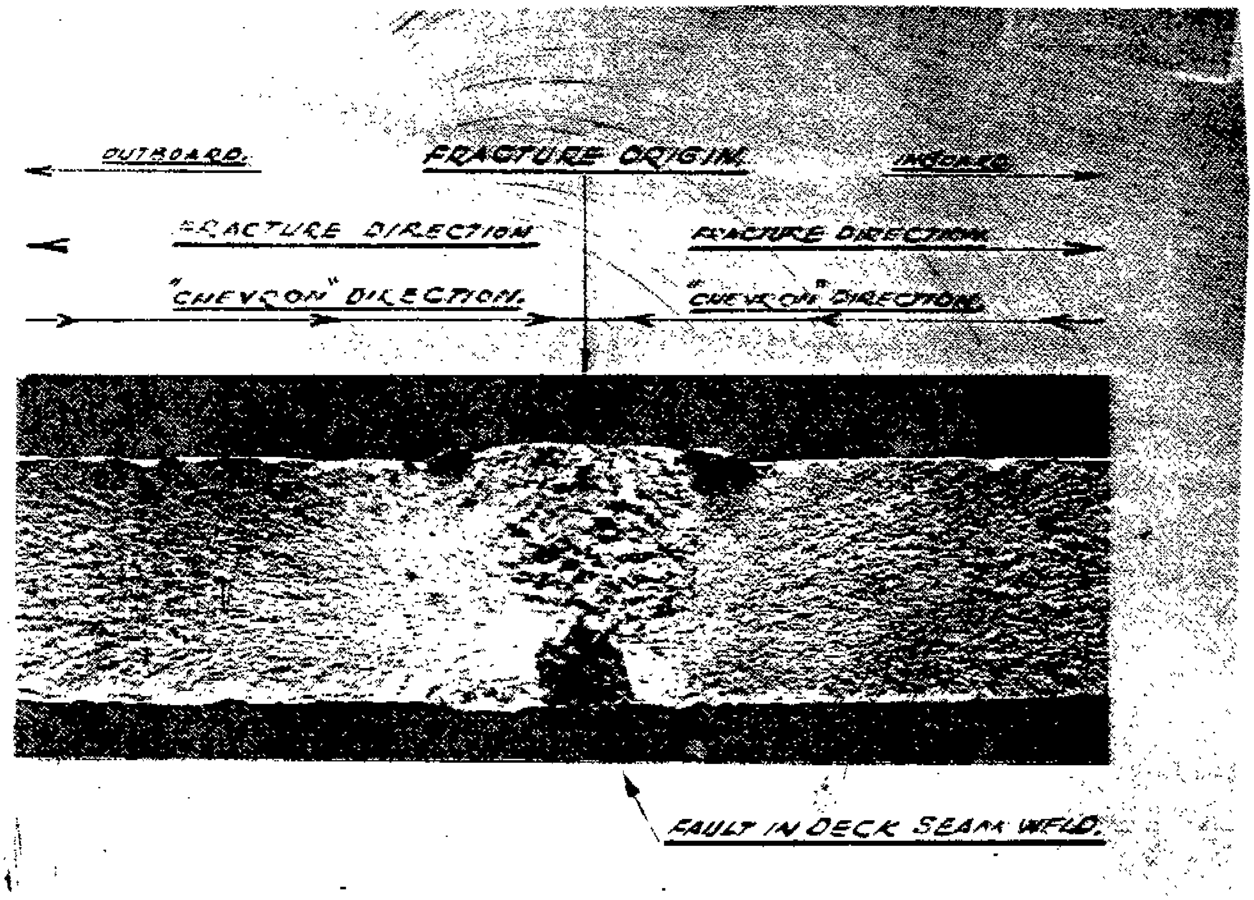

Figure 3-63 Fracture Origin of the Fracture on the Great Lakes Bulk Carrier

TABLE 3-3
TENSILE TESTING REQULTS

ITEM	SPEC NO.	TENSILE TESTING				ELONGATIONS	
		Y.S. (0.2% offset)		U.T.S.		% in 2"	$5.65\sqrt{S_0}$
		Tons/sq in	MPa	Tons/sq in	MPa	%	%
Main Deck Grade 'D'	1	18.52	280	28.48	440	37.50	35.
	2	19.99	309	28.52	440	38.00	35.
Longitudinal ASTM A36	1	17.81	275	28.70	443	38.00	33.
	2	17.81	275	28.70	437	40.00	35.
Main Deck Welded Sedm.	1	--	--	31.07	480	--	--
	2	--	--	31.16	481	--	--

1. Lloyds Rules (1966): Deposited weld metal: UTS >26 Tons/sq in (400 MPa)

2. Lloyds Rules (1966): Grade 'D' Steel: UT.S = 26-32 Tons/sq in (400-490 MPa)
   Elongation more than 5-65/Sq = 22%

3. ASTM (1974) A36 Grade Steel: Y.S. >16.0 Tons/sq in (250 MPa), UTS = 26-36 Tons/sq in
   (400-550 MPa), elongation >21% in 2" (50%).

TABLE 3-4
IMPACT TESTING RESULTS

ITEM		SPEC NO.	IMPACT TEST (CHARPY NOTCH TEST)					
			TESTING ENERGY ABSORBED				LLOYDS REQMTS	
			J.	(AV)	FT/LBS	(AV)	J.	FT/LBS
Main Deck Grade 'D'		1	122	90				
		2	120	119.	88	87	48.40	35
		3	114		84		(Min)	(Min)
Longitudinal ASTM A36		4	28		21		(ASTM)	(ASTM)
		5	16	24	12	18	20.74	15
		6	28		21		(Min)	(Min)
Main Deck Weld Material	'A'	1	26		19			
		2	28		21			
		3	34		25			
	'B'	7	28		21			
		8	23	31.67	17	23.33	34.60	25.00
		9	33		24		(Min)	(Min)
	'C'	10	42		31			
		11	52		36			
		12	19		14			

'A' Specimens prepared from material near top surface of deck seam.

'B' Specimens taken at mid depth of weld near to top of welding defect.

'C' Specimens taken near bottom of weld at same level as weld defect.

'D' All charpy notch testing results & specifications are for 0°C.

TABLE 3-5
SPECTROCHEMICAL ANALYSIS (COMPOSITION %)

ELEMENT	MAIN DECK GRADE 'D'	LONGITUDINAL GRADE A36	LLOYDS GRADE 'D'	ASTM GRADE A36
C. (Carbon)	0.160	0.175	0.21 (Max)	0.26 (Max)
S. (Sulphur	0.025	0.035	0.05 (Max)	0.05 (Max)
P. (Phosphorus)	0.010	0.028	0.05 (Max)	0.04 (Max)
Si (Silicon)	0.020	0.033	0.35 (Max)	-
Mn (Manganese)	1.100	0.640	0.60-1.40	-

Factors Contribution To Fracture Initiation:

Sudden wave impacts as the forefoot and flat bottom emerged and slammed into heavy head seas caused intermittent loads, resulting in longitudinal vibrations at the fundamental frequency of the hull girder; this transient condition is known as "whipping". In turn, slamming plus whipping created high stress at the weld flaw which resulted in the propagation of the brittle fracture across the main deck and into the longitudinal bulkhead.

Factors Contributing to Fracture Arrest:

The incorporation of a riveted longitudinal gunwale bar and a riveted deck seam inboard of the line of hatchways acted as crack arrestors, effectively stopped the progress of the fracture, and prevented propagation into the side shell plating.

3.14 TANKER (31,400 DWT) BOW FRACTURE AND HULL FAILURE

Description of the Vessel:

A fracture occurred in a tanker [3-10] built in 1973 with the following particulars:

Length between perpendiculars:	600.0 ft
Beam (molded)	88.25 ft
Depth molded	44.75 ftt
Draft (winter)	33.38 ftt
Dead weight	31,389 tons.

The vessel was built to Lloyds' rules and carried an Ice Class 1 +LMC. The machinery and crew accommodations were located aft. The tanker had six cargo tanks (P, S, and center). The vessel was of all welded construction and built entirely of Grade A steel except for a Grade D plate in the deck adjacent to the pump room. In the midship 40 percent of the length, the deck plating, gunwale and sheer strake were .8" thick. The keel was .95" thick; the bottom shell was .77" thick and the bilge strake and the strake above were .58" thick. The two strakes between the light and load water lines forming the ice belt were .86" thick. The ship had heating coils in the cargo tanks to carry heavy oils.

Description of the Circumstances at the Time of Fracture:

On the 15th of March, 1979 the tanker entered an ice field in a position south of Cabot Straight on a voyage between Point Tupper, Nova Scotia to Baie des Sept-Iles, Quebec. The ship was fully laden with a cargo of heated Bunker C fuel oil. The ship exited the ice field and emerged into open water and encountered a south-southeastely gale taking the seas on her starboard bow. The observed sea height was 14 - 15 feet. Shorthy thereafter the bow of the vessel paused in the middle of a downward pitch and shuddered. Immediately afterwards oil was seen escaping from two fractures, one on each side of No. 3 cargo tanks. The vessel proceeded at dead slow ahead into moderating conditions. Later the wind changed to the northwest. The ship altered course to reduce the vessel motions when there was a further shuddering. The bow of the vessel rose in the air and the vessel broke in two in way of No. 3 cargo tanks. The bow section eventually sank; the stern section remained afloat and was later salved. The sea had moderated to sea state 4. The air temperature was approximately 41°F, the water temperature was between 32°F and 35.6°F. The temperature of the cargo (heated oil) was approximately 60°C (142°F). The drafts at the time of fracture were 33.7 ft aft and 33.1 ft fwd.

Description of the Fracture

Examination of the fracture surface on the salved stern section revealed that although there were initiation sites on both the port and starboard sheer strakes. The most important fracture had initiated in the port bilge keel flat bar butt weld at Frame 171. The weld showed a lack of penetration and no sign of a weld cutout at the side shell. The bilge keel detail is illustrated in Figure 3-64. After inspection of the fracture origin, it was learned that the bilge keel was damaged forward of Frame 171 from grounding and repaired at a drydocking prior to the fracture occurrence. It was apparent from the presence of the characteristic chevron markings that the fracture had occurred in a brittle manner and propagated from the butt weld across the bottom of the ship to the starboard bilge keel at Frame 174 and vertically up the port and starboard side. Many of the longitudinals had also failed in a brittle manner.

Analysis of the Fracture

Analysis was conducted as part of the court investigation [3-10] and consisted of fractographic analysis of the fracture origin, metallurgical analysis of fracture samples and stress analysis of the hull structure.

Fractographic analysis of the fracture origin indicated the presence of fatigue crack growth along more than half the length of the bilge keel flat bar butt weld. Faint beach markings were observed and chevrons pointed away from the fatigue crack into the bulb angle and into the bilge strake.

Metallurgical examinations were conducted to verify metal properties and quantify crack tolerance. The plate samples examined were acceptable with regard to the specifications for Grade A steel. There are no requirements for toughness values for Grade A plate, but tests were conducted to determine the fracture resistant characteristics of the plate and weld. Charpy-V notch impact tests indicated that the NDT temperature varied between 32°F to +41°F A limited number of crack opening displacement (COD) tests were conducted at three strain rates. The following trends were observed:

- At low strain rates, the material exhibited ductile behavior.
- At medium strain rates at 30°F some stable ductile tearing occurred before cleavage instability.
- At high strain rates all valves of COD were low and brittle behavior was exhibited.

Stress calculations were performed for still water wave bending, thermal, and wave impact stresses at the initiating defect. Primary stresses were estimated for the area of the initiating defect. The still water bending moments were calculated based on a known loading condition and wave bending moments were calculated for the fully developed North Atlantic conditions at the observed wave

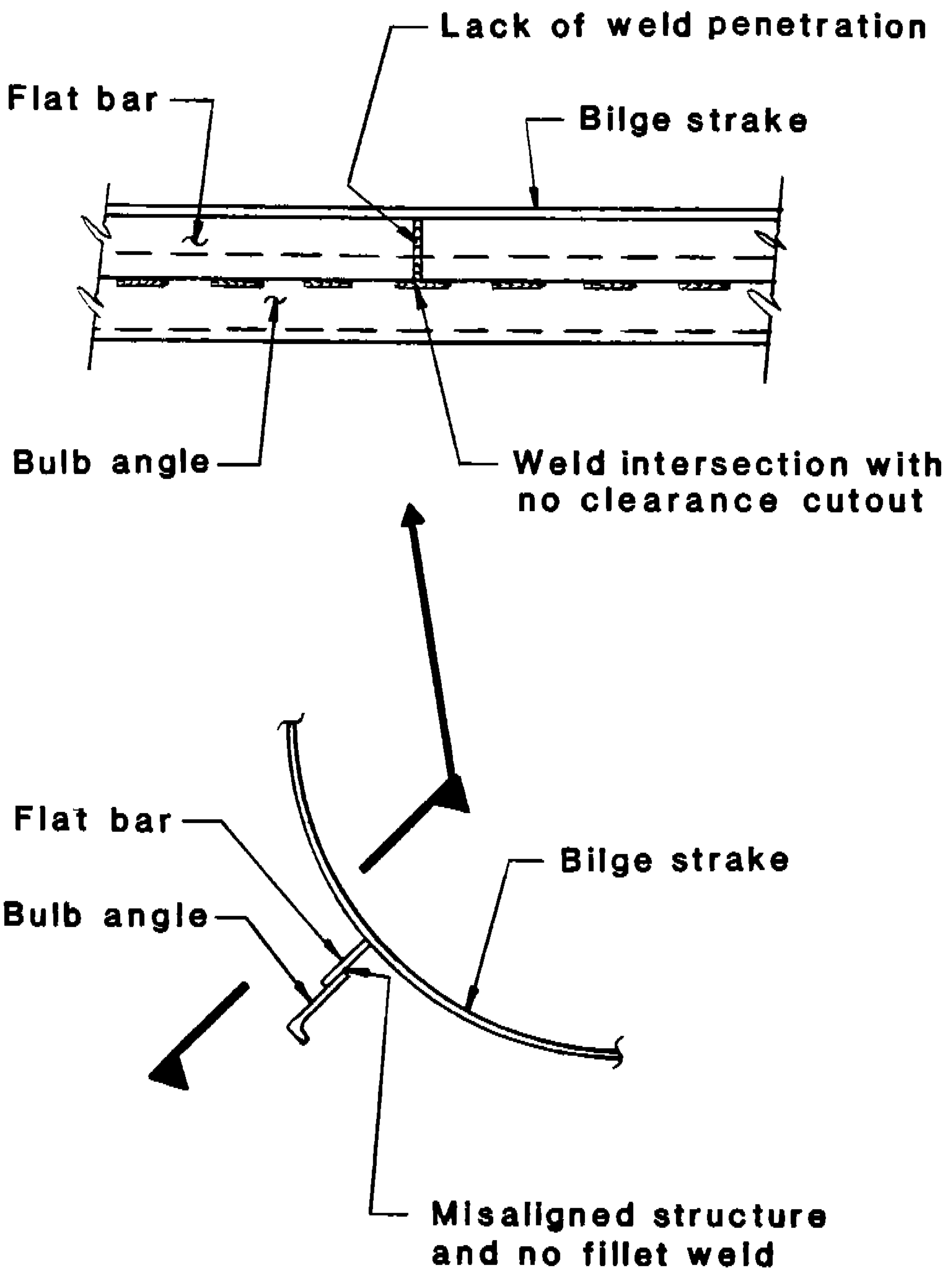

Figure 3-64 Bilge Strake Detail of the Tanker Hull Failure

heights. A frequency domain computer program was used to determine wave bending moments. The thermal induced stress calculations were based on the theory developed by Timoshenko and Goodier [3-12]. The wave impact forces were assumed from past experience. Bottom slamming and flare slamming were discounted for the fully loaded tanker. The resulting calculated stresses were as follows:

Maximum still water and wave bending stress	3,768 psi
Thermal Stress	7,826 psi
Wave impact stress	1,449 psi
Total	21,739 psi

This stress condition is near the allowable stress indicating a large load in the structure at the time of fracture.

Factors Contributing to Fracture Initiation:

The following factors contributed to the initiation of the fracture:

- The fracture originated at a serious welding defect in a bilge keel located in a primary stress region
- The fracture was triggered by a wave impact at the bow of the ship, followed by fracturing of the hull girder.

Factors Contributing to the Fracture Arrest:

The primary fracture caused total structural failure there was no arrest (the bow of the ship was completely separated from the aft portion of the hull and subsequently sank).

3.15 TANKER (123,000 DWT) LONGITUDINAL BULKHEAD AND MAIN DECK FRACTURE

Description of the Vessel:

A fracture occurred in a tanker that operates in the Alaska and West Coast oil trade.* The particulars of the vessel are:

Length between perpendiculars:	825.0 ft
Beam	136.0 ft
Depth	71.67 ft
Draft	54.99 ft
Dead Weight:	123,000 LT.

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* The source of information is not identified due to proprietary considerations.

Description of Circumstances at the Time of Fracture

The fracture was discovered when the vessel was in port during gas freeing operations. Gas was noted leaking from the deck. No other circumstanes at the time of fracture are known.

Description of the Fracture

The fracture was located in a longitudinal bulkhead and main deck two feet aft of Frame 75. The location of the fracture and surrounding structures are illustrated in Figure 3-65. The steel in the vicinity of the fracture was ABS DH36 .75" thick.

Analysis of the Fracture

The entire fracture was removed for further examination and fractographic analysis at Lehigh University. Visual examination of the fracture surface revealed that the fracture surface was caused by fatigue above a longitudinal shelf and brittle fracture below as shown in Figures 3-66, 3-67, and 3-68.

Figure 3-66 shows that the failure in the structure below the shelf plate is by brittle fracture starting at the transverse weld and then becoming a shear fracture. Distinct chevron markers are seen to extend not only down the main fracture but also across the shelf plate. A thumbnail fatigue region is apparently centered on the weld toe on the short side of the shelf plate. This is seen particularly well in Figure 3-66 where it is marked with an arrow. It appears that this crack progressed a short distance into the bulkhead below the shelf plate before chevron markers developed. The termination of this crack is seen in Figure 3-66.

There are two regions of the major fracture in the weld seam which appear to show faint chevron markers. These are seen in Figures 3-67A, 3-67B, 3-67C and 3-67D. It is the investigators' opinion that the only area that is likely to be evidence of a fast fracture is the area in Figures 3-67C and 3-67D. The chevrons in this case point upward toward the deck. This suggests that initiation was by fatigue, from some point at the toe of the seam near the deck, and the crack grew downward, mostly by fatigue. It may have had short areas of brittle crack extension. When the fatigue crack crossed the shelf plate, it extended by brittle fracture until the arrest seen in Figure 3-66.

Examination of the fracture surfaces did not reveal any notable weld defects in the fracture path. Porosity, large inclusions, lack of fusion, etc., were not in evidence except in the angle stiffener weld where some lack of fusion was noted.

The tip of the crack in the deck plate was opened in the laboratory, cleaned with alconox and examined with the scanning electron microscope. The results are seen in Figure 3-69. At this low magnification, faint clamshell markings seen running left to right across the field are evidence of fatigue. The surface is heavily oxidized and higher magnification microscopy did not prove helpful.

Factors Contributing to Fracture Initiation:

The project investigators believe that the fracture initiated by fatigue along the toe of a butt weld in the bulkhead, probably at several places, and progressed along the seam by both fatigue and brittle fracture. A clear brittle fracture region occurs in the bulkhead below the longitudinal shelf plate. The

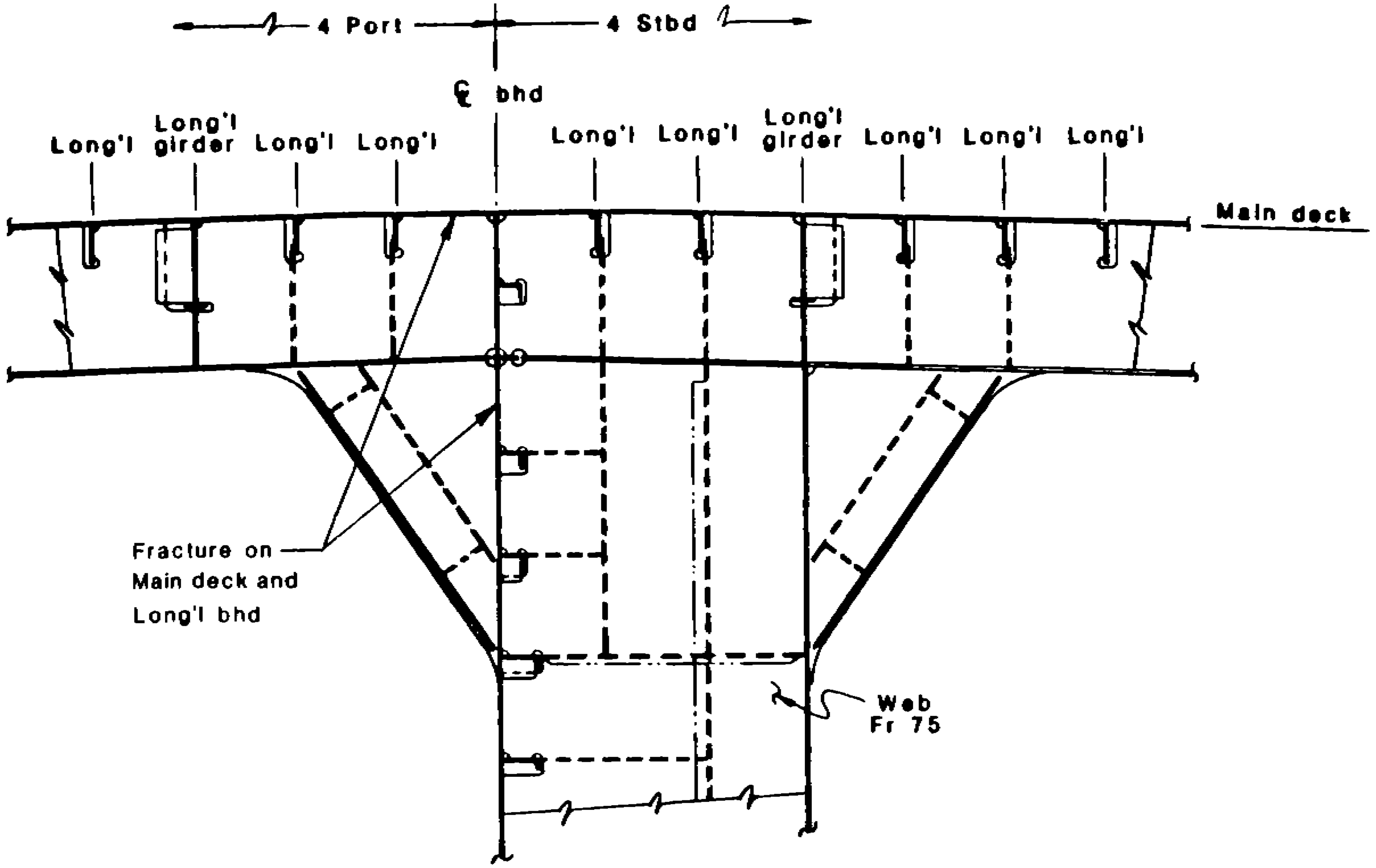

Figure 3-65 Structure of the Tanker With a Longitudinal Bulkhead Fracture

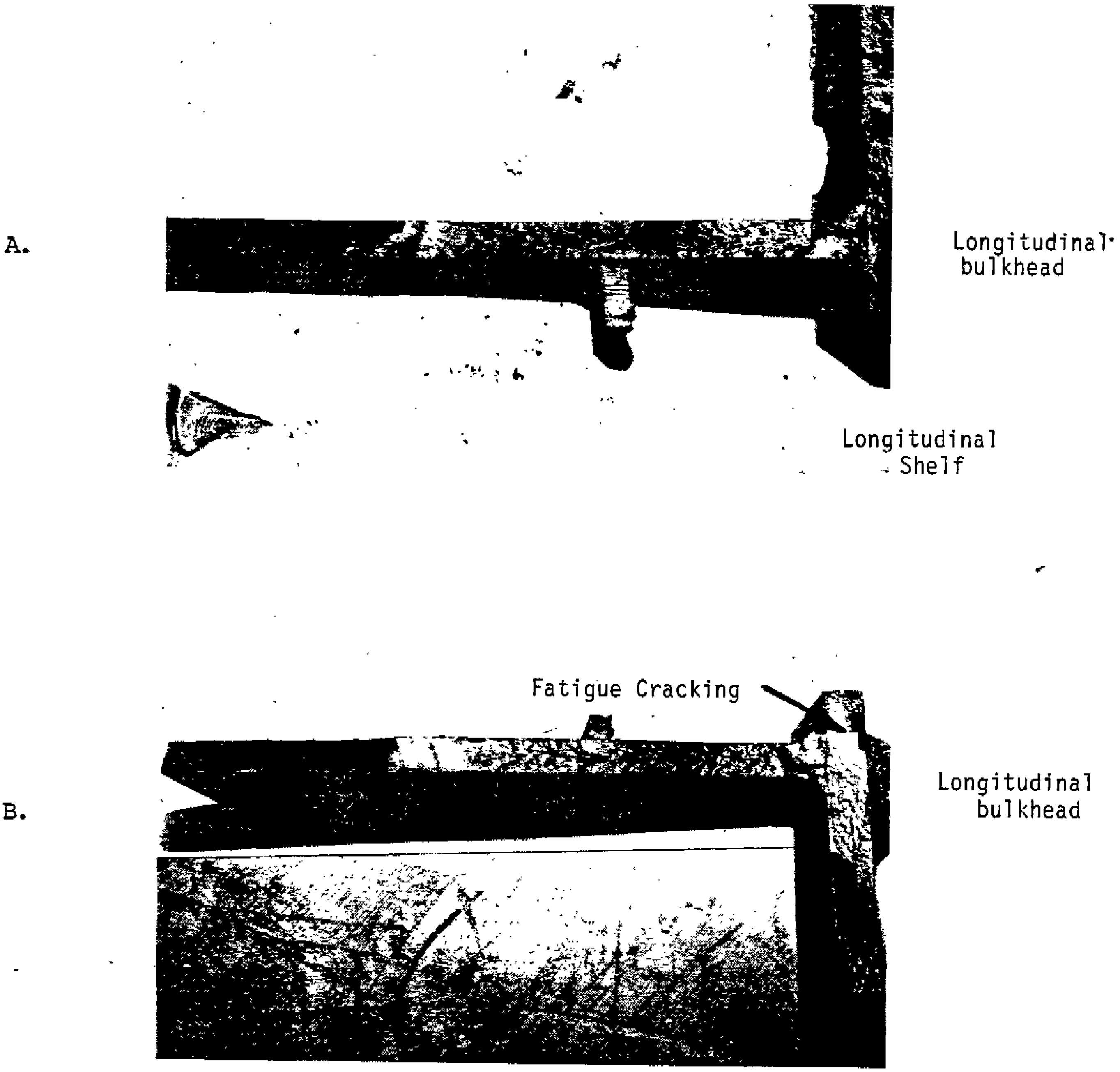

Figure 3-66 Detail of Chevron Marks and Fatigue Initiation

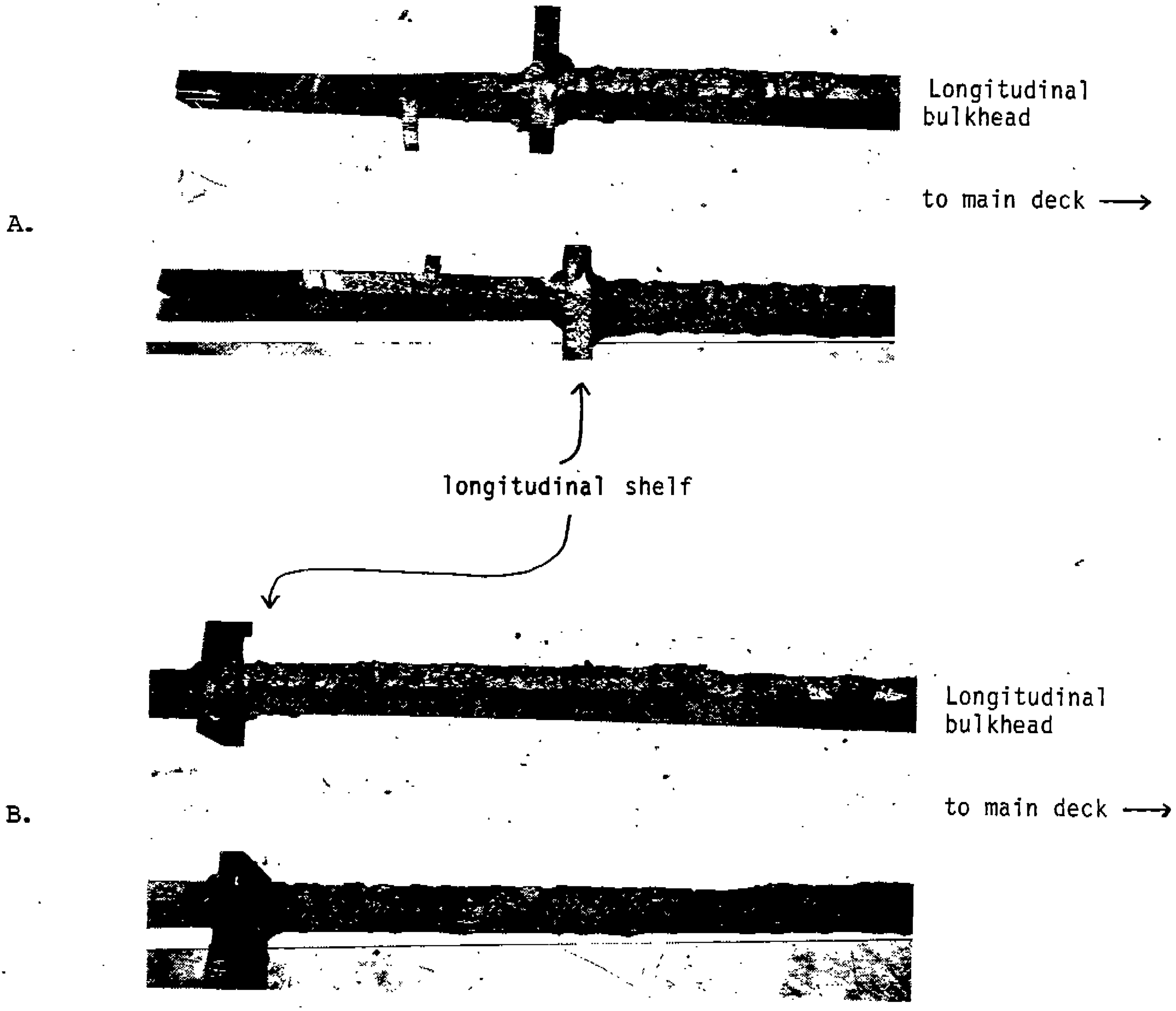

Figure 3-67 Details of the 123,000 DWT Tanker Fracture Surface

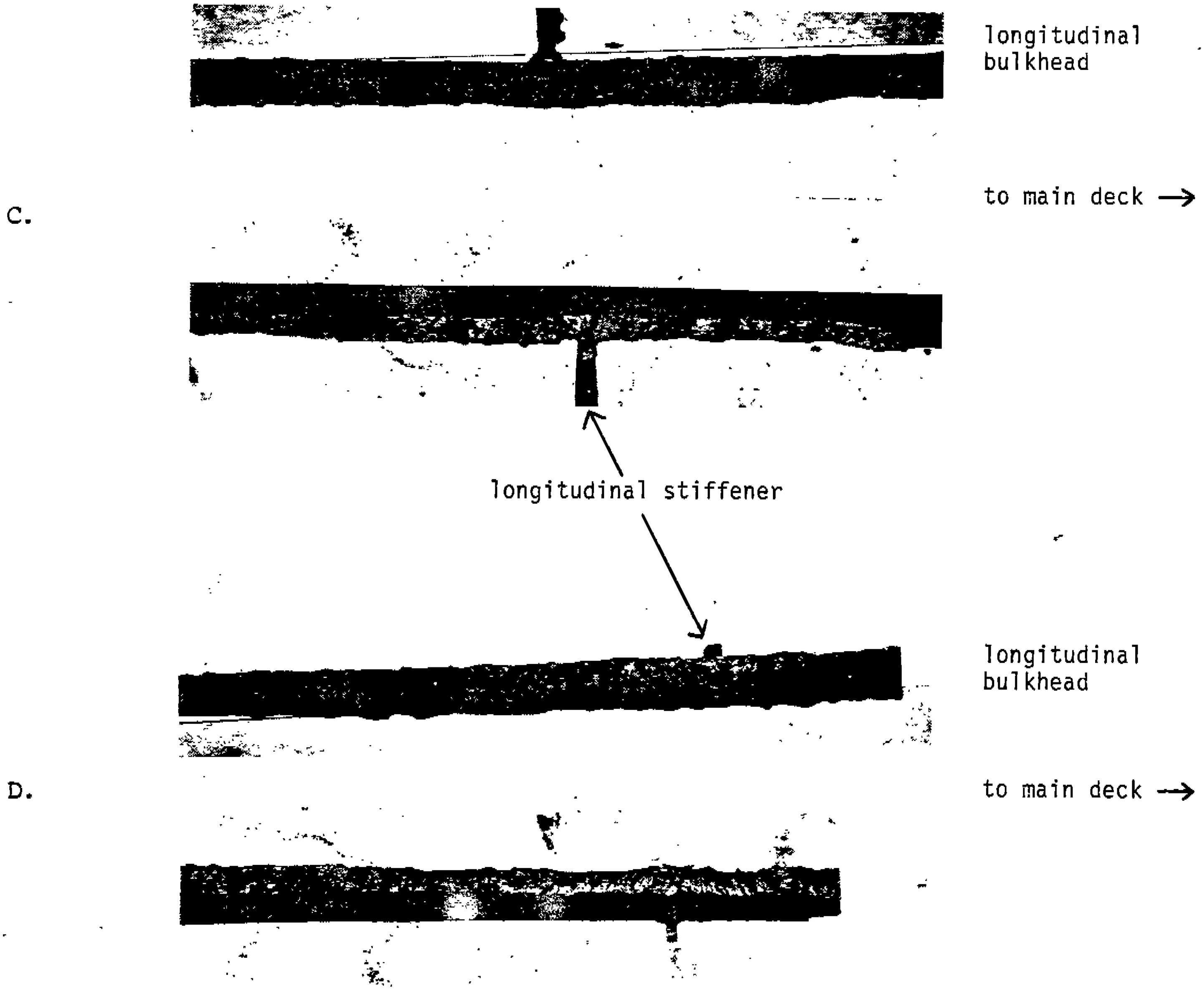

Figure 3-67 (Cont'd) Details of the 123,000 DWT Tanker Fracture Surface

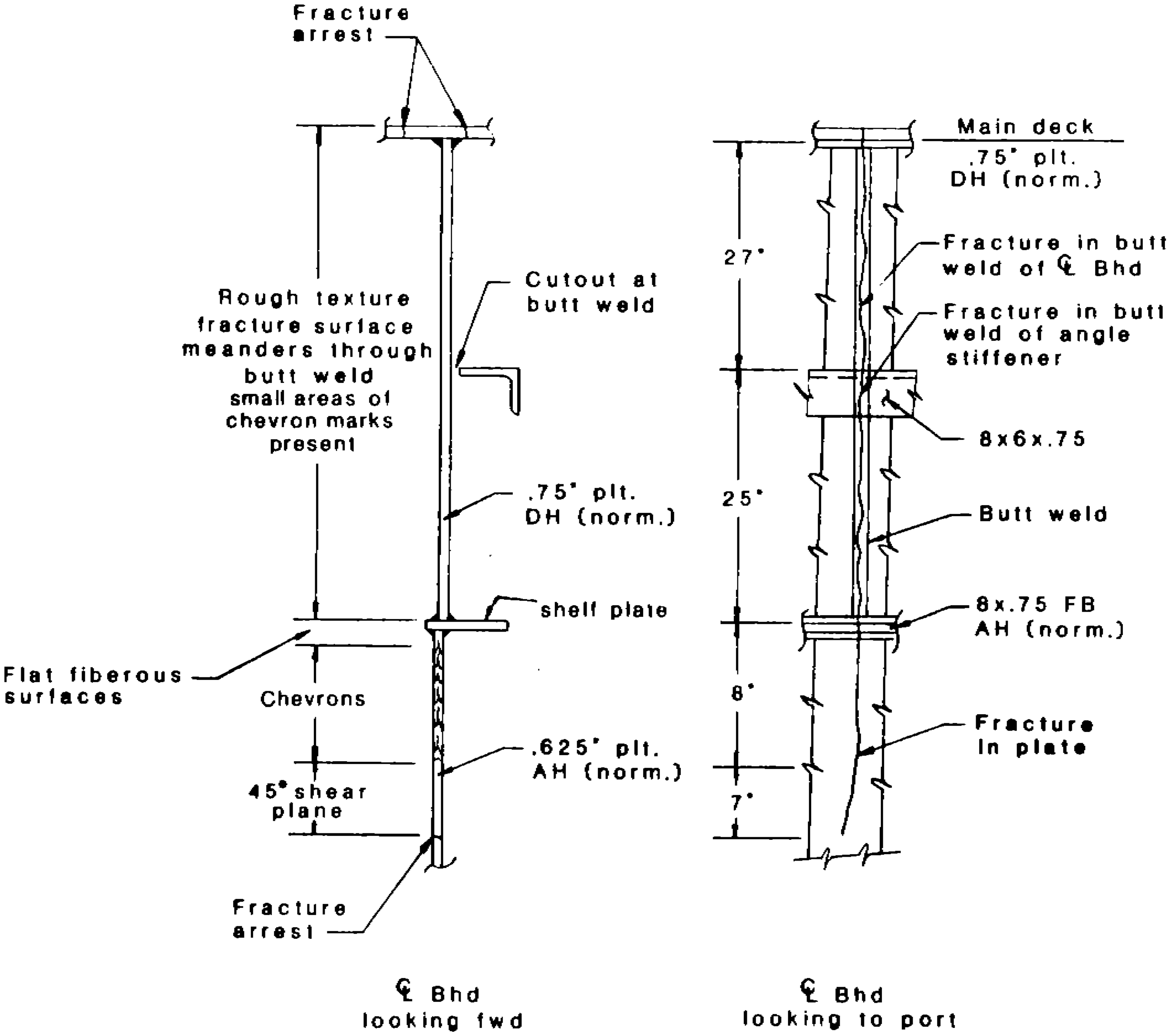

Figure 3-68 Key Illustration of the Longitudinal Bulkhead Fracture

Figure 3-69 Scanning Electron Micrograph of Fracture Surface of Deck Crack

brittle fracture progressed across the transverse shelf plate and downwards through the bulkhead where it terminated as a shear fracture. There was no evidence of significant defective welding. The fracture in the deck was a result of fatigue crack growth from the initial crack in the bulkhead. The investigation indicated that the fracture propogated in a region of suspected high local residual stress caused during the welding of the deck subassemblies.

Factors Contributing to Fracture Arrest

The investigators believe that the fracture propagated out of the local area of high residual stress and subsequently arrested in the low stress field. The fracture was detected and repaired.

3.16 TANKER (173,000 DWT) MAIN DECK FRACTURE

Description of the Vessel:

A fracture occurred in a segregated ballast tanker.* The particulars of the vessel are:

Length overall	06.0 ft
Length between perpendiculars	864.0 ft
Beam	173.0 ft
Depth	75.0 ft
Draft	57.0 ft
Dead Weight	173,000 LT.

A cargo tank arrangement drawing is shown in Figure 3-70. All main deck plate, with the exception of the outboard deck strakes port and starboard, is AH36. The outboard strakes on the main deck are DH36. The sheer strakes, bilge, and flat keel are DH36. All other structure is AH36.

Description of Circumstances at the Time of the Fracture

The tanker was departing a Yokohama shipyard and was in open water when the fracture occurred. The ship was in a normal ballast condition. The air temperature at the time of fracture was 38°F. The captain reported feeling the ship lurch just prior to the fracture

Description of the Fracture

The fractures were located approximately 50 ft forward of the deck house in way of No. 5 cargo tanks. The port side fractures occurred between Frames 63 and 64, in the main deck, 22 ft from the sheer strake and included:

- One transverse fracture 27 ft. long
- One transverse fracture 7 ft. long
- One transverse fracture 3 ft. long.

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* The source of information is not identified due to proprietary considerations.

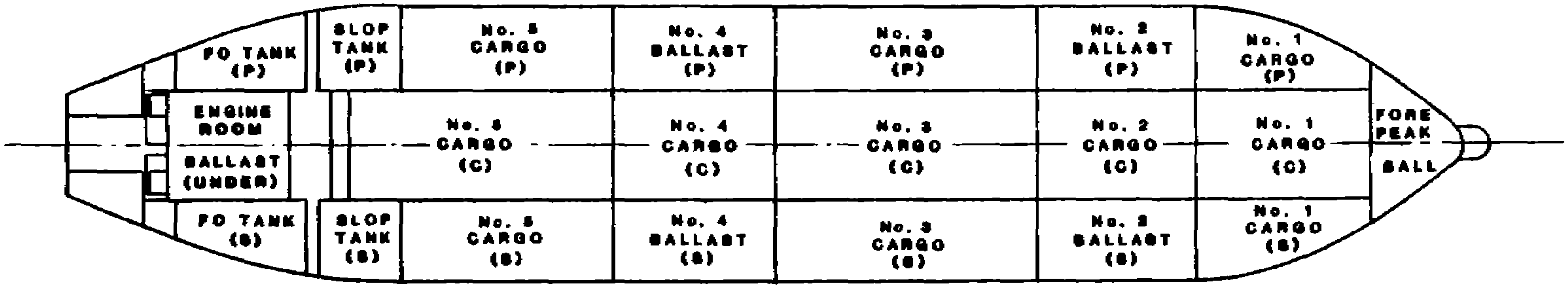

Figure 3-70 Cargo Hold Plan of the 173,000 DWT Tanker

Brittle fractures occured on the starboard side of the main deck 6 in. aft of Frame 64 and 10 ft from the sheer strake, including one transverse fracture 10 ft long.

The apparent point of origin is at a notch in the underdeck longitudinals between the longitudinals and a bracket in the transverse web frame as shown in Figure 3-71. Fatigue propagation was observed in the longitudinal fractures.

Analysis of the Fracture:

The ship operator reported that the fracture originated at the details described above. Fatigue extension was observed in the longitudinal and for a short distance in the main deck.

Factors Contributing to Fracture Initiation:

Fatigue cracks propagated in the longitudinals and reached a critical length that initiated the brittle fractures.

Factors Contributing to the Fracture Arrest:

The fracture reportedly terminated at EH Grade steel arrestor strakes .

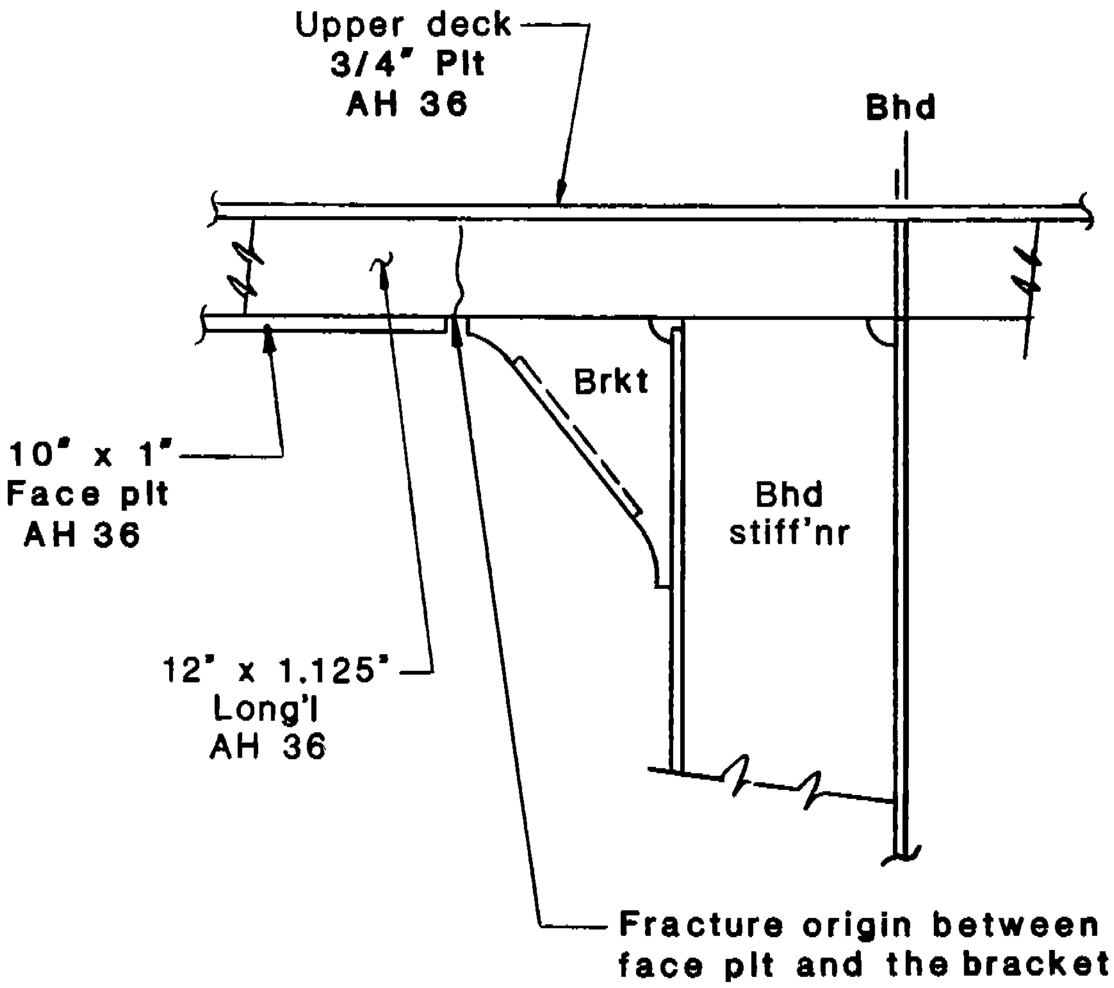

Figure 3-71 Structural Detail at the Origin of the Fracture in the 173,000 DWT Tanker

4.0 COMPARISON OF STRUCTURAL DETAILS ASSOCIATED WITH THE CASE STUDIES TO THOSE INSPECTED AND DESCRIBED IN SSC-272, SSC-294 AND OTHER SOURCES

Ships are designed and built of various structural members including plates, girders, stiffeners and brackets. These structural components are welded to form continuous structures. The connections, intersections and cutouts associated with this type of construction are known as structural details. Structural details have been the subject of research because details are often the source of cracks and other failures. Research sponsored by SSC includes a study of the service performance of standard structural details, and results have been reported by Jordan in SSC 272 [4-1] and SSC 294 [4-2]. Thousands of standard details were examined and failures were documented during the study. The types of details examined included beam brackets, tripping brackets, non-tight collars, tight collars, gunwale connections, knife edge crossings, miscellaneous cutouts, clearance cuts, deck cutouts, stanchion ends, stiffener ends, and panel stiffeners. This statistical data base was compared to the fractures reported in this study to correlate failure statistics and to determine the prevalance of similar failures.

A comparison of the fractured details examined in this study and fractured detailes documented in the SSC Documents is presented in Table 4-1. It is apparent that the failure statistics for structural details listed in Table 4-1 do not correlate well with failure presented in this report. This is chiefly because the structural details located at the origins of the significant fractures studied here were often related to specialized details peculiar to various construction methods or repairs, and not to one of the standard details of the SSC Reports.

Other sources of stastical data on fractured details were investigated and included the USCG Casualty Reports. No other statistics were identified in the literature that correlate to the fractured details investigated in this study. This reinforces the conclusion that significant fractures originate at specialized details.

Clearly, fractures do originate at standard details and require frequent repairs; however, they do not pose a significant threat to structural integrity unless they are located in primary structure. Additionally, specialized details should be analysed and inspected thoroughly during detail design to prevent significant fractures and associated damaging consequences.

TABLE 4-1
COMPARISON OF STRUCTURAL DETAILS

VESSEL	STRUCTURAL DETAIL AT THE FRACTURE ORIGIN	SIMILAR FAILURES REPORTED IN THE LITERATURE
1. Great Lakes Bulk Carrier	Coped flange of a longitudinal channel stiffener	-
2. High Speed Containership	Hatch corner detail	Fractures prevalant in all 9 ships of the class. Documented in USCG casualty reports.
3. Tanker (100,000 DWT)	Vertical butt weld in side shell	-
4. I.O.S. 3301 Tank Barge	King post base at a weld detail	-
5. Ocean going bulk carrier	Stanchion base and eye plate	-
6. Converted Containership	Bottom shell butt weld in transversely framed ship	Common to 9 ships of the class and a similar ship of another owner. Documented in the USCG casualty data base
7. Tanker (250,000 DWT)	Butt weld in a side shell longitudinal stiffener	-
8. Tanker (70,000 DWT)	Machined notch in a bleeder plug insert	The ship had 15 bleeder plugs and 4 of them fractured (Documented in this report)
9. Containership	Cutout in a transverse bulkhead at a hatch corner	Similar to the high speed containership (2) (Documented in this report)
10. Containership	Remains of a repair weld at a longitudinal stiffener cutout	-
11. Tanker (Jumbo T-2)	Butt Weld	-
12. Tanker (123,000 DWT)	Butt Weld in longitudinal bulkhead	-
13. Great Lakes Bulk Carrier	Butt weld	-
14. Tanker (31,369 DWT)	Butt weld in a bilge keel	Common fracture origin reported also reported for the converted Containership (6); Documented in Ship Owners & Operators Files
15. Tanker (120,000 DWT)	Bulkhead stiffener and side shell bracket	One similar failure reported in SSC 272; where a bracket failed
16. Tanker (173,000 DWT)	Construction detail at a bulkhead bracket and main deck longitudinal stiffener connection	The detail is common to two other ships in the class. Cracking was reported in similar details. Documented in USCG Casualty Data

5.0 EVALUATION OF FRACTURE CONTROL APPROACHES

The examination of actual ship fractures was performed to determine the modes of fracture that pose a significant threat to the ship's structural integrity; to evaluate approaches to control the significant fractures; and, where possible, to develop the elements of a fracture control program. Findings and conclusions were derived from the fracture case histories and are presented in this section. The pertinent information for each fracture case history is summarized in Table 5-1 for quick reference.

5.1 REVIEW OF FRACTURE MODES AND CONSEQUENCES

The review of fracture modes is presented to highlight fracture modes that are most threatening to the structural integrity of ship structure. Future research can therefore be directed toward control of the significant fractures.

As shown in Table 5-1, the following fracture modes were observed:

- Fatigue cracking was observed or reported in 11 of the 16 case studies examined.
- Fatigue cracking preceded brittle fracture in 9 cases examined.
- Brittle fracture was observed in 11 of the 16 cases examined.
- Ductile fracture was located at the point of fracture arrest in two cases examined.

These findings indicate that fatigue and brittle fractures were observed in the majority of case histories studied and that they were a significant threat to the ships' structural integrity. In fact, complete hull girder failure resulted from brittle fracture in two case studies. Brittle fracture caused loss of watertight integrity in nine case studies. Fatigue cracking was observed in many of the ship fractures studied and contributed to occurrence of brittle fracture. Later sections will address methods that should be used to control these fracture modes.

In addition the following was observed:

- All of the fractures investigated originated at a design or a fabrication detail.
- The majority of brittle fractures examined originated in steel Grades A and B.
- Brittle fracture arrest was attributed to riveted construction in 3 cases, and structural redundancy in one case. Riveted seams and joints and various forms of structural redundancy appear to be the most effective means of arresting running fractures in ship structure.
- In only one case out of 11 did special material contribute to the arrest of a dynamic running fracture.

TABLE 5-1
SUMMARY OF FRACTURES INVESTIGATED

VESSEL	YEAR BUILT	DATE OF FRACTURE	STEEL TYPE	STRUCTURAL DETAIL AND LOCATION	FRACTURE MODE	PROBABLE CAUSE OF FRACTURE INITIATION	REASON FOR ARREST
Great Lakes Bulk Carrier	1952, lengthened 1957	1984	unknown	Notch in channel longitudinals, main deck	Brittle fracture (14')	Stress overload, poor fabrication detail	Riveted joints and areas of reduced stress
High Speed Containership	1972	1974-1977	EH-33 & CS	Hatch cutout, main deck	Fatigue (24")	Stress concentration from detail design	Detected and repaired
Tanker 100,000 DWT	1965	1975	unknown	Longitudinal cutout in web frame at side shell	Fatigue & brittle fracture	Inadequate structural detail	Reorientation of fracture path detected and repaired
I.O.S. 3301 Tank Barge	1972	1973	ABS-A and ABS-B	King post base, main deck	Brittle fracture (entire hull except bottom shell)	High constraint and sharp notch in structural detail	Not arrested, complete failure of structure resulted
Ocean-Going Bulk Carrier		Prior to 1982	A&D	Stanchion base and eye plate, main deck	Fatigue & brittle fracture (12')	Stress concentration at two local structural details	Material toughness and structural configuration
Converted Containership	1952, lengthened 1969	1970-1983	ABS-A	Primarly butt welds in vessel bottom plate	Corrosion fatigue (brittle fracture in isolation instances)	Inadequate scantlings at time of conversion and poorly fabricated welds	Detected and repaired ships are now out of service pending final resolution of the cracking problem
Tanker 250,000 DWT	1967	1972	A,DH, EH	Butt inside shell longitudinals	Brittle fracture (50')	High stress from local wave loading at improper weld detail	Material toughness of deck plating
Tanker 70,000 DWT	1981	1985	ABS-A	Bleeder plug insert, bottom	Fatigue (5")	Stress concentration caused by improper installation of structural detail	Detected and Repaired

TABLE 5-1
SUMMARY OF FRACTURES INVESTIGATED
(CONTINUED)

VESSEL	YEAR BUILT	DATE OF FRACTURE	STEEL TYPE	STRUCTURAL DETAIL AND LOCATION	FRACTURE MODE	PROBABLE CAUSE OF FRACTURE INITIATION	REASON FOR ARREST
Container-ship	1982	1985	DH-36 .3125"	Hatch Corner cut-out, transverse bulkhead, bow	Fatigue (10")	Lack of structural continuity, high stress	Detected & repaired
Container-Modified	1969 1968 1975	January	.69	Repair weld shell longitudinal cut-out, bow flare	Fatigue (micro) Brittle fracture (30 ')	Bow slamming and structural overload at a poorly designed structural detail	Propagated into an area of reduced stress
Tanker (Jumbo T-2)	1943 Lengthened 1961	February 1975	.75"	Butt weld, main deck, insert repair	Brittle fracture deck, midship	Weld flaw (19')	Propagated into a riveted seams construction
Tanker (123,000 DWT)	1978	December 1985	DH-36 .62", .75	Longitudinal bulkhead, main deck mid ship	Fatigue (6') Brittle fracture (15")	Local residual stress	Detected & repaired
Great Lakes Bulk Carrier	1963	April 1984	D 1.46"	Butt weld, main deck; midship	Brittle fracture (12.5')	Bow slamming structural over-load, weld flaw	Propagated into riveted seams construction
Tanker (31,369 DWT)	1973	March 1979	A .75"	Bilge keel, fwd of midship	Fatigue (micro) brittle fracture	Poor weld, fatigue, structural overload	Complete failure of hull girder
Tanker (170,000 DWT)	1977	January 1986	AH-36 .625"	Transverse bulkhead, aft. .4L	Fatigue (16")	Stress concentra-tion from detail design	Detected & repaired
Tanker (173,000 DWT)	1979	March 1986	AH-36 .75, EH	Main deck and longitudinal, aft .4L	Fatigue (12") Brittle fracture (10')	Stress concentra-tion at a con-struction detail	Material toughness of arrestor strake

- The majority of fractures examined occurred between October and April indicating the sensitivity of materials to lower temperature and therefore reduced notch toughness. These are also the months which the most severe sea conditions occur leading to higher structural loadings.

- Of the 16 fractures examined, four occurred in containerships, eight in tankers, two in Great Lakes bulk carriers, one in an ocean going bulk carrier and one in a tank barge. This represents a cross section of ship types.

- Categorized by operational area, three fractures occurred in the mid-Pacific, one in the Pacific coast of Japan, three in the U.S. Pacific coast, three in the North Atlantic, two in the Atlantic, two in the Great Lakes, and two at dockside or in calm water. This represents a cross section of ship operational areas.

5.2 EVALUATION OF FRACTURE CONTROL APPROACHES

Approaches to fracture control may be divided into three caregories: quantification of material flaw tolerance, minimization and evaluation of flaws and notches, and determination of structural stress. In the following paragraphs we explore each category and evaluate its contributions to the control of fractures in hull structure in light of the fractures investigated.

5.2.1 Material Flaw Tolerance

Material flaw tolerance is the ability of a material to perform plastically in the presence of a flaw, crack or notch [5-1]. It is a direct quantified link between a material's properties and fracture control. However, material flaw tolerance alone is not a panacea for fracture control. Indeed, today's ship steels exhibit adequate flaw tolerance under service conditions to prevent fractures if design details and welds are designed and executed properly. Rather, quantified material flaw tolerance is one of several considerations which, taken together, will improve our ability to control fractures in ships.

Recent research efforts in the area of material flaw tolerance have focused on flaw tolerance criteria and tests, which together would provide minimum fracture levels. Rolfe et al presented material guidelines in SSC-244 [5-2] and stimulated subsequent research [5-3, 5-4 and 5-5]. The combined research advanced the state of the art by proposing fracture mechanics methods for material test evaluations. However, the material guidelines were shown by the subsequent research to be too conservative. Pense [5-5] evaluated the criteria and suggested that Rolfe's proposed dynamic tear test and criteria are not representative of service conditions and recommended less severe criteria. Pense's primary conclusion centered around the strain rate at which the tests are conducted. He concluded that material tests must be conducted to evaluate the flaw tolerance of ship steels at intermediate strain rates in the elastic-plastic range instead of the linear-elastic range. Thus, while important results are already in hand, the research in this area is still in the developmental stage.

This research will also be used to correlate material flaw tolerance and critical flaw sizes. The material flaw tolerance is used as criteria for evalution of flaws and notches as described next.

5.2.2 Flaws and Notches

Flaws are defects in materials or weldments, such as slag inclusion, crack, porosity, undercut and lack of penetration. Notches are macroscopic, sharp radii. Flaws and notches constitute "Stress Risers", and as such, increase the opportunity for the initiation and propagation of a fracture within a given stress environment. Fabrication flaws were located at the origin of the majority of the fractures investigated in this report; thus the minimization and evaluation of flaws and notches are primary considerations in controlling fractures in ship structues.

The approach of minimizing flaws and notches is based on establishing criteria for acceptance or rejection of base materials and weldments which have some form of defect, and then working within those criteria during the material procurement, fabrication, and operational phases of the ship's life cycle. Note that not all defects degrade the material or weldment sufficiently to prevent its use. Existing materials criteria for ships are based on a "worst possible case" condition; i.e., many defects are treated as sharp cracks, when in fact they are not, which may lead to rejection of otherwise good material or weld, creating an unnecessary increase in fabrication cost.

Currently there are no verified methods for analyzing and evaluating flaw characteristics and growth rates for flaws in ship structures. However, there are techniques that have been proposed to assess flaws in structural details. The two basic approaches being proposed are those based on cumulative fatigue damage theories and those based on crack growth rates. Munse [3-9] developed a method to minimize the extent of fatigue damage in structural details. However, proven reliability factors have not been established or validated for ship design, fabrication and operational parameters. Fatigue assessment based on estimates of crack growth rates have been presented by Francis [5-7], Bokalvard [8-8], and Thaymbal [5-9] and are more complex than Munse's method. These methods relate crack initiation to critical crack size required to initiate brittle fractures. However, they also use reliability factors which have not been quantified for practical use. For example, fracture control approaches based on crack propagation rates require quantitative analyses of a structure's performance, and comparison of these analyses to "rational" design criteria and reliability. These criteria take the form of a statement of the system's design life, time between overhauls, etc. The criticality of a component must also be assessed since this enters into establishing confidence limits and probability of failure limits.

Thus, as with material flaw tolerance, important results are in hand but significant development remains to be done.

5.2.3 Structural Stress

Structural stress is the stress experienced by the various elements of the ship's structure. Estimating the state of stress in structural elements is a critical ingredient in effectively preventing fractures. In cases where fracture mechanics based fracture control approaches are used for complex structures, the load paths and changes in load paths which result from structural failure are crucial. For joints where crack growth and fracture are important considerations, it is imperative that exact internal stresses are defined from detailed calculations.

Research in this area has been quite profuse in the present decade, especially with the practical and extensive application of finite element techniques. Finite element computational techniques provide a wealth of information on stress in complex structures, even down to a detailed level. Unfortunately, finite element analysis of the required detail has not been able to support design and construction schedule constraints and has often not been justifiable until after a fracture has occurred. This situation is changing as new generation programs become available and techniques are developed.

Aside from these advances, the underlying finding derived from the review of case studies is that current stress prediction techniques are not able to determine the state of stress at the time of fracture even with the benefits of hindsight. This is caused by insufficient definition of the loading environment and lack of knowledge regarding various other factors such as residual stress. The case studies described in Section 3.0 highlight this conclusion. For example, residual stress, complex stress patterns and triaxial effects of notch constraints played a role in the fracture of the Great Lakes bulk carrier and the Tank Barge.

Again, as with material flaw tolerance and flaws and notches, important results are in hand but significant development remains yet to be done.

5.3 COMPREHENSIVE APPROACH FOR FRACTURE CONTROL IN SHIP STRUCTURE

The perspective gained from the examination (Section 3.0) and review (Section 5.1) of ship fractures indicates that fracture control is the responsibility of all those who design, classify, build, operate, inspect and repair ships. Each of these groups or individuals plays an important role in the control of ship fractures, whether it be select proper materials, eliminating design details which cause stress concentrations, ensuring adequate fabrication and welding procedures, or finally, operating the vessel in a prudent manner. An outline of the pertinent aspects of a comprehensive fracture control approach of this type is presented in Table 5-2.

TABLE 5-2

ELEMENTS OF A COMPREHENSIVE FRACTURE CONTROL APPROACH FOR SHIP STRUCTURES

I. Design (Goals: Specification of Strength & Fracture Resistance Properties)

   A. Determine/estimate stress distribution and related information (including operational temperatures, strain rates) and determine regions of greatest fracture hazard.

   B. Specify materials, strength properties, fracture properties, recommended heat treatments.

   C. Determine flaw tolerance in regions of greatest fracture hazard.

   D. Recommend fabrication procedures, welding methods, and allowable flaw sizes.

   E. Estimate stable crack growth for typical periods of service.

   F. Recommend safe operating conditions for specified invervals between inspection from the results of A-E. This may be ship specific or ship class specific based on the first few years of service and may be greatly influenced by building yard, area of operations, etc.

II. Fabrication (Goals: Protection of Specified Strength and Fracture Properties)

   A. Develop controls for residual stress, grain coarsening, grain direction.

   B. Inspect prior to final assembly.

   C. Inspect defects using appropriate non-destructive (ND) evaluation techniques at specified times after fabrication (welding).

   D. Maintain fabrication records.

III. Operations (Goals: Maintenance of Strength Parameters)

   A. Control the stress level and stress fluctuations in service.

   B. Maintain corrosion protection systems.

   C. Perform periodic in-service inspections as specified in 1F.

   D. Monitor growth of subcritical flaws.

   E. Repair or renew affected areas.

6.0 GUIDE FOR THE NON-EXPERT TO EVALUATE THE SIGNIFICANT CAUSES OF SHIP STRUCTURAL FRACTURES

The examination of ship structural fractures in most instances provides a wealth of information from which the causes contributing to the fracture occurrence can be determined. It is difficult for those involved in examining ship fractures who are neither metallurgists nor fracture experts to interpret information that is obtained by visual fracture inspection. A guide has been developed which will enable the non-expert to identify and document a fracture so that experts will have sufficient information to determine the origin and cause of the fracture. The guide explains in relatively simple terms the various fracture modes and their causes, and in addition gives the reader instruction and guidance for inspecting and documenting ship fractures. Numerous photographs and drawings are used to illustrate the text. This guide is presented in Part 2.

7.0 FURTHER RESEARCH ON SHIP STRUCTURAL FRACTURES

In the previous sections we identified the factors that contributed to fracture initiation. These factors must be controlled by using engineering approaches and methods to prevent significant fractures. However, these approaches and methods have not been fully validated for applications in ship structural design, construction and operation. Future research should be directed in key areas.

The recommended research topics are as follows:

1. Institute a program to survey major ship fractures in which the fractures are analyzed so that engineering methods and fracture mechanics techniques are developed and validated. Project tasks would include:
    - Survey actual significant ship fractures and document circumstances, environment, and characteristics of the fracture.
    - Conduct engineering analysis to determine detailed stress levels in the vicinity of the fracture.
    - Conduct material tests to quantify material crack tolerance, crack growth, and arrest capabilities by using and validating fracture mechanics techniques. Tests should be conducted in elastic-plastic ranges using CTOD, J-integral, etc..
    - Develop necessary reliability factors by hind casting methods to be used with fatigue and fracture control approaches for ship structures.
2. Develop a data base of material properties which characterize the crack growth rate, crack tolerance (based on the appropriate tests determined above) and arrest capabilities of ship steels and weldments. The objective of the research in the area of material toughness is not to develop materials with increased levels of toughness. The objective of this research is to quantify materials' ability to deform plastically in the presence of a flaw or notch by fracture mechanic techniques.
3. As confidence develops through the programs described above, integrate the fracture mechanics techniques into the existing fracture control methods as outlined in Table 5-2.
4. Maintain and publish a statistical analysis of major failures which would be sufficient to pinpoint problem materials, design and construction details, ship types, areas of operation and reason of occurrence.

If future research is directed in this manner, it will advance the state of fracture control in ship structures and permit those who design, classify, build, inspect, operate and repair ships to make rational decisions based on proven, integrated techniques.

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APPENDIX A

A. SUMMARY OF SELECTED FRACTURE CONTROL APPROACHES FOR VARIOUS TYPES OF METAL STRUCTURES

A.1 EXISTING FRACTURE CONTROL APPROACHES USED FOR MERCHANT SHIP STRUCTURES

A.1.1 Merchant Ships (Existing Approach)

The fracture control approach that is used for merchant ships, particularly those which are U.S. flagged, involves rules and regulations, typically ABS rules for building and classing steel vessels [A1-1] (although other rules may be used) and U.S. Coast Guard Inspection Regulations [A-2]. The general approach to fracture control includes design specifications for scantlings and welds which have a technical basis but include factors that have evolved from empirical data. Material specifications include yield strength, tensile strength, elongation, material toughness, chemical make-up and manufacturing processes. Operational limitations are imposed on still water stress levels and in cases allowable areas of operation.

The ABS rules for ordinary strength steels include two grades that require toughness testing, Grades D and E. For most applications, it is permissible to use Grades DS or CS, which do not require testing and consequently cost less, in place of Grade D or E, respectively. The reason for deleting test requirements is that experience has shown that Grades DS and CS consistently meet the toughness requirements for Grades D and E, respectively, due to controls on chemistry, deoxidation practice, and heat treatment. The metallurgical controls contribute directly to material toughness whereas the Charpy V-notch test simply measures toughness. Fabrication procedures are incorporated in the form of welding controls to qualify welders and welding procedures. Qualification of welders, welding design and testing, and inspection of welds are covered in ABS rules. Non-destructive testing (NDT) requirements are also required for critical welded joints, typically for butt welds in the primary hull girder structure and major welds as determined by the shipyard, ABS, USCG and the ship owner. On a case-by-case basis ships are required to carry means for the crew to control static loadings (bending moments) imposed on the hull girder by distribution of cargo and consumables.

A.1.2 Fracture Control Guidelines for Merchant Ships Proposed by Rolfe et al

Rolfe [A-3] and his co-workers developed a fracture control plan based on fracture mechanics principles. The plan involved specification of toughness at service temperature, assuming a loading rate and plate thickness; an assumed knowledge of the anticipated flaw size in the structure which could initiate brittle fracture; and an assumed knowledge of stress which might be expected at the point of initiation. These three factors can be interrelated by use of fracture mechanics concepts and they can be used to define conditions under which brittle fracture could initiate or could be prevented. Of these parameters for fracture control, Rolfe concluded that the stress and flaw size were too difficult to predict and therefore he put the full burden of fracture control on material toughness.

Rolfe determined that ship hull materials (plate, stiffeners and welds) should satisfy the criterion that nil ductility temperature based on the dynamic tear test be equal to or less than 0°F and critical stress intensity factors were developed.

Additional criteria were presented by Rolfe for load carrying members in the secondary stress regions. Qualifications were included to help take the burden from the material toughness requirements by stating the importance of proper design (avoiding details that lead to stress concentrations) and proper fabrication (good quality welding and inspection).

A.1.3 Proposed Modifications to Fracture Control Guidelines for Merchant Ships, SSC 307

Pense recommended modifications (SSC 307 [A-4]) to the Guidelines that were presented in SSC 244. Pense concluded from the review of material toughness data for typical ship steels, that the stress intensities presented by Rolfe were not representative of stress intensities commensurate with ship service loading rates. Pense also concluded in SSC 307 that it was not possible at this time to establish the crack arrest toughness energy requirements in the absence of knowledge of arrester configuration. This is one case where design and material toughness interact so closely that no simple material specification can be written. The conclusion was also made that base material could not realistically (economically) be expected to exhibit sufficient toughness to arrest dynamic running cracks that occur in ships.

A.2 FRACTURE CONTROL APPROACHES FOR SHIP TYPES OTHER THAN MERCHANT SHIPS

A.2.1 Fracture Control Approach Used in the Design of the USCG Icebreaker, POLAR STAR

An extensive research program was conducted prior to the design and construction of the POLAR STAR [A-5] icebreaker. The primary considerations for fracture control developed from this research included in-service load measurement, stress analysis, hull material definition, detail design and fabrication considerations, and procedures for inspection. Operational loading rates were inferred from measured strains on other types of icebreakers.

A grillage type structure was selected for the hull structural framing system because of its ability to retain strength following responses to overloads. This type of framing system may experience local plastic deformation under overloads but will not necessarily lose its ability to sustain additional loads at the design load level.

Material selection considerations were identified early in the design. Low temperature toughness characteristics were desirable. A service temperature of -50°F was considered applicable based on past data measured on icebreakers. Ease of fabrication and repair was considered since the heavy plating and dense framing systems involved can result in extensive forming, fabrication and welding. Yield point and ultimate strength were factors considered because of the severe impact loads caused by icebreaking operations. Plastic analysis was used for structural design and scantling selection.

Finally, cost was considered but since material characteristics were optimized, cost was considered subordinate to the other requirements. The structural designers examined several existing ASTM steels and modified the material composition to meet determined requirements.

The detail design of the icebreaker consisted of the development of S-N curves for critical details, especially for side shell frames which connect to deck beams. Structural details fatigue tested by Nibbering [A-6] were used as a guide to select details with adequate resistance to fatigue.

A.2.2 Naval Surface Ships and Submarines

The fracture control plan currently used by the Navy for surface ships and submarines is, like that used for merchant ships, an empirical program based on past experience. The "safe-metal" or "safe life" philosophy for fracture control is utilized for both surface ships and submarines. This entails selection of structural details, materials and fabrication processes that have been refined over decades of design experience. This approach is utilized because it is difficult to predict operating loads with a high degree of precision for most ships because of the environment in which they operate (including underwater explosions). Design manuals for details contain acceptable weld joint configurations and time-proven formulas to determine scantlings. The dynamic tear test is currently used to quantify the toughness of such hull structural materials as HY80 and HY130. Fabrication controls are used to guide structural inspections; however, the acceptance of the fabricated structures is based on past experience and no attempts are made to determine critical fabrication flaw sizes. Corrosion has received widespread attention for the higher strength materials, especially with reference to fatigue. The prevention of corrosion by coatings is the approach taken. Although fabrication controls are strict for all applications of high strength materials, submarine structures have required more care in fabrication, inspection and maintenance than have the structures for surface ships. Materials property criteria and qualification of suppliers of materials and fabrication processes are utilized to certify that the materials meet standards for indirect prevention of critical flaws.

Although the Navy has sponsored extensive research in the area of fracture mechanics, notably the works of Pellini [A-7], these techniques have no formal application in the fracture control of naval surface ships or submarines other than to qualify material toughness.

A.3 FRACTURE CONTROL APPROACHES FOR METAL STRUCTURES OTHER THAN SHIPS

A.3.1 Fixed Offshore Structures

The code approach to fracture control is used for the majority of fixed offshore structures. The codes which generally apply to fixed offshore structures are the USGS OCS Order 8 [A-8] and API RP24 [A-9]. The fracture control approach basically includes design loads and response considerations, material selection, quality assurance and service inspection. Loads imposed on the fixed offshore structure are typically a combination of static and dynamic loads, ranging from launching loads to earthquake loads. The design analysis includes stress analysis on both a global and local scale using space frame and finite element computer models. The damage tolerance of typical jacket rigs is improved by providing multiple load paths. Fatigue or brittle failure is generally localized to one brace. The remaining structure exhibits sufficient strength and further deterioration is sufficiently gradual to permit survival until the next periodic inspection. While the redundancy factor is part of the fixed structure design, other types of offshore structures such as floating platforms may or may not be designed with redundancy (redundancy is where the failure of one member does not lead to ultimate failure or loss of the entire structure). The design procedure typically includes fatigue analysis for "hot spot" stress spectra. Cumulative damage is computed using Miner's Rule and the AWS-X modified S-N curve.

Materials selection includes specified criteria and specifications. For redundant tubular bracing in the underwater jacket structure subjected to nominal stresses less than yield, dependencies on the initiation barrier at slow to moderate loading rates [A-10] permit the use of ordinary mild steel. Where higher strength steels are used, modest Charpy V-notch requirements similar to ASTM A709 are specified. Material specifications are given in codes (API) and ASTM standards for redundant bracing on fracture critical members such as joint cans. Processing requirements include effects of rolling plates to pipes on material toughness and welding processes. Fabrication requirements involve weld qualification and inspection of welds by radiographic and ultrasonic examination.

Inspection while in service is scheduled yearly for visual inspection for collision damage, splash zone corrosion, and effectiveness of cathodic protection. More detailed visual surveys are scheduled every 5-10 years for underwater braces. In some instances marine growth is removed to permit detailed color photographs for surface pitting and cracks.

A.3.2 Steel Bridges

Steel bridges in general use the code approach to fracture control. Primary codes include the standard specifications for Highway Bridges-American Association of State Highway and Transportation Officials (AASHTO).

The design procedure includes loads from the AASHTO code for dead load, live load and impact factors. Redundancy of structural components is encouraged. Fatigue analysis includes selection of details from AASHTO standards which are grouped into categories. The fatigue analysis includes the Miner's cumulative damage and S-N curve type approach. Material selection procedures include specifications for AASHTO materials (ASTM grades). Material toughness is gauged by Charpy V-notch requirements for fracture critical members. Toughness values are based on an intermediate loading rate and temperature shift criteria. This allows satisfactory notch toughness levels to be obtained that are well below the dynamic transition behavior, i.e., below the NDT temperature. Fabrication controls include welding codes and inspection of butt welds by radiography.

A.3.3 Gas and Oil Pipelines

Gas and oil pipelines also follow the code approach. The applicable codes are ANSI and API [A-11, A-12, A-13]. Applicable regulations include those in 49 CFR [A-14, A-15].

Structural design considerations include estimates of a wide variety of static and dynamic loads. A method for allowable stresses is included in the API code and is based on service application and welding procedures. Material properties, along with energy levels of toughness, are specified by the API codes. Requirements on pipeline quality are commonly specified by owner companies and usually exceed the requirements of the applicable codes and regulations. Crack arrest, although not required by codes and regulations, is specified by owner companies which require crack arrest capabilities in gas pipelines. This is generally achieved by specifying minimum toughness requirements sufficient to avoid long running cracks or by specifiying the use of mechanical crack arrestors at intervals along the line. Non-destructive testing of field welds is required by federal regulations.

A.3.4 Nuclear Pressure Vessels

The fracture control approach utilized for nuclear pressure vessels has developed out of a requirement for a high degree of safety. Various rules and regulations apply, namely the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code and, of course, regulations of the Nuclear Regulatory Commission (NRC). Structural design consists of calculation of various stresses (normal, shear, bending, thermal, fatigue) from several deterministic load sources, including internal and external pressure, deadweight and environmental loads (including earthquakes). Material toughness is specified for the NDT based on Charpy V-notch tests and K_I based on a surface flaw of 1/4 wall thickness values to establish allowable pressure at any operating temperature. Material certification and fabrication inspection is quite rigorous for acceptance of weld metal and heat affected zones. Periodic inspections are conducted according to ASME standards.

A.3.5 USAF Aircraft

The design and construction of USAF aircraft involve a variety of different materials. The fracture control approach utilizes fracture mechanics methods in contrast to the code approach to fracture control. Many concepts are state-of-the-art as far as applications are concerned. The performance specification approach is used for USAF advanced aircraft. There are standards and specifications and engineering approaches are utilized to develop a specific system that will perform for a given utilization.

The design and analysis of three basic structure types include damage tolerance considerations which are as follows:

- Slow crack growth structure: Design concepts where stress levels are limited to assure that cracks will not grow to critical sizes during specified periods of usage which depend on the degree of inspectability

- Crack arrest fail-safe structure: Structure design such that unstable, rapid propagation is stopped within a continuous area of structure and subsequent growth is slow enough to permit detection prior to complete failure

- Multiple load path, fail-safe structure: Structure designed in segments such that localized damage is contained within one or two segments and the remaining structure exhibits slow crack growth and provides sufficient strength until the subsequent inspection.

The stress analysis consists of the analytical determination of the stresses, deformations and margins of safety resulting from the external loads and temperature imposed on the air frame. The stress analysis is also used to verify air frame strength, provide stresses for fracture mechanics analysis, identify critical components, and to select loading conditions for structural testing.

Fatigue analysis for the USAF consists of the (full scale) semi-empirical determination of the growth behavior of small flaws assumed to exist at critical locations throughout the structure due to application of the design loads spectra. The analysis accounts for applied load sequence and environmental interactions, material property variations, and analytical uncertainties. The fatigue analysis is also used to verify that the economic life of the air frame is commensurate with the design service life.

Fracture mechanics analysis consists of flaw growth analysis and is used to verify the safety of the air frame from potentially catastrophic effects of initial defects caused by material manufacturing or processing malfunctions. Analysis is used to calculate critical flaw sizes, residual strengths, safe crack growth periods, and inspection intervals. Materials are selected based on concept/weight/material/cost trade-off studies, and not selected from a set list as in some codes. Specifications are developed by the contractor and approved by the USAF.

Fabrication and processing controls are used to ensure that the fastener installations do not invalidate the benefits of fatigue resistant systems. Processing requirements are imposed so that material toughness is not degraded to a value below that used in design. Inspection plans are approved by the USAF so that material flaws assumed in the design are detected. Prior to operation of USAF prototypes, full-scale tests are conducted to verify design assumptions and procedures.

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