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Weld Failures in Oil Tankers Due to Groundings - Finite Element Approach

by

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Abstract

The objective of this research supported by the Joint MIT-Industry Project on Tanker Safety is to develop a new technology in structural design and outflow control necessary to assess, design, build, certify, and operate a fleet of oil spill resistant tankers. The research seeks to develop hull design and fabrication methods including welding. Finite element method has been chosen as a way to understand the behavior of fillet welds in tanker structures. A two dimensional model of an oil tanker was first used to understand qualitatively the behavior of the welds as part of the structures. This study has led to a re-evaluation of the current rules on fillet welds sizes set by the ship classification societies and a further study of plate under combined bending and tension at hard-points support.

As part of a study of failure of plates at hard-point supports such as bulkheads, plate under combined bending and tension was modeled and analyzed using finite element method. The study showed that a combination of bending and tension loading only reduce the maximum loading by 2.5%, but it reduces the elongation of the plate by 40%.

The Lazy-L test configuration provides an understanding of the behavior of weld failure due to folding or tripping. Finite element analysis was performed to validate the upper bound analysis to the limit moment of the Lazy-L test configuration. This analysis, in turn, gives the slip-line field solutions to the single fillet weld Lazy-L test under predominant opening bending and predominant weld leg shear.

Thesis Supervisor: Professor K. Masubuchi
Title: Kawasaki Professor of Engineering

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Chapter 1

Introduction

1.1 Overview

The history of commercial ship design, construction, operation, and maintenance has been one of generally slow evolutionary change. This can be seen from the current ship structure classification society guidelines. These guidelines have been developed over the last hundred years, with concentrated development since the 1940's. The scantlings as derived from the modern rules and the over-all strength of structure do not differ significantly from those established 50 years ago. Furthermore, there has been no new scientific knowledge or service experience which would indicate that the classical rules are anything but sound standards. Safety considerations for the oil tankers nowadays are also the same as those for other classes of ships. Oil tankers have been designed to be safe under "normal" conditions. Naval architects have taken into account the safety of ships against fire, electrical installation, and instrumentation in designing ships. The integrity of the structures under groundings, however, has never been a design consideration.

With the advent of very large crude oil carriers (VLCCs) and the amount of tankers traffic in today's world, many phenomena occurred which had not previously existed with smaller ships. For example, a typical 100,000 deadweight tons (DWT) oil tanker, whose length is comparable to the Empire State building's height and whose draft is as deep as a five-story building, may damage many tanks before the vessel's massive kinetic energy is dissipated in the event of grounding or collision. The grounding or collision incident will cause an oil spill which will in turn damage the environment. Furthermore, tanker accidents such as the Exxon Valdez, and public concerns over the oil pollution, have drawn the maritime industry and classification societies' attention to the risks associated with marine transportation of crude oil and other hazardous materials cargoes. Attention has been directed especially towards the risks regarding groundings and collisions of tankers.

A considerable amount of study has been directed towards the structural strength of ships during collision, but very little effort towards the ship grounding problems [SSC-238, 1979]. Most of the research in the field of ships collision damage and protection has been devoted to the design of the reactor and nuclear spaces of nuclear powered ships. Relatively little attention has been paid to the development of methodologies for designing hull structures which can sustain the impact induced by a striking vessel, or during grounding incidents, without rupturing the plate. Many ships and tankers have been lost because of the structural failure following accidents such as collisions and groundings. Structural failure can eventually cause an oil spill, especially when the failure involves a rupture either of the plate or of the weld of the ship.

A typical construction of a tanker is an assembly of flat, or nearly flat, thin shell, orthogonally-stiffened panels. This panel structure is composed of transverse and longitu-

dinal stiffeners which are connected by fillet welds to the base plates. About 75% of welds in a ship structure are fillet welds. An overriding concern by ship designers and fabricators over the years has been to make sure that the fillet welds are strong enough. To reduce the weight and fabrication cost of ships, in the 1980's there was a consideration that the current specifications on fillet welds may be too conservative [SSC-296, 1980]. On the other hand, with the Exxon Valdez incident where the shell plates peeled off from the stiffeners, there is a concern that the current specifications on fillet welds are not cautious enough. From these contradictions, obviously, there is a lack of understanding of fillet welds behavior and a need to study the fundamental theory of the welds both in 'normal' and 'accidental/grounding' conditions. In addition, with a renewed consideration of the oil tankers crash worthiness, as emphasized by Wierzbicki et. al. (1991), there is a need for more intensive research into hull fillet weld failure due to grounding loads.

1.2 Objectives

An effort to study the amount of damage of tankers and other ships (single and double hulls) in grounding accidents was established within the MIT-Industry Project on Tanker Safety in 1992. A *Welding and Fabrication Research Team* was created to conduct an analytical and experimental study of fillet weld behavior and strength. Specific tasks included a survey of current welding practice and the failures of welded connections during the first year of the project. For the second year of the project, the *Welding and Fabrication Research Team* conducted an experimental study of the tearing strength of fillet welds subjected to peeling failure mechanism and an analytical study of tensile and shear strength of fillet welds using simple plasticity and fracture mechanics methods. In the third year, the focus of the welding and fabrication team is to study the behavior and

strength of fillet welds under combination of transverse shear, tension, and bending, and also the development of procedures for testing strength of fillet welds.

In view of studying the behavior and the strength of fillet welds under combined loading, a 2-D single hull tanker stranded on a rock is modeled and analyzed using the finite element method. The objective of this analysis is to study the behavior of the welds qualitatively. The analysis is also an attempt to predict the loads needed to rupture the plate. From the same general setup, with a slight modification, the behavior of the bottom plate near rigid supports, i.e., longitudinal and transverse bulkheads, can be studied. The purpose of this is to study the effect of bending moment on the maximum load the plate can carry and fracture of the plate due to the existence of the rigid supports. Finally, the Lazy-L test was proposed by Brooks in 1995 as a tool for designers and fabricators of fillet welded T-joints and to provide data for the strength of the fillet weld under combined transverse shear, tension, and bending load. Finite element analysis is utilized to study the strength and deformation for the single fillet weld Lazy-L test configuration.

1.3 Organization of This Thesis

This thesis is organized to provide the reader with an understanding of the behavior of fillet welds under grounding loads especially combination of transverse shear, tension, and bending.

Chapter 1 is an overview and discusses objectives of this study. The need of research in the crash worthiness of oil tanker including characterization of hull fillet weld failure due to grounding is stated.

Chapter 2 discusses the study of a 2-D single hull in stranding with an emphasis on the interaction between the bottom plate and the fillet welds. Review of the current rules on

fillet welds sizes and allowable root gap, set by the classification societies, is also presented in this chapter.

Chapter 3 reports the behavior of the bottom plate near the rigid support. This chapter discusses the necking conditions of the plate under combined bending and tension, up to the maximum load.

Chapter 4 discusses the finite element study of the strength and deformation for the single fillet Lazy-L test under predominant opening bending and predominant weld leg shear. In addition to finite element analysis, the upper bounds of the limit load and slip-line field theory are also utilized to study the strength of single and double fillet Lazy-L test.

Finally, Chapter 5 presents conclusions and recommendations for future work. Supporting calculations referred to in the body of the report are included in the Appendices at the end of every chapter.

Chapter 1 References

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Chapter 2

Single-Hull Tanker Stranding

2.1 Introduction to Chapter 2

Fillet welds are extensively used in tanker structures. However, in current practice, the fillet welds are designed only to meet minor shear stress loads under normal ship service conditions. Prevention of damage and rupture of the tankers due to collision or grounding has never been a design consideration.

Improved welding and steel-making techniques are causing an increase in the use of high-strength steel and smaller size welds in tanker hull design. Most modern tankers are built using high strength steel. It is known that higher strength steels have a characteristic of increasing strength but decreasing fracture toughness. Furthermore, the weld metal being used to match the base metal is usually a little bit higher strength which means an even lower fracture toughness. As a consequence, modern tankers are more susceptible to failure under unusual stress conditions. General concern over oil spill contamination plus recent interest in ship grounding behaviors necessitate ship designers to consider loads

associated with ship grounding in preliminary design of the vessel [National Research Council (NRC), 1991].

The dynamics of the grounding process are highly interactive [NRC, 1991]. This means that the amount of energy dissipated by the vessels during grounding incidents depends on several aspects such as the characteristics of the obstacle and the strength of the hull. The hull plating, longitudinal and transverse stiffeners, web frames, longitudinal and transverse bulkheads are all structural members that may be affected directly during collision or grounding. Most of these parts are connected by fillet welds. In current practice, the size of the fillet weld is relatively small compared to the plate thickness of the structural members. Typical fillet weld size to join a 15 mm thick stiffener to a 20 mm thick bottom plate is only 6mm. Although the yield strength of the weld metal is a little higher than the base metal, the leg length of a fillet weld is so significantly small that the welds might fail or deform before the base plate during groundings or collisions.

The goal of the MIT “Joint Industry Project on Grounding Protection of Tankers” is to improve hull design and fabrication methods against grounding. In order to achieve this goal, an extensive study about welds behaviors under different loading conditions is needed. From the results of the first year and the beginning of the second year, the *Welding and Fabrication Research Team* discovered that welds are difficult to scale down due to the many parameter involved in the welding process. On the other hand, if the weld size is not scaled down, the size of the specimen will be too big to be tested on any testing machine available at MIT. In addition, it is too expensive to run experiments on a complex structural model of the tankers at MIT. Therefore, an alternative approach was taken, namely using finite element method (FEM).

There are several types of fillet weld failures. The ‘peeling’ of the fillet welds is one type of failure that has been observed in tankers during groundings including the Exxon Valdez. This mode of failure has been studied during the first and second year of the Phase I Joint MIT-Industry Program on Tanker Safety [Kirkov, 1994 & Wilcox, 1995]. Another type of failure is the fracture of fillet welds due to folding or tripping of the longitudinal stiffeners or frames (see Figure 2.1 on p. 28). Although the fracture of fillets due to folding or tripping has not been found, this mode of fracture might be of importance in ship grounding and collision. This section of the thesis reports the study the fillet welds behavior due to folding or tripping and their interaction with the surrounding plates using finite element method.

2.2 Two-Dimensional Bottom Single-Hull Model

Finite element method (FEM) has been used extensively used in ship design and structural analysis. Most FEM studies explore the plasticity and elasticity of the plate of ships. Few studies have taken into account the welds as part of the structure. Most studies treat welds as part of the boundary conditions such as fixed ends boundaries. In the two-dimensional FEM study, the welds as part of the structures by using different material properties are considered. That is, the properties of the base metal are different from those of the weld metal.

The two-dimensional finite element model of a single-hull tanker in stranding is intended to study the behavior of fillet welds qualitatively. The interaction of the welds with the surrounding plates, namely the longitudinal web stiffener and bottom shell, is the main concern in this study. In addition, the study is also an attempt to determine the

strength of a fillet welded joint under given loading conditions, in this case a combined bending and tension loading.

2.2.1 Stranding location and boundary conditions

The geometry of the single-hull model used in this study is based on the midship section taken from 140,000 dwt VLCC, provided by Fernandez [private communications, 1993]. The VLCC prototype has a LBP of 269.0 m and a beam of 43.2 m. To study the behavior of the fillet welds under a combined bending and tension load, a cross section of the bottom shell of a single-hull oil tanker was modeled. Dimensions of the stiffeners and plate for the VLCC prototype are given in Figure 2.2 on p. 29.

The typical bottom structure of a single-hull tanker consists of longitudinal bulkheads, longitudinal girders, longitudinal stiffeners, and transverse bulkheads (see Figure 2.3 on p. 30). The rock is assumed to rupture the bottom shell midway between two longitudinal stiffeners. The longitudinal bulkhead on the left of the first stiffener and the longitudinal girder on the right of the second stiffener (section A-A on Figure 2.3 on p. 30) are assumed to be rigid. Therefore, for simplicity, both longitudinal bulkhead and bottom longitudinal girder are modeled as fixed ends boundary conditions. Figure 2.4 on p. 31 shows half of the 2-D single-hull bottom structure finite element model along with the boundary conditions.

To accommodate the three dimensional effect of the longitudinal stiffeners, a series of springs are modeled along the web and the flange of a stiffener. A series of transverse springs with a total stiffness equal to the bending resistance of the longitudinal stiffener web is prescribed along the web. Figure 2.6 on p. 32 shows the series of springs along the web of the stiffener which are fixed at the bottom part. Another series of springs was pre-

scribed horizontally along the flange of the stiffener (see Figure 2.5 on p. 32). The lateral springs were modeled to simulate the resistance given by the stiffener flange which prevents the longitudinal stiffener from moving sideways or rotating. The springs were attached to the nodal points of the stiffener web and flange. Calculation of the spring stiffness can be found in Appendix 2.A.

The maximum allowable gap (1/16"), as specified by the American Bureau of Shipping (ABS) classification society, was modeled between the web of the longitudinal stiffener and the bottom plate. The mesh was finer near the fillet welds area and on the fillet welds themselves. The finer mesh on these locations was incorporated to obtain more accurate results on the stress-strain of the fillet welds. The bottom shell was assumed to be straight before loading and the tank section was idealized without any oil or fluid inside the tank.

2.2.2 Rock geometry

There are various types and shapes of rocks in the ocean. Selecting a typical rock for use in the analysis is not easy. Certain assumptions need to be made due to lack of knowledge regarding the geometry of the sea rock encountered in groundings. In this study, it was decided to model the rock as a blunt wedge, i.e., a wedge with a curved edge where the rock is in contact with the bottom plate of the ship. A blunt wedge was chosen over a sharp wedge to avoid high stress concentration on the plate at the contact point with the wedge. Furthermore, a sharp, knife-like edge is relatively uncharacteristic of sea rock. Bracco (1994) explained the thought process behind choosing a radius on the cutting edge and choosing a broad semi-angle, θ . The cutting edge radius of the wedge was decided upon the bending strain when the bottom plate wraps around the rock. The bottom plate

was expected to wrap around the rock before the analysis terminated. Bending strain, ϵ , of 0.02 was decided based on the previous work [Turgeon, 1995]. From the strain given, the radius of curvature can be obtained by using

$$\epsilon = \frac{t/2}{R} \quad (2.1)$$

For the 2-D single-hull model analyzed, with plate thickness of 20 mm, the radius of the curvature turned out to be 500 mm. Finally, the angle of attack, α , of the rock with respect to the hull plate required definition. The angle of attack at the base of the rock was decided to be 30°. The shape and dimension of the rock can be seen in Figure 2.7 on p. 33.

2.2.3 Materials

The materials used are in compliance with the ABS Rules for Building and Classing Steel Vessels which are also in compliance with the NK Classification Society rules. The weld metal has a slightly higher yield strength. Elastic-plastic strain hardened material is used for the analysis except for the rock. The rock material is elastic with higher modulus of elasticity to prevent deformation of the rock. For this purpose, a tool steel was chosen as the material of the rock. The material properties for the base plate, weld metal, and the rock are as follows:

Base metal:

EH36 (ABS Specification) or KA36 (NK Specification)

Tensile strength = 560 N/mm² (490 ~ 620 N/mm² by specification)

Yield strength = 420 N/mm² (> 355 N/mm² by specification)

Maximum allowable effective plastic strain = 19%

Deposited (weld) metal:

Shielded Metal Arc Welding

Electrode: AWS A5.1.E7016

(Kobe Steel “LB-52”)

Tensile strength = 560 N/mm^2 ($490 \sim 620 \text{ N/mm}^2$ by specification)

Yield strength = 490 N/mm^2 ($> 355 \text{ N/mm}^2$ by specification)

Maximum allowable effective plastic strain = 22%

Wedge (Rock):

Tool Steel

Modulus of elasticity = $5.5 \times 10^5 \text{ N/mm}^2$

Tensile strength = $2,475 \text{ N/mm}^2$

The material characteristics input to the computer program was elastic-plastic material with bi-linear isotropic strain hardening stress-strain curve. The tangent modulus was chosen to be $1/40$ of the elastic modulus $E_t = \frac{1}{40}E$. The fracture criterion given was the maximum allowable equivalent plastic strain in simple tension. The weld metal has a slightly higher effective plastic strain (22%) compared to the base plate's effective plastic strain (19%).

The type of element used in this analysis was plane strain, 2-D solid, with 8 nodes in each element.

2.3 Finite Element Analysis

2.3.1 Methods

A frictionless contact problem was considered in this analysis. Contact between the bottom plate of the model and the rock was considered. In this study, besides studying the behavior of the fillet welds, the maximum load that the structure can support prior to structural instability or collapse was also estimated. The most appropriate way to calculate the maximum load which the structure can carry safely is to perform an incremental analysis using the non-linear formulation such as the Total Lagrangian Formulation. If equilibrium iterations are performed in the incremental solution, the analyst may observe convergence difficulty as the collapse load is approached. The convergence difficulty arose because the analyst has to prescribe the various load levels for which the equilibrium configurations are to be calculated. This can be difficult without knowledge of the approximate load carrying capacity of the structure. The best method to use is the automatic load-displacement control (automatic LDC) method which is available in the ADINA program. The automatic LDC method is usually used to solve for the nonlinear equilibrium path of a model until its collapse. The main feature of this method is that the level of externally applied loads is adjusted automatically by the program. With the automatic LDC method, the computer will terminate the program if one of the following conditions is satisfied:

1. The maximum displacement specified by the user is reached.
2. A critical point on the equilibrium path has been passed and solution termination is requested by the user.
3. The number of converged solution is reached.

4. The incremental solution has been attempted four (4) times from a calculated equilibrium configuration using different strategies but each time the solution has failed to converge within the number of allowed iterations.

The advantage of using automatic LDC method is that the analyst does not need to prescribe the various load levels, the program selects the load increments automatically. Using the automatic LDC method, the user only needs to specify the displacement at a node corresponding to the first load level. In addition to the four stopping conditions mentioned above, the program will be terminated if the fracture criterion for any material is reached for elastic-plastic analysis.

2.3.2 Results

The deformed configuration at the end of the analysis can be seen in Figure 2.8 on p. 34. The dashed lines show the original configuration while the solid line shows the deformed configuration. The bottom plate was expected to wrap around the rock due to the radius of the wedge chosen. The rock should penetrate all the way before the plate ruptures. It turned out that the computation was terminated much sooner, before the bottom plate wrapped around the rock. The maximum displacement in the z-direction at the end of the analysis was only 346.75 mm (see Figure 2.8 on p. 34). The force per unit width obtained from the analysis was 13,893 N/mm.

There are several possible reasons for the termination of the program. One possibility is that there is high strain concentration on the fillet welds and the welds deform or fail. Another possibility is that the plate near the fixed end ruptures. It appears from this analysis that there is a high strain concentration on the fillet welds. Figure 2.9 on p. 35 shows the plot of principal plastic strains on both lower and upper joints of the structure. However, the maximum strain on the welds is only 0.06. The plot of the accumulative effec-

tive plastic strain on the whole structure showed that the highest plastic strain was at the bottom plate near the fixed end (see Figure 2.10 on p. 36). The value of the plastic strain, indicated by the triangle, is 0.1894 which is very close to the equivalent strain at fracture (19%). Some curvature was also observed near the fixed end (see Figure 2.11 on p. 37). Figure 2.11 shows a curvature near the fixed end, where the dashed lines indicate the original structure and the solid lines indicate the deformed structure. From this result, more study was conducted on the size of the fillet welds and the behavior of the plate near the bulkhead which serves as a hard-point support. The following sections discuss the current rules regarding fillet weld sizes and plate behavior at hard-point support.

2.3.2.1 Current rules from classification societies and effects of gaps

The current rules from ship classification societies allow a gap between the bottom plate and the longitudinal stiffener. This gap is called a root gap. Fillet weld design and sizes are found in Part 3 Section 23 “Weld Design” of the ABS Rules for Building and Classing Steel Vessels 1992 and Chapter 1 Table C 1.4 of NK Classification Society Rules (Appendix 2.B on p. 42 and Appendix 2.C on p. 47 respectively).

The ABS Rules specify that the gaps between the faying surfaces of members being joined should be kept to a minimum with a maximum gap of 2 mm (1/16 in) without increasing the amount of the weld size. If the gap is greater than 2 mm (1/16 in), the weld leg size is to be increased by the amount of the opening and if the opening is greater than 5 mm (3/16 in), corrective procedures are to be specially approved by the Surveyor. Table 3/23.1 of ABS Rules on Double Continuous Fillet Weld Sizes lists the weld size for the lesser thickness of members joined for different areas of the steel vessels. Similarly, Table C 1.4 of NK Classification Society Rules lists the welds size, including the minimum

allowable size to be used to connect different parts of tanker structures with different plate thicknesses.

It appears from the single-hull stranding finite element study that for structures with the maximum allowable gap between the faying surfaces, deformation can happen on the welds instead of the web under combined loading. For sufficiently strong fillet welds we want the web to bend before the fillet shear. To achieve this we want the bending strength of the web to be less than the bending strength of the fillet weld. To ensure the fillet weld is strong enough, we can estimate the ratio of fillet to web bending strength using

$$\frac{2k_w t_w^2}{4} < 2k_f d_f \frac{t_w}{2} \quad \text{or} \quad \frac{2k_f d_f}{k_w t_w} > 1 \quad (2.2)$$

After reviewing the current rules set by ABS and NK classification societies, we found that in some plate-welds configurations, with the maximum allowable gap, the welds might deform before the web.

Table 2.1 Table of fillet/web bending strength for ABS rules^a

Web thickness (t_w), mm	Fillet leg length (d), mm	Effective leg length (d_f), mm	Ratio ($2*k_f*d_o/(k_w*t_w)$) without gap	Ratio ($2*k_f*d_f/(k_w*t_w)$) with gap
9	6	4.41	1.15	0.84
10	6	4.41	1.03	0.76
11	6	4.41	0.93	0.69
18	6	4.41	0.57	0.42
20	6	4.41	0.52	0.38

a. $k_w = 490$ MPa, $k_f = 420$ MPa

Table 2.2 Table of fillet/web bending strength for NK rules^a

Web thickness (t_w), mm	Fillet leg length (d), mm	Minimum leg length (d_f), mm	Ratio $(2*k_f*d)/(k_w*t_w)$	Ratio $(2*k_f*d_f)/(k_w*t_w)$ for min. leg length
9	6	4	1.14	1.04
10	6	4	1.02	0.93
11	6	4	0.93	0.85
18	9	7	0.86	0.91
20	9	7	0.77	0.82

a. $k_w = 490$ MPa, $k_f = 420$ MPa

Table 2.1 and 2.2 show that for some combinations of plate and welds, the values of fillet to web bending ratios are less than one. This means the deformation is on the weld instead of the web. The NK rules give a better weld strength, compared to the ABS rules where the ratio values are closer to one.

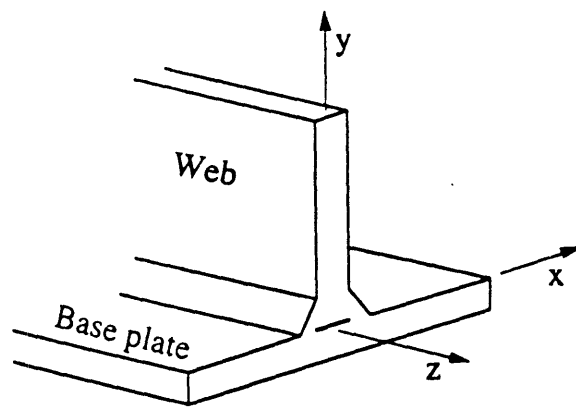
2.3.2.2 Plate at the hard-point support

It is known that large plates used in structures are vulnerable to fracture near their clamped or reinforced edges due to the constraint induced by the reinforcements. This phenomenon is called hard-point fracture. The longitudinal bulkhead on the 2-D single-hull model serves as a hard point, and often in accidents the plates break off rather cleanly at the bulkhead.

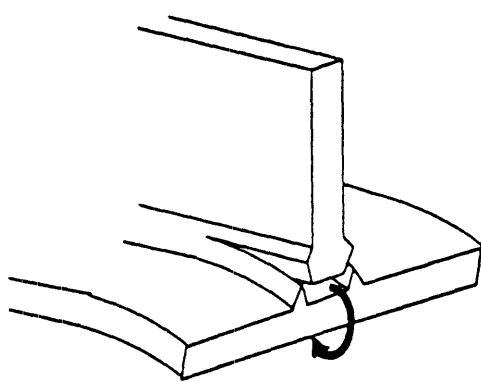
From the 2-D single-hull stranding analysis, some curvature near the clamped edge where the longitudinal bulkhead is located was observed. It was also observed that some necking localization started to develop near the clamped edge (see Figure 2.11 on p. 37). Due to the mesh size used in this model, the behavior of the plate at the hard-point support

cannot be seen in details. Therefore, a refined mesh is needed to study the behavior of the plate near the hard-point support more accurately.

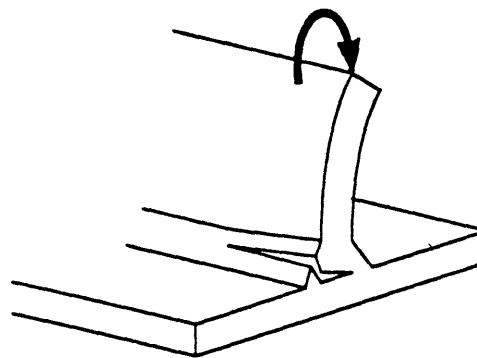
The study of the plate under combined bending and tension at the hardpoint support is presented in Chapter 3 of this thesis. The effect of bending on the tensile necking to the maximum load and plate extension is the focus of the study.



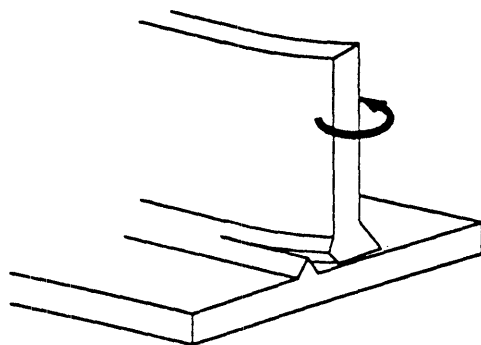
Coordinate axes for a T-joint



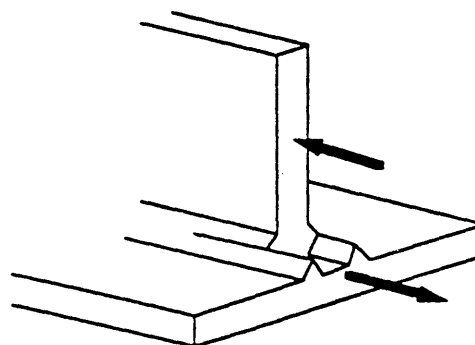
(a) Tearing



(b) Web folding



(c) Web bending



(d) Longitudinal shearing

Figure 2.1 Fillet welds mode of failures

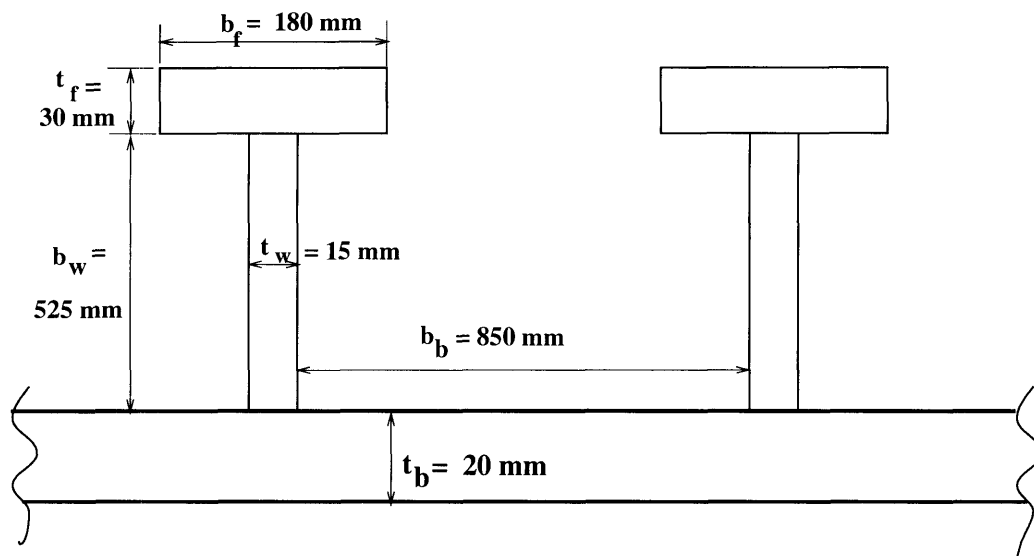


Figure 2.2 Stiffener and plate dimensions

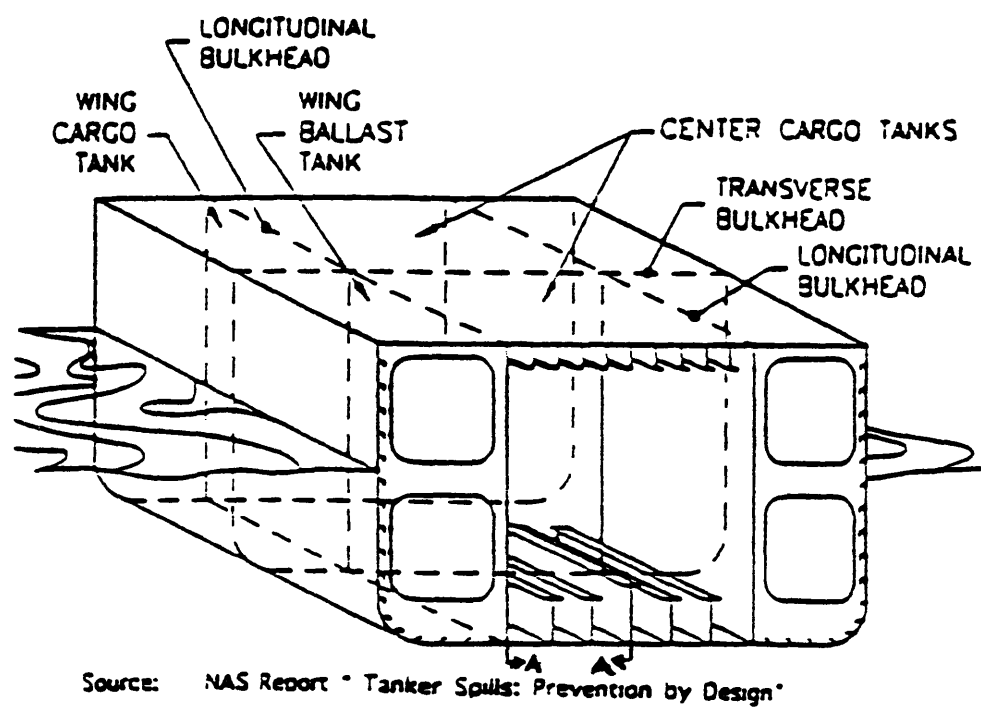


Figure 2.3 Typical bottom structure of single-hull oil tanker

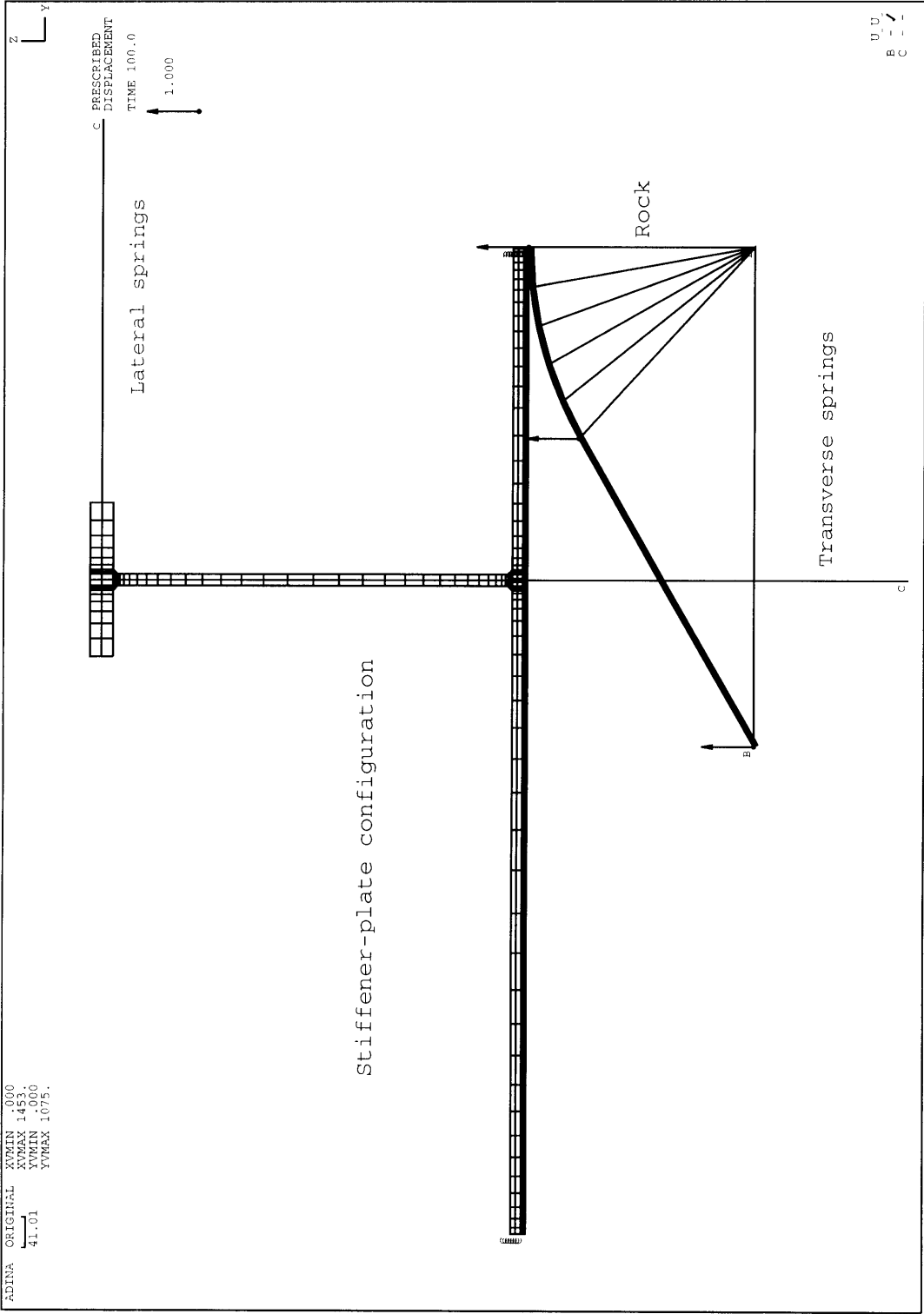


Figure 2.4 Finite element model and boundary conditions

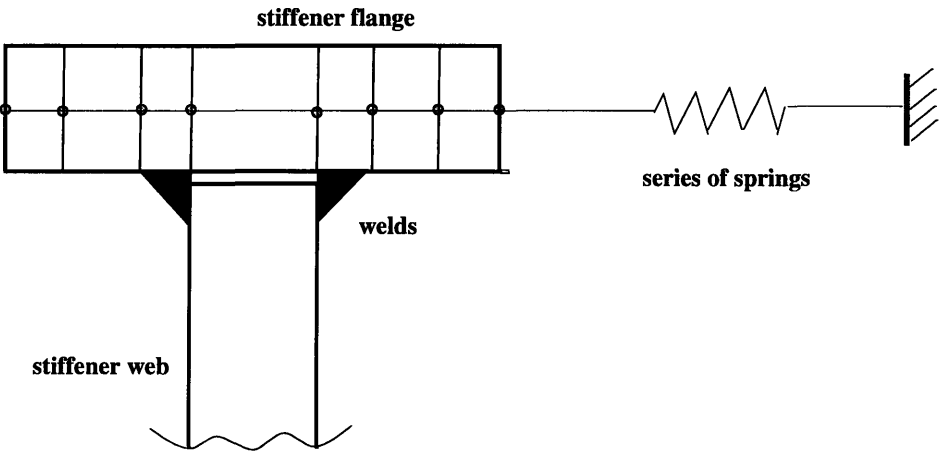


Figure 2.5 Lateral springs along the stiffener flange

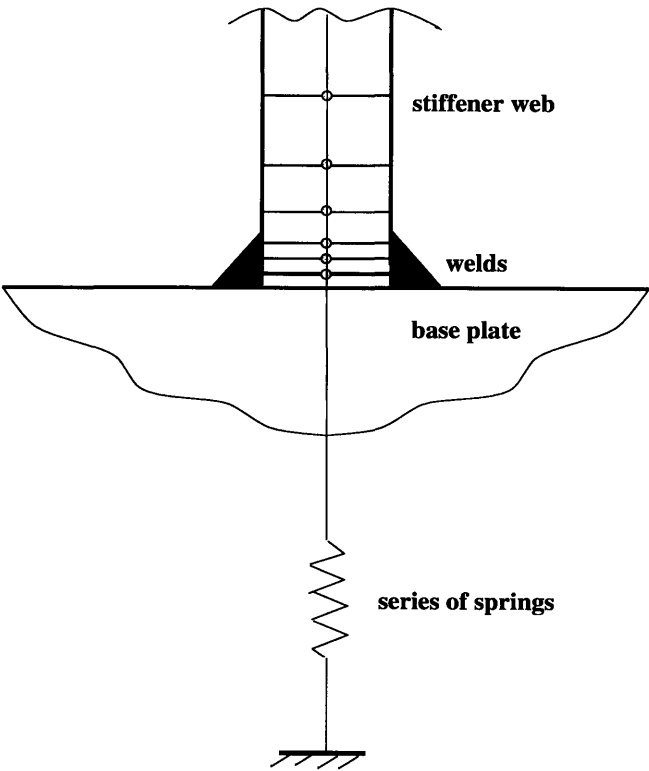


Figure 2.6 Transverse springs along the stiffener web

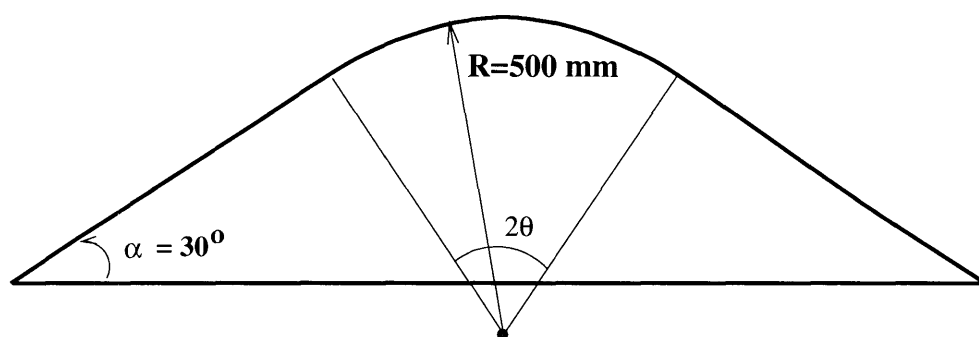


Figure 2.7 Shape and dimensions of the rock

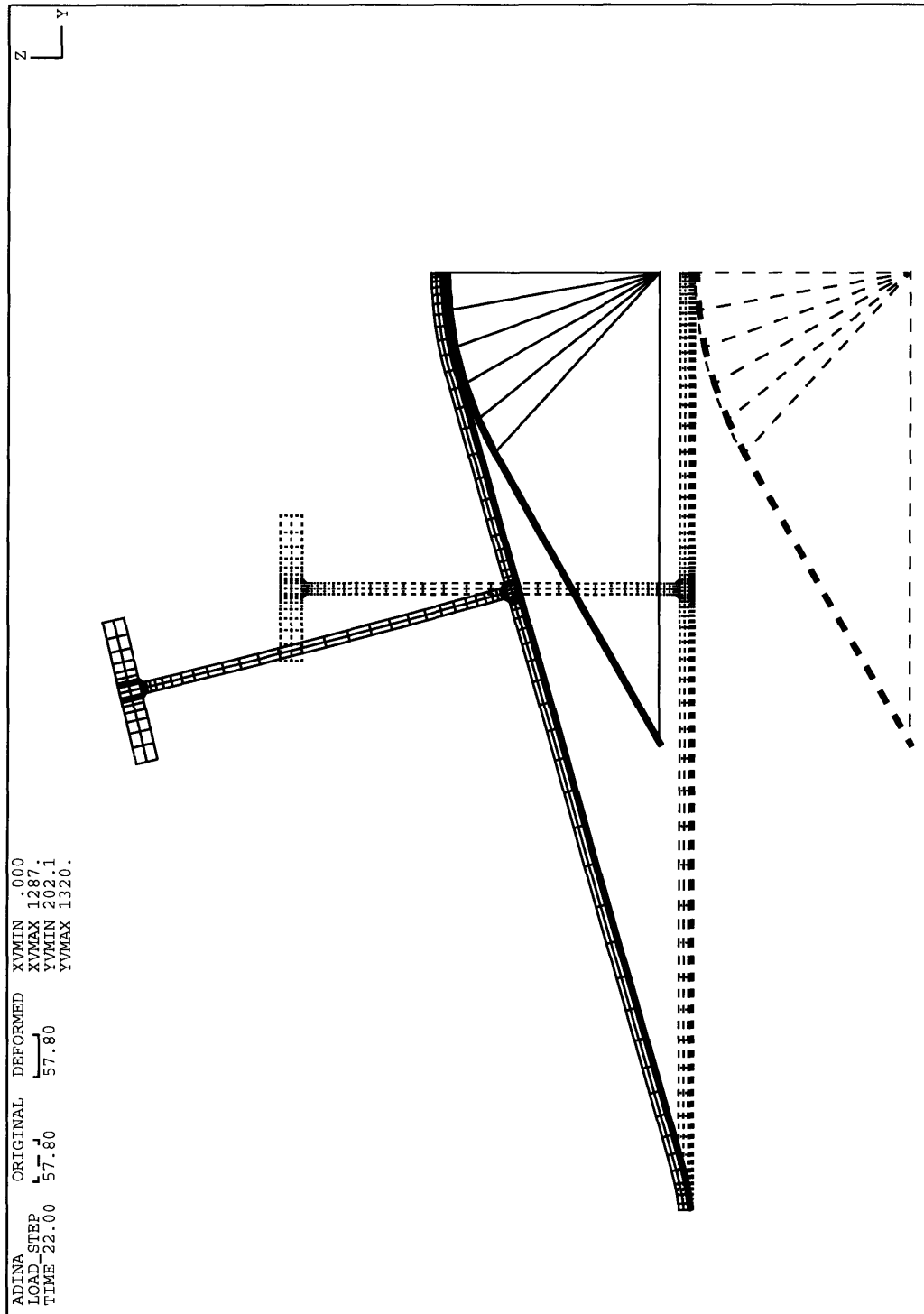
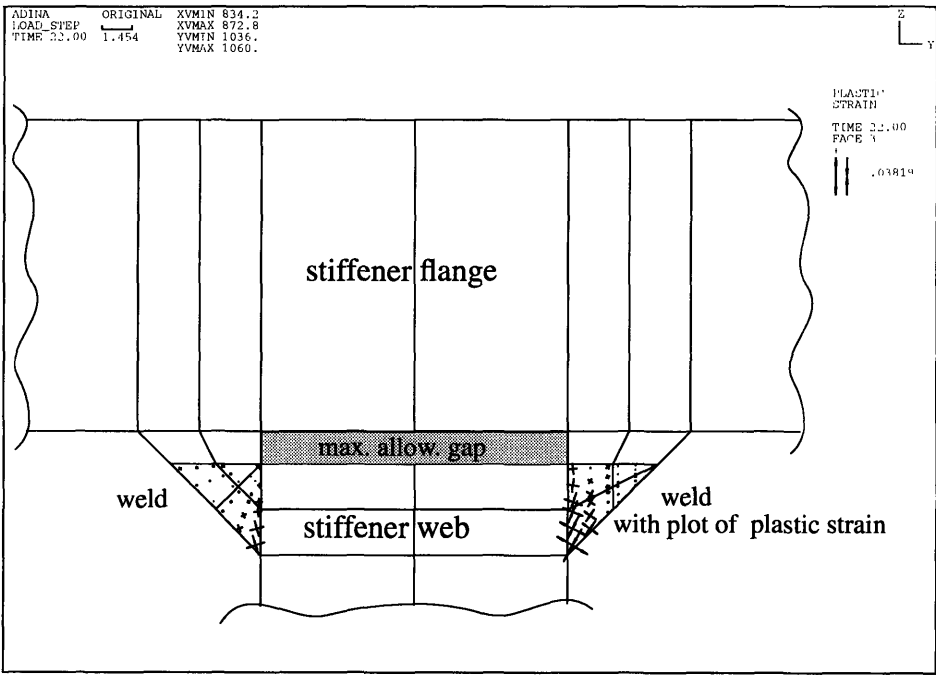
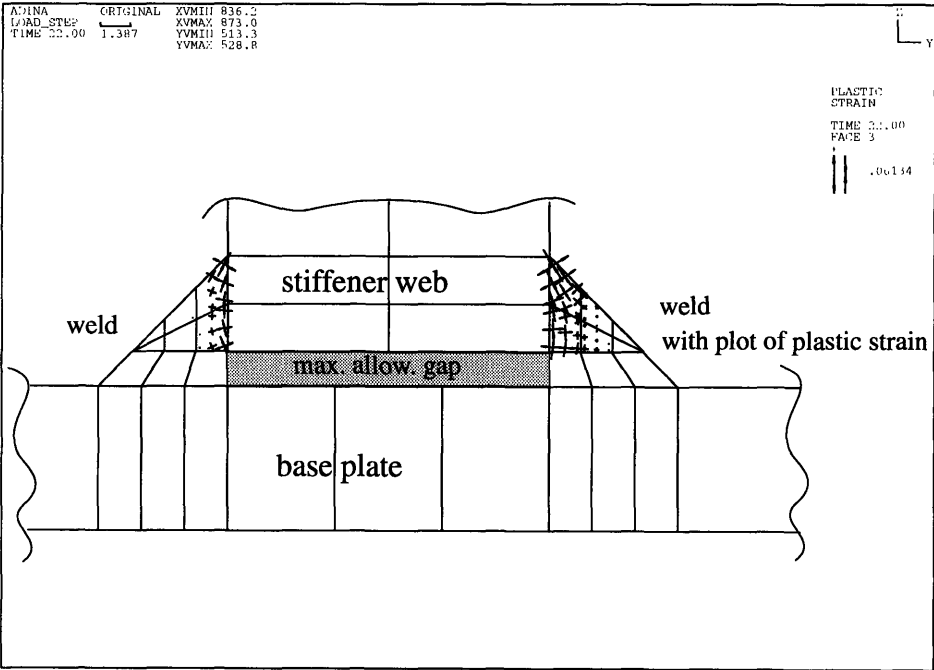


Figure 2.8 Deformed configuration



a. Upper joint



b. Lower joint

Figure 2.9 Principal plastic strain on the upper and lower joint

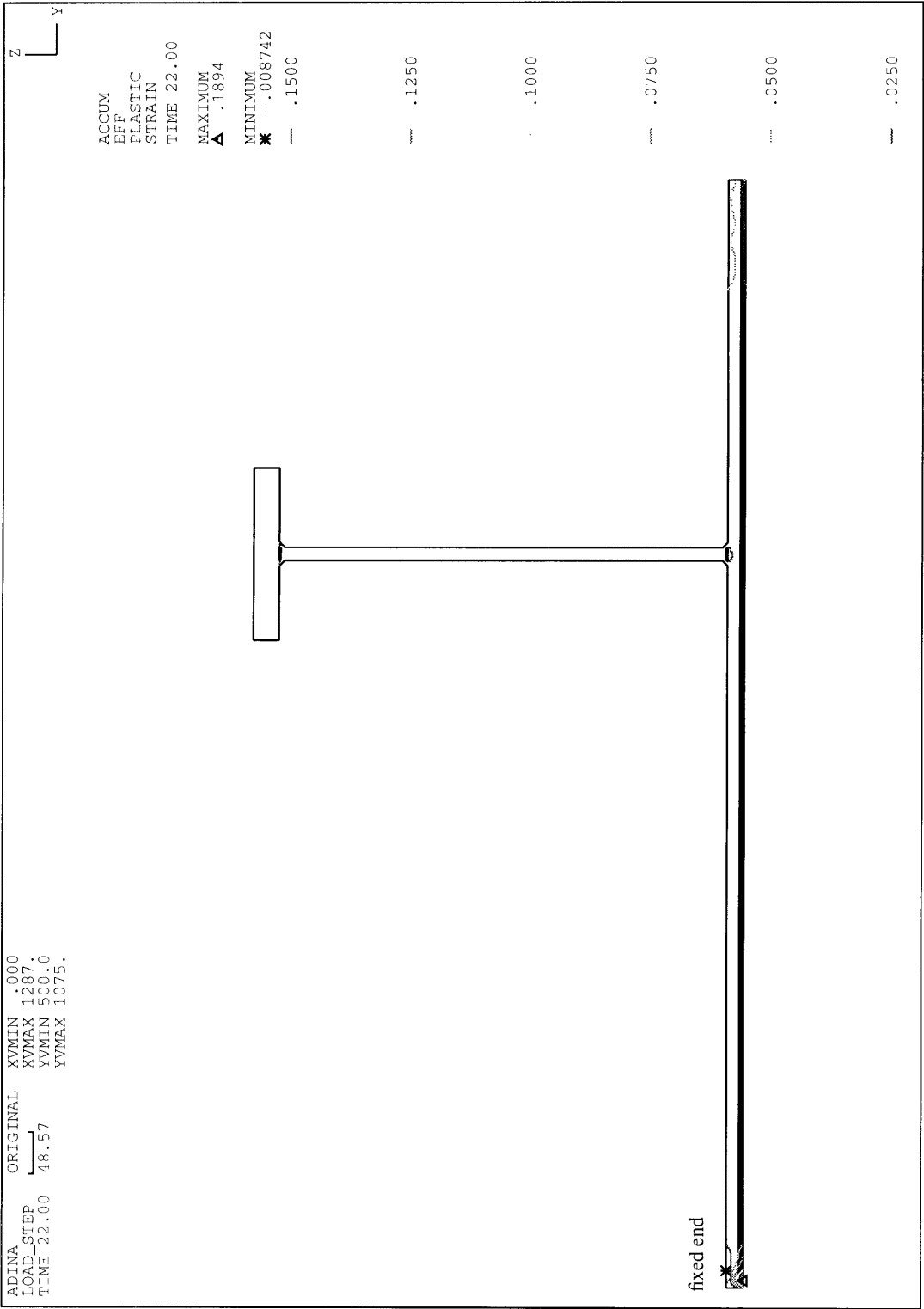


Figure 2.10 Accumulative effective plastic strain of the structure

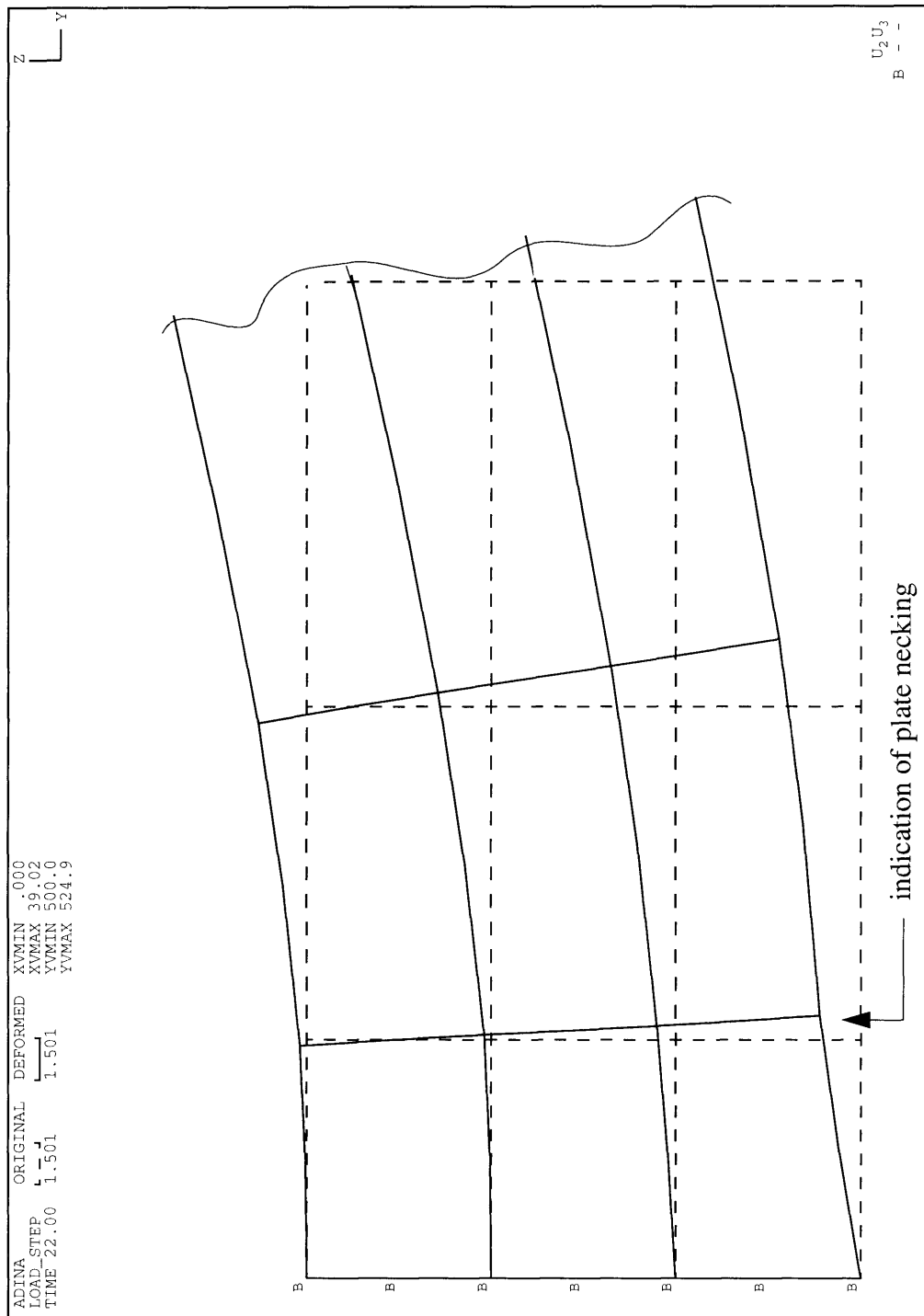


Figure 2.11 Curvature and necking near the clamped edge

Chapter 2 References

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Appendix 2.A

Spring Stiffness Calculations

This appendix describes the calculations of the transverse spring stiffness to simulate the bending resistance of the stiffener web and the lateral spring stiffness to simulate resistance of the stiffener flange.

2.A.1 Transverse Spring Stiffness Calculations

The transverse springs are modeled to simulate the bending resistance along the longitudinal stiffener in the third dimension. The stiffener is assumed located longitudinally between two transverse bulkheads. The transverse bulkheads are assumed to be rigid, therefore, the boundary conditions at both ends of the longitudinal stiffeners are fixed (see Figure 2.A.1 on p. 41). Displacement on the y-direction along the beam can be calculated using

$$\delta = \frac{1}{EI} \left[\frac{1}{6} w a x^3 - \frac{1}{24} w (x-a)^4 - \frac{5}{12} w a^2 x^2 - \frac{1}{6} w a^3 + \frac{1}{24} w a^4 \right] \quad (2.A.1)$$

Maximum displacement is at $x=2a$, therefore, the maximum displacement is

$$\delta = \frac{1}{EI} \left(-\frac{2}{3} w a^4 \right) \quad (2.A.2)$$

The stiffness k of the beam for a unit width can be calculated from the load per unit length on the beam divide by the displacement δ

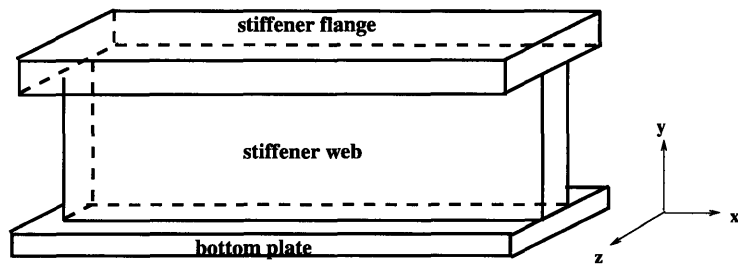
$$k = \frac{P / (2a)}{\delta} \quad (2.A.3)$$

where in our case, $P = 2wa$. Plugging in this value and Equation 2. A.2 into Equation 2. A.3, the spring stiffness per unit width becomes

$$k = \frac{w}{\frac{1}{EI} \left(-\frac{2}{3} wa^4 \right)} = -EI \frac{3}{2a^4} \quad (2.A.4)$$

2.A.2 Lateral Spring Stiffness Calculations

The lateral spring is modeled to simulate the stiffness of the stiffener flange which prevents the longitudinal from moving sideways or rotating. The calculation is similar to the calculation for the transverse spring stiffness except the shape of the beam is not an I-beam but a simple rectangle (see Figure 2.A.2). The stiffness of the spring is calculated using Equation 2. A.4.



Drawn not to scale

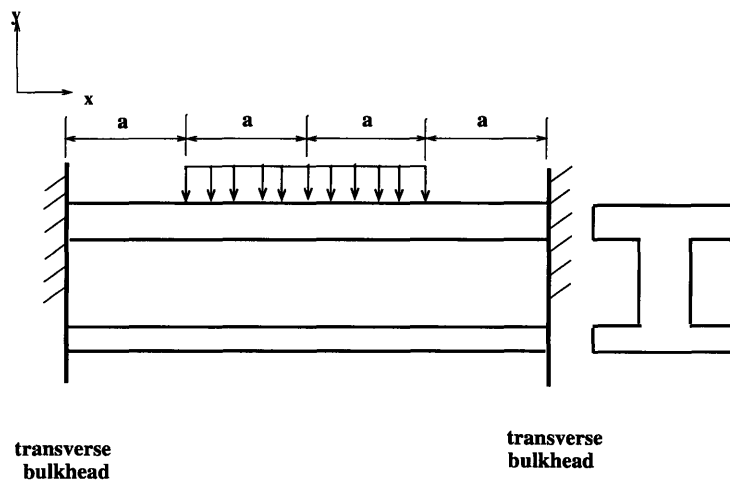


Figure 2.A.1 Longitudinal stiffener/ base plate combination

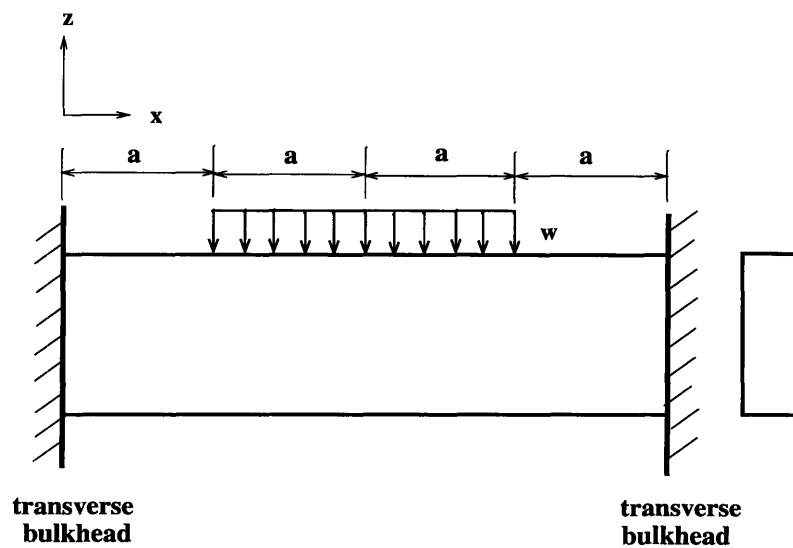


Figure 2.A.2 Stiffener flange

Appendix 2.B

ABS Rules for Building and Classing Steel Vessels 1992

PART 3 SECTION 23

Weld Design

3/23.1 Fillet Welds

3/23.1.1 General

a Plans and Specifications

The actual sizes of fillet welds are to be indicated on detail drawings or on a separate welding schedule and submitted for approval in each individual case.

b Workmanship

Completed welds are to be to the satisfaction of the attending Surveyor. The gaps between the faying surfaces of members being joined should be kept to a minimum. Where the opening between members being joined exceeds 2.0 mm (1/16 in.) and is not greater than 5 mm (3/16 in.), the weld leg size is to be increased by the amount of the opening. Where the opening between members is greater than 5 mm (3/16 in.), corrective procedures are to be specially approved by the Surveyor.

c Special Precautions

Special precaution such as the use of preheat or low-hydrogen electrodes or low-hydrogen welding processes may be required where small fillets are used to attach heavy plates or sections. When heavy sections are attached to relatively light plating, the weld size may be required to be modified.

3/23.1.2 Tee Connections

a Size of Fillet Welds

Tee connections are generally to be formed by continuous or intermittent fillet welds on each side, as required by Table 3/23.1. The leg size, w , of fillet welds (see figure in Table 3/23.1) is obtained from the following equations.

$$w = t_{pl} \times C \times \frac{s}{l} + 2.0 \text{ mm}$$

or

$$w = t_{pl} \times C \times \frac{s}{l} + 0.08 \text{ in.}$$

$w_{min} = 0.3 t_{pl}$ or 4.5 mm (4.0 mm where 3/23.1.5 is applicable) if that be greater.

Where

- l = the actual length of weld fillet, clear of crater, in mm or in.
- s = the distance between successive weld fillets, from center to center, in mm or in.
- s/l = 1.0 for continuous fillet welding
- t_{pl} = thickness of the thinner of the two members being joined in mm or in.
- C = weld factors given in Table 3/23.1

In selecting the leg size and spacing of matched fillet welds, the leg size is to be taken as the lesser of the designed leg size or $0.7 t_{pl} + 2.00 \text{ mm}$ ($0.7 t_{pl} + 0.08 \text{ in.}$).

In determining weld sizes based on the above equations the nearest half millimeter or one-thirty second of an inch may be used.

The throat size, t , is to be not less than $0.70 w$

For the weld size for t_{pl} less than 6.5 mm (0.25 in.), see 3/23.1.2f.

b Length and Arrangement of Fillet

Where an intermittent weld is permitted by Table 3/23.1, the length of each fillet weld is to be not less than 75 mm (3 in.) for t_{pl} of 7 mm (0.28 in.) or more nor less than 65 mm (2.5 in.) for lesser t_{pl} . The unwelded length is to be not more than $32 t_{pl}$.

c Intermittent Welding at Intersection

Where beams, stiffeners, frames, etc., are intermittently welded and pass through slotted girders, shelves or stringers, there is to be a pair of matched intermittent welds on each side of each such intersection and the beams, stiffeners and frames are to be efficiently attached to the girders, shelves and stringers.

d Welding of Longitudinal to Plating

Welding of longitudinals to plating is to have double continuous welds at the ends and in way of transverses equal in length to depth of the longitudinal. For deck longitudinals only, a matched pair of welds is required at the transverses.

e Stiffeners and Webs to Hatch Covers

Unbracketed stiffeners and webs of hatch covers are to be welded continuously to the plating and to the face plate for a length at ends equal to the end depth of the member.

f Thin Plating

For plating of 6.5 mm (0.25 in.) or less, the requirements of 3/23.1.2a may be modified as follows:

$$w = t_{pl} C \frac{s}{l} + 2.0 \left(1.25 - \frac{t}{s} \right) \text{ mm}$$

$$w = t_{pl} C \frac{s}{l} + 0.08 \left(1.25 - \frac{t}{s} \right) \text{ in.}$$

$w_{min} = 3.5 \text{ mm}$ (0.14 in.)

The use of above equations for plating in excess of 6.5 mm (0.25 in.) may be specially considered depending upon the location and quality control procedure.

3/23.1.3 Tee-Type End Connections

Tee-type end connections where fillet welds are used are to have continuous welds on each side. In general the leg sizes of the welds are to be in accordance with Table 3/23.1 for unbracketed end attachment, but in special cases

where heavy members are attached to relatively light plating, the sizes may be modified. Where only the webs of girders, beams and stiffeners are required to be attached to plating, it is recommended that the unattached face plate or flanges be cut back.

3/23.1.4 Ends of Unbracketed Stiffeners

Unbracketed stiffeners of shell, watertight and oiltight bulkheads and house fronts are to have double continuous welds for one-tenth of their length at each end.

Unbracketed stiffeners of nontight structural bulkheads, deckhouse sides and after ends are to have a pair of matched intermittent welds at each end.

3/23.1.5 Reduced Weld Size

Reduction in fillet weld sizes except for slab longitudinals of thickness greater than 25 mm (1.0 in.) may be specially approved by the Surveyor in accordance with either 3/23.1.5a or b provided the requirements of 3/23.1.2 are satisfied.

a *Controlled Caps*

Where quality control facilitates working to a gap between members being attached of 1 mm (0.04 in.) or less, a reduction in fillet weld leg size w of 0.5 mm (0.02 in.) may be permitted.

b *Deep Penetration Welds*

Where automatic double continuous fillet welding is used and quality control facilitates working to a gap between members being attached of 1 mm (0.04 in.) or less a reduction in fillet weld leg size of 1.5 mm (1/16 in.) may be permitted provided that the penetration at the root is at least 1.5 mm (1/16 in.) into the members being attached.

3/23.1.6 Lapped Joints

Lapped joints are generally to have overlaps of not less width than twice the thinner plate thickness plus 25 mm (1 in.)

3/23.1.6a Overlapped End Connections

Overlapped end connections of longitudinal strength members within the midship $0.4L$ are to have continuous fillet welds on both edges each equal in size w to the thickness of the thinner of the two plates joined. All other overlapped end connections are to have continuous welds on each edge of sizes w such that the sum of the two is not less than 1.5 times the thickness of the thinner plate.

3/23.1.6b Overlapped Seams

Overlapped seams are to have continuous welds on both edges of the sizes required by Table 3/23.1 for the boundaries of deep tank or watertight bulkheads, except that for seams of plates 12.5 mm (1/2 in.) or less clear of tanks, one edge may have intermittent welds in accordance with Table 3/23.1 for watertight bulkhead boundaries.

3/23.1.7 Plug Welds or Slot Welds

Plug welds or slot welds may be specially approved for particular applications. Where used in the body of doublers and similar locations, such welds may be spaced about 305 mm (12 in.) between centers in both directions.

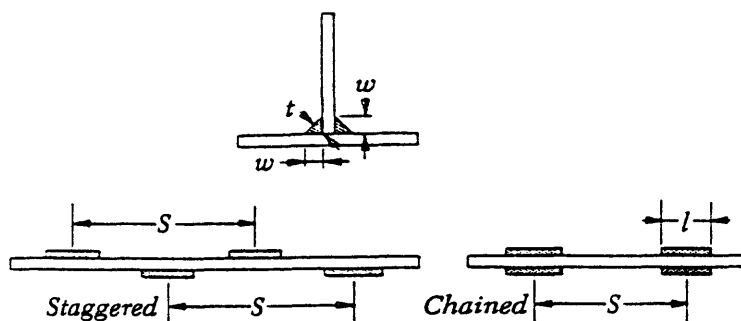
3/23.2 Full or Partial Penetration Corner or Tee Joints

Measures taken to achieve full or partial penetration corner or tee joints, where specified, are to be to the satisfaction of the attending Surveyor. The designer is to give consideration to minimize the possibility of lamellar tearing in such joints.

3/23.3 Alternatives

The foregoing are considered minimum requirements for electric-arc welding in hull construction, but alternative methods, arrangements and details will be considered for approval. See 2/3C.5. Fillet weld sizes may be determined from structural analyses based on sound engineering principles provided they meet the overall strength standards of the Rules.

TABLE 3/23.1
Weld Factors



w = leg size in mm or in.

t = throat size in mm or in.

I. Periphery Connections

Factor C

C = Continuous
DC = Double Continuous

A. Tight Joints

- | | |
|--|-----------------|
| 1. Strength deck to sheer strake (See 3/23.2) | 0.42 DC |
| 2. Main longitudinal bulkhead to deck, bottom or inner bottom (See 3/23.2) | 0.42 DC |
| 3. All other tight joints except X.B. (See 3/12.7.3c) | 0.35 DC |
| a. watertight bulkhead, | one side 0.58C |
| $t_{pt} \leq 12.5$ mm (0.50 in.) | other side 0.12 |
| b. all other joints | 0.35 DC |

B. Non-tight Joints

- | | |
|--------------------------------------|---------|
| 1. Platform decks | 0.28 DC |
| 2. Swash bulkheads in deep tanks | 0.20 |
| 3. Non-tight bulkheads other than B2 | 0.15 |

II. Bottom Floors

- | | |
|--|---------|
| 1. To Shell | |
| a. aft peak of high power fine form vessels | 0.25 DC |
| b. in machinery space | 0.20 DC |
| c. flat of bottom forward | 0.15 |
| d. in peaks | 0.15 |
| e. elsewhere (See note 5) | 0.12 |
| 2. To Inner Bottom | |
| a. in machinery space | 0.20 DC |
| b. at forward end (fore end strengthening) | 0.15 |
| c. elsewhere (See note 5) | 0.12 |
| 3. To Center or Side Girder | |
| a. in way of engine | 0.30 DC |
| b. with longitudinal framing | 0.30 DC |
| c. with transverse framing | 0.17 |
| 4. To Margin Plate, Side Shell, Longitudinal Bulkhead or Bilge | 0.35 DC |
| 5. Open Floor Bracket | |
| a. to center girder | 0.15 |
| b. to margin plate | 0.30 DC |

TABLE 3/23.1 (continued)

III. Bottom Girder		
1. Center Girder		
a. to inner bottom in way of engine	0.30 DC	
b. to inner bottom clear of engine, non-tight	0.23	
c. to shell, non-tight	0.25 DC	
2. Side Girder		
a. to floors in way of transverse bulkheads	0.35 DC	
b. to shell—flat of bottom forward	0.23	
—elsewhere	0.15	
c. to inner bottom—in way of engine	0.23	
—elsewhere	0.15	
IV. Web Frames, Stringers, Deck Girders and Deck Transverses		
1. To Plating		
a. in tanks	0.20	
b. elsewhere	0.15	
2. To Face Plates		
a. face area $\leq 64.5 \text{ cm}^2$ (10 in. ²)	0.12	
b. face area $> 64.5 \text{ cm}^2$ (10 in. ²)	0.15	
3. End Attachment		
a. unbracketed (see note 1)	0.55 DC	
b. bracketed	0.40 DC	
V. Frames, Beams and Stiffeners		
1. To Shell		
a. in aft peaks of high power fine form vessels	0.25 DC	
b. flat of bottom forward	0.25 DC	
c. 0.125L forward	0.15	
d. in peaks	0.15	
2. To Deck-slab longitudinals (see note 2)	0.20 DC	
3. To plating elsewhere	0.12	
4. End attachment		
a. unbracketed (see note 1)	0.45 DC	
b. bracketed	0.35 DC	
VI. Hatch Covers		
1. Oiltight Joints	0.40 DC	
2. Watertight Joints		
outside	0.40 C	
inside	0.15	
3. Stiffeners and Webs to Plating and to Face Plate (see note 4)	0.12	
4. Stiffeners and Web to Side Plating or other stiffeners		
—unbracketed (see note 1)	0.45 DC	
—bracketed	0.35 DC	
VII. Hatch Coamings and Ventilators		
1. To Deck		
a. at hatch corner	0.45 DC	
b. elsewhere	0.25 DC	
2. Coaming stays		
a. to deck	0.20 DC	
b. to coaming	0.15 DC	

TABLE 3/23.1 (continued)

VIII. Foundations (See 3/23.2)	
1. Main Engine and Major Auxiliaries	0.40 DC
2. Boilers and other Auxiliaries	0.35 DC
IX. Rudders—Diaphragms	
1. To Side Plating	
a. in way of rudder axis	0.45 DC
b. elsewhere	0.20
c. slot welds (see note 4)	0.45 DC
2. To Diaphragms	
a. to vertical diaphragms in way of rudder axis	0.45 DC
b. elsewhere	0.20
c. to top and bottom casting in way of rudder axis	Full penetration welds
X. Additional Weld Factors for Oil Carriers and Similar Vessels	
A. Deep Supporting Members	
1. To Bottom Shell	
a. end quarter span	0.45 DC
b. mid half span (See note 3)	0.40 DC
2. To Deck	
a. end quarter span	0.40 DC
b. mid half span (See note 3)	0.35 DC
3. To Side Shell and Longitudinal Bulkheads	0.40 DC
4. To Transverse Bulkheads	
a. end quarter span	0.45 DC
b. mid half span	0.35 DC
5. To Face Plate	0.30 DC
B. Boundaries of Cargo Segregation (See 3/12.7.3c and 3/23.2)	0.42 DC

Notes

1. The weld size is to be determined from the thickness of the member being attached.
2. Slab longitudinals—where the thickness on which the weld size is based is greater than 25mm the leg size is not to be less than 0.3 times that thickness but need not be greater than 8 mm provided the lesser thickness of members being joined is not greater than 34 mm. Where the lesser thickness of members being joined is greater than 34 mm special consideration will be given to the weld size.
3. This may be applied only where the shearing forces over the mid-half span are no greater than one half the maximum shearing-force on the member and where the web is of the same depth clear of end brackets and of the same thickness throughout the length of the member. The weld size is to be determined from the thickness of member being attached.
4. Unbracketed stiffeners and webs of hatch covers are to be welded continuously to the plating and to the face plate for a length at ends equal to the end depth of the member.
5. With longitudinal framing the weld size is to be increased to give an equivalent weld area to that obtained without cut-outs for longitudinals.

General Notes

For oil carriers and similar vessels, the leg size in cargo tanks and in ballast tanks in the cargo area is not to be less than 6 mm ($\frac{1}{4}$ in) except where approval has been given in accordance with 3/23.1.5.

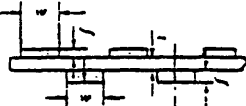
Appendix 2.C

NK Classification Societies Rules on Fillet Welds

C Chap. 1

NIPPON KAIJI KYOKAI

Table C 1.4 Kinds and Sizes of Fillet Welds (Unit: mm)

Kind of fillet weld									
	Lap joint		Tee joint		Measurement of weld length and pitch				
	Continuous fillet weld				Intermittent fillet weld				
	Size of fillet f		Size of fillet f		Length of fillet w		Pitch p		
Thickness of members	$F1$	$F2$	f			$F3$	$F4$		
Up to 5	3	3	3	60	150	250			
6	4		4	75	200	350			
7	5	4	5						
8			6						
9	6		7						
10			8						
11	7		9						
12			10						
13	8	5	11	75					
14			12						
15	9		13						
16			14						
17	10		15						
18			16						
19	11	6	17						
20			18						
21	12		19						
22			20						
23	13		21						
24			22						
25	14		23						
From 26 to 40	11	8	11						

Notes:

- 1 The size of fillet " f " for Tee joints is in general to be determined according to the thickness of webs in case of connections of beams, frames, stiffeners and girders to deck plating, inner bottom plates, bulkhead plates, shell plating or face plates, and the thickness of the thinner plate in case of connections of other members.
- 2 Lap joint is to have the fillet size of $F1$ determined according to the thickness of the thinner plate.
- 3 The throat thickness of fillet is to be $0.7f$.
- 4 In general $F2$ is to be the minimum fillet size.
- 5 Intermittent fillet welds are to be staggered and w at the ends is to be welded on both sides.
- 6 The minus tolerance for fillet size is to be 10% of the nominal size.

Appendix 2.D

Finite Element Program Input Files

```
***** A D I N A - I N INPUT FILE *****
**      Program: Tankers Stranding on a Rock
**      Plastic Analysis, Contact Problem
**      BY: JULIANA ATMADJA
*****

HEAD 'Stranding Contact - Plastic'
*

FILEUNIT LIST=8 LOG=7
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
DATABASE CREATE MEMORY=1000
MASTER IDOF=100111 NSTEP=100 REACTION=YES MTOTK=1000
ITERATION METHOD=FULL-NEWTON LINE-SEARCH=YES
KINEMATIC DISPLACEMENT=LARGE STRAINS=LARGE
AUTOMATIC-LDC NODE=8 DIR=3 DISPL=10 DISPM=1000.0 CONT=YES
PRINTOUT VOLUME=MIN PRINTDEFAULT=STRAINS
PORTHOLE FORMATTED=YES
*****
**      POSTSCRIPT OUTPUT HEADER FILE FOR ADINA-IN      **
*****

FILEUNITS LIST=8 LOG=7 ECHO=7
*

CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
FCONTROL SIZE=ISO ISO=-4.5 XSF=10 YSF=5
*CONTROL PLOTUNIT=CM HEIGHT=0.25
*FCONTROL SIZE=ISO ISO=-4.5 XSF=2 YSF=1.5
WORKSTATION SYS=12 COLORS=RGB BACKGROUND=WHITE
COLORS ORI=INVERSE EL=INVERSE BC=INVERSE XYA=INVERSE XYL=
INVERSE VE=INVERSE
*

**  HEADING OPTIONS:
FCONTROL HEADING=UPPER
*FCONTROL HEADING=LOWER
*
```

** FOR LANDSCAPE ORIENTATION, UNCOMMENT THE NEXT LINE:

FCONTROL ORIGIN=UPPERLEFT

*

COORDINATES

ENTRIES	NODE	Y	Z
1	0.0	500.0	
2	420.0	500.0	
3	840.0	500.0	
4	846.0	500.0	
5	861.0	500.0	
6	867.0	500.0	
7	1077.0	500.0	
8	1287.0	500.0	
9	1287.0	520.0	
10	1077.0	520.0	
11	867.0	520.0	
12	861.0	520.0	
13	846.0	520.0	
14	840.0	520.0	
15	420.0	520.0	
16	0.0	520.0	
17	841.59	521.59	
18	846.0	521.59	
19	861.0	521.59	
20	865.41	521.59	
21	846.0	526.0	
22	861.0	526.0	
23	846.0	782.5	
24	861.0	782.5	
25	846.0	1039.0	
26	861.0	1039.0	
27	753.5	1045.0	
28	840.0	1045.0	
29	846.0	1045.0	
30	861.0	1045.0	
31	867.0	1045.0	
32	953.5	1045.0	

```

33      753.5   1075.0
34      840.0   1075.0
35      846.0   1075.0
36      861.0   1075.0
37      867.0   1075.0
38      953.5   1075.0
39      853.5   1045.0
40      853.5   1075.0
*** Coordinate for vertical spring
41      853.5     0.0
*** Coordinates for upper weld gap
42      841.59   1043.41
43      846.0    1043.41
44      861.0    1043.41
45      865.41   1043.41
*** Nodes for the rock
46      1287.0     0.0
47      1037.0   433.012701892
48      637.0    202.07
49      1287.0    202.07
50      1287.0    500.0

*
***** Coordinate for lateral spring
51      1453.0   1060.0
LINE ARC N1=50 N2=47 NCENTER=46 EL=5 MIDNODE=1
*****
* Material properties *****
*
* Material properties for base plate
MAT 1 PLASTIC E=2.1E5 NU=0.3 ET=5.25E3 DEN=7.8 YIELD=4.2E2 EPA=0.19
* Material properties for welds
MAT 2 PLASTIC E=2.1E5 NU=0.3 ET=5.25E3 DEN=7.8 YIELD=4.9E2 EPA=0.22
* Material properties for spring
MAT 3 ELASTIC E=1.0 DEN=0.0
* Material properties for rock
MAT 4 ELASTIC E=5.5E5 DEN=14.5
*
EGROUP 1 TWODSOLID SUBTYPE=STRAIN DISPL=LARGE MATERIAL=1

```

*

CONTROL PLOTUNIT=PERCENT HEIGHT=0.5

* Base plate formulation

GSURFACE 1 2 15 16 EL1=14 EL2=3 NO=8 RATIO1=6

GSURFACE 2 3 14 15 EL1=14 EL2=3 NO=8 RATIO1=0.067

GSURFACE 3 4 13 14 EL1=3 EL2=3 NO=8

GSURFACE 4 5 12 13 EL1=3 EL2=3 NO=8

GSURFACE 5 6 11 12 EL1=3 EL2=3 NO=8

GSURFACE 6 7 10 11 EL1=10 EL2=3 NO=8 RATIO1=6

GSURFACE 7 8 9 10 EL1=14 EL2=3 NO=8 RATIO1=0.067

*

* Stiffeners formulation

GSURFACE 18 19 22 21 EL1=2 EL2=2 NO=8

GSURFACE 21 22 24 23 EL1=2 EL2=14 NO=8 RATIO2=12

GSURFACE 23 24 26 25 EL1=2 EL2=14 NO=8 RATIO2=0.08

GSURFACE 25 26 44 43 EL1=2 EL2=2 NO=8

*

* Top flange formulation

GSURFACE 27 28 34 33 EL1=6 EL2=2 NO=8 RATIO1=0.25

GSURFACE 28 29 35 34 EL1=2 EL2=2 NO=8

GSURFACE 29 39 40 35 EL1=1 EL2=2 NO=8

GSURFACE 39 30 36 40 EL1=1 EL2=2 NO=8

GSURFACE 30 31 37 36 EL1=2 EL2=2 NO=8

GSURFACE 31 32 38 37 EL1=6 EL2=2 NO=8 RATIO1=4

*

* Material for the weld

*EGROUP 2 TWODSOLID SUBTYPE=STRAIN DISPL=LARGE MATERIAL=2

EGROUP 2 TWODSOLID SUBTYPE=STRAIN DISPL=SMALL MATERIAL=2

*

* Lower part of weld

GSURFACE 14 13 18 17 EL1=3 EL2=1 NO=8

GSURFACE 12 11 20 19 EL1=3 EL2=1 NO=8

GSURFACE 17 18 21 17 EL1=3 EL2=2 NO=8

GSURFACE 20 19 22 20 EL1=3 EL2=2 NO=8

*

* Upper part of weld

GSURFACE 42 43 29 28 EL1=2

GSURFACE 43 42 25 43 EL1=2 EL2=2

GSURFACE 45 44 26 45 EL1=2 EL2=2

GSURFACE 44 45 31 30 EL1=2

*

* Spring formulation

*** Vertical Spring

EGROUP 3 TRUSS MATERIAL=3

ENODES / ENTRIES EL N1 N2

1	41	724
2	41	731
3	41	738
4	41	745
5	41	753
6	41	761
7	41	769
8	41	777
9	41	785
10	41	793
11	41	801
12	41	809
13	41	817
14	41	825
15	41	833
16	41	841
17	41	848
18	41	855
19	41	863
20	41	871
21	41	879
22	41	887
23	41	895
24	41	903
25	41	911
26	41	919
27	41	927
28	41	935
29	41	943
30	41	951
31	41	958

32 41 965

33 41 972

*

EDATA / ENTRIES EL AREA

1	0.0006195
2	0.000622232
3	0.00079889955
4	0.0014831341
5	0.0021850939
6	0.002914365
7	0.0036805452
8	0.0044932117
9	0.0053619625
10	0.0062963837
11	0.0073060609
12	0.0084005897
13	0.0095895595
14	0.010882549
15	0.012289153
16	0.01381897
17	0.014506464
18	0.007040458
19	0.0071800842
20	0.013524515
21	0.012846978
22	0.012058039
23	0.011167402
24	0.010184785
25	0.0091199224
26	0.0079825279
27	0.0067823041
28	0.0055289242
29	0.0042322737
30	0.0029019049
31	0.0015475917
32	0.0017150626
33	0.0017201197

*

**** Lateral Spring

EGROUP 4 TRUSS MATERIAL=3

ENODES / ENTRIES EL N1 N2

1	51	992
2	51	994
3	51	996
4	51	998
5	51	1000
6	51	1002
7	51	1004
8	51	1029
9	51	1031
10	51	1040
11	51	1046
12	51	1055
13	51	1057
14	51	1081
15	51	1083
16	51	1085
17	51	1087
18	51	1089

*

EDATA / ENTRIES EL AREA

1	0.00072260888
2	0.00059328765
3	0.00047393937
4	0.00036290107
5	0.00025851072
6	0.0001591071
7	8.1971827e-05
8	8.1555327e-05
9	0.00020284707
10	0.00020024394
11	7.9056327e-05
12	7.8639827e-05
13	0.0001503627
14	0.00023811771
15	0.0003219951

16 0.00040033204

17 0.00047146648

18 0.00053373711

*

* Wedge/rock formulations

EGROUP 5 TWODSOLID SUBTYPE=STRAIN DISPL=SMALL MATERIAL=4

GSURFACE 48 49 47 48

GSURFACE 49 50 47 49 EL2=5

*

BZONE NOSPRING YMAX=1288 ZMIN=200.0

BZONE ROCK YMIN=1000.0 YMAX=1288 ZMIN=200.0 ZMAX=505

*

**** Combining lines for contact surfaces ****

LINE COMBINED N1=1 N2=8,

2 3 4 5 6 7

LINE COMBINED N1=50 N2=48,

53 55 57 59 47

LIST LINE N1=50 N2=48

***** Contact surfaces definition ****

CGROUP 1 CONTACT2 SUBTYPE=STRAIN

CONTACTSURFACE 1 TYPE=LINES / 1 8

CONTACTSURFACE 2 TYPE=LINES / 50 48

CONTACTPAIR 1 TARGET=2 CONTACTOR=1

* Loading conditions

LOADS DISPLACEMENTS TYPE=NODES

50 3 1.0

47 3 1.0

48 3 1.0

*

FIXB DIR=23 TYPE=LINE

1 16

FIXB DIR=2 TYPE=LINE

8 9

FIXB DIR=2 TYPE=NODES

49/ 48

* Boundary condition for the spring

FIXB DIR=23 / 41 / 51

*

CONTROL PLOTUNIT=PERCENT HEIGHT=0.6

*

FRAME

MESH BCODE=ALL

EVECTOR VAR=PDISP OUTPUT=ALL

*

ADINA

END

```
***** A D I N A - P L O T INPUT FILE *****
**      Program: Tankers Stranding on a Rock
**      Plastic Analysis, Contact Problem
**      BY: JULIANA ATMADJA
*****
FILEUNITS LIST=8 LOG=7 ECHO=7
FCONTROL HEADING=UPPER ORIGIN=UPPERLEFT
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
DATABASE CREATE FORMATTED=YES MEMORY=1000
EINFO VAR=YES
NINFO VAR=YES
*
*****
**      POSTSCRIPT OUTPUT HEADER FILE FOR ADINA-IN      **
*****
FILEUNITS LIST=8 LOG=7
*ECHO=7
*
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
FCONTROL SIZE=ISO ISO=-4.5 XSF=10 YSF=5
*CONTROL PLOTUNIT=CM HEIGHT=0.25
*FCONTROL SIZE=ISO ISO=-4.5 XSF=2 YSF=1.5
WORKSTATION SYS=12 COLORS=RGB BACKGROUND=WHITE
COLORS  ORI=INVERSE  EL=INVERSE  BC=INVERSE  XYA=INVERSE
XYL=INVERSE VE=INVERSE,
  DE=INVERSE
*
**  HEADING OPTIONS:
FCONTROL HEADING=UPPER
*FCONTROL HEADING=LOWER
*
**  FOR LANDSCAPE ORIENTATION, UNCOMMENT THE NEXT LINE:
FCONTROL ORIGIN=UPPERLEFT
*****
PLOTAREA 1 5.0 95.0 5.0 85.0
*LIST PLOTAREA
ALIAS AEP ACCUM_EFF_PLASTIC_STRAIN
*
```

```
BZONE BASEL YMAX=50 ZMIN=490 ZMAX=521
BZONE CONTACT YMIN=950 YMAX=1209 ZMIN=490 ZMAX=521
* this is for the curvature
*FRAME
*MESH ZONE=BASEL ORI=2 DE=1 MARGIN=YES BCODE=ALL
***** with gap included
*BZONE WELDL YMIN=830 YMAX=850 ZMIN=510 ZMAX=530
*BZONE WELDR YMIN=855 YMAX=870 ZMIN=510 ZMAX=530
BZONE WELD YMIN=830 YMAX=880 ZMIN=510 ZMAX=530
*
** without gap plotted
BZONE WELDL YMIN=830 YMAX=850 ZMIN=521 ZMAX=530
BZONE WELDR YMIN=855 YMAX=870 ZMIN=521 ZMAX=530
BZONE WELDCUT YMIN=830 YMAX=880 ZMIN=521 ZMAX=530
*
*ZLIST ZONE=BASEL TSTART=23 TEND=23 VAR=EFFECTIVE_STRESS
*ZLIST ZONE=CONTACT TSTART=23 TEND=23 VAR=EFFECTIVE_STRESS
FRAME HEADING=NONE
MESH BASEL ORI=2 DE=1 MARGIN=YES BCODE=ALL
*BAND ZONE=BASEL VAR=EFFECTIVE_STRESS
*TEXT XP=20 YP=85 STRING='EFFECTIVE STRESS NEAR CLAMP'
*FRAME
*MESH BASEL ORI=1 DE=0 MARGIN=YES
*EVECTOR ZONE=BASEL VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*TEXT XP=20 YP=85 STRING='NEAR CLAMP'
*
*FRAME
*MESH CONTACT ORI=1 DE=0 MARGIN=YES
*BAND ZONE=CONTACT VAR=EFFECTIVE_STRESS
*TEXT XP=20 YP=80 STRING='CONTACT ZONE'
*FRAME
*MESH CONTACT ORI=1 DE=0 MARGIN=YES
*EVECTOR ZONE=CONTACT VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*TEXT XP=20 YP=80 STRING='CONTACT ZONE'
*
*FRAME
*MESH WELDL ORI=1 DE=0
```

```
*EVECTOR ZONE=WELDL VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
*FRAME
*MESH WELDR ORI=1 DE=0
*EVECTOR ZONE=WELDR VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
*FRAME HEADING=NONE
*MESH WELD ORI=1 DE=0 MARGIN=YES
*EVECTOR ZONE=WELDCUT VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
**FRAME
**MESH WELD ORI=1 DE=0 MARGIN=YES LINES=1
**BAND ZONE=WELD VAR=EFFECTIVE_STRESS MAXLAB=YES TYPE=LINES
COLORMAX=7
*
*FRAME
*MESH WELD ORI=1 DE=0 MARGIN=YES
*BAND ZONE=WELD VAR=AEP MAXLAB=YES TYPE=LINES COLORMAX=7
*
BZONE NOSPRING YMAX=1288 ZMIN=200.0
*FRAME HEADING=NO
*MESH ZONE=NOSPRING ORIGINAL=2 DEFORMED=1 MARGIN=YES
*TEXT XP=20 YP=80 STRING='FINAL CONFIGURATION'
*
*FRAME
*MESH ZONE=NOSPRING ORIGINAL=2 DEFORMED=1 TIME=5.0 SUB-
FRAME=2211
*TEXT XP=20 YP=80 STRING='TIME=5.0'
*MESH ZONE=NOSPRING ORIGINAL=2 DEFORMED=1 TIME=8.0 SUB-
FRAME=2111
*TEXT XP=20 YP=80 STRING='TIME=8.0'
*
*FRAME
*MESH ZONE=NOSPRING ORI=2 DE=1 TIME=10.0 SUBFRAME=2211
*TEXT XP=20 YP=80 STRING='TIME=10.0'
*MESH ZONE=NOSPRING ORI=2 DE=1 TIME=15.0 SUBFRAME=2111
*TEXT XP=20 YP=80 STRING='TIME=15.0'
*
```

```

*FRAME
*MESH NOSPRING ORI=2 DE=1 TIME=16.0 SUBFRAME=1122
*MESH NOSPRING ORI=2 DE=1 TIME=17.0 SUBFRAME=1121
*
*FRAME
*MESH NOSPRING ORI=2 DE=1 TIME=18.0 SUBFRAME=1122
*MESH NOSPRING ORI=2 DE=1 TIME=19.0 SUBFRAME=1121
*
NPOINT MIDDLE NODE=8
EPOINT MID GROUP=1 ELEMENT=23 POINT=11
EPOINT W_LEFT_ROOT GROUP=2 ELEMENT=3 POINT=11
EPOINT W_LEFT_TOE GROUP=2 ELEMENT=1 POINT=11
EPOINT W_RIGHT_ROOT GROUP=2 ELEMENT=4 POINT=11
EPOINT W_RIGHT_TOE GROUP=2 ELEMENT=6 POINT=11
*LIST EPOINT
*
*AXIS 1 0.0 0.0 0.0 0.0 2.5 'TIME'
*AXIS 2 0.0 0.0 0.0 0.0 100. 'LOAD'
*FRAME
*GRAPH Z-DISPLACEMENT MIDDLE LAMBDA NULL SYMBOL=1 OUT-
PUT=ALL,
* SUBFRAME=2211
*GRAPH TIME NULL LAMBDA NULL SYMBOL=1 OUTPUT=ALL,
* SUBFRAME=2111
*
*ZLIST ZONE=WELD VAR=AEP
*
***** FLANGE *****
*BZONE FLANGE YMIN=730 YMAX=960 ZMIN=495 ZMAX=530
*FRAME
*MESH FLANGE ORI=1 DE=0
*BAND ZONE=FLANGE VAR=EFFECTIVE_STRESS TYPE=LINE COLORMAX=7
*
*FRAME
*MESH FLANGE ORI=1 DE=0
*BAND ZONE=FLANGE VAR=pressure TYPE=LINE COLORMAX=7
*

```

```

*FRAME
*MESH FLANGE ORI=1 DE=0
*EVECTOR VAR=STRESS POSITIVE=3 NEGATIVE=4
*
***** STIFFENER NEAR THE FLANGE *****
BZONE STIFFTOP YMIN=835 YMAX=870 ZMIN=1030 ZMAX=1050
* Strain concentration checking ****
*FRAME
*MESH ZONE=STIFFTOP ORI=1 DE=0 MARGIN=YES SUBFRAME=1122
*BAND ZONE=STIFFTOP VAR=EFFECTIVE_STRESS COLORMAX=7
**FRAME
*MESH ZONE=STIFFTOP ORI=1 DE=0 MARGIN=YES SUBFRAME=1121
*EVECTOR ZONE=STIFFTOP VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
***** UPPER WELDS *****
**BZONE WELUPL YMIN=830 YMAX=850 ZMIN=1020 ZMAX=1060
BZONE WELUPL YMIN=830 YMAX=850 ZMIN=1035 ZMAX=1044
*FRAME
*MESH WELUPL ORI=1 DE=0 MARGIN=YES
*EVECTOR VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*TEXT XP=20 YP=90 STRING='UPPER WELD LEFT'
*
**BZONE WELUPR YMIN=855 YMAX=880 ZMIN=1020 ZMAX=1060
BZONE WELUPR YMIN=855 YMAX=880 ZMIN=1035 ZMAX=1044
*FRAME
*MESH WELUPR ORI=1 DE=0 MARGIN=YES
*EVECTOR VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*TEXT XP=20 YP=90 STRING='UPPER WELD RIGHT'
*
BZONE WELDUP YMIN=830 YMAX=880 ZMIN=1035 ZMAX=1060
BZONE WELDUPCUT YMIN=830 YMAX=880 ZMIN=1035 ZMAX=1044
*
*FRAME HEADING=NONE
*MESH WELDUP ORI=1 DE=0 MARGIN=YES
*EVECTOR ZONE=WELDUPCUT VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
**FRAME
**MESH WELDUP ORI=1 DE=0 MARGIN=YES LINES=1

```

```
**BAND ZONE=WELDUP VAR=EFFECTIVE_STRESS COLORMAX=7 MAXLA-
BEL=YES TYPE=LINES
*
*FRAME
*MESH WELDUP ORI=1 DE=0 MARGIN=YES
*BAND ZONE=WELDUP VAR=AEP COLORMAX=7 MAXLABEL=YES
TYPE=LINES
***** Base Plate zones *****
***** to check distorted mesh *****
BZONE DIST YMIN=1080 ZMIN=490 ZMAX=521
bzone wirock ymin=1000.0 zmin=100.0 zmax=521.0
BZONE BASEPLT ZMIN=490 ZMAX=521
BZONE NOSPROCK ZMIN=400 YMAX=1290
*
*FRAME HEADING=NO
*MESH NOSPROCK ORI=1 DE=0 MARGIN=YES LINES=1
*BAND ZONE=NOSPROCK VAR=AEP COLORMAX=7 MAXLABEL=YES
TYPE=LINES
*
*FRAME
*MESH BASEPLT ORI=1 DE=0 MARGIN=YES
*BAND ZONE=BASEPLT VAR=EFFECTIVE_STRESS COLORMAX=7 MAXLA-
BEL=YES TYPE=LINES
*
*FRAME
*MESH BASEPLT ORI=1 DE=0 MARGIN=YES LINES=1
*BAND ZONE=BASEPLT VAR=AEP COLORMAX=7 MAXLABEL=YES
TYPE=LINES
*
*frame
*mesh wirock ori=1 de=0
*FRAME HEADING=NONE
*MESH WIROCK ORI=0 DE=1 MARGIN=YES LINES=1
*BAND ZONE=WIROCK VAR=AEP COLORMAX=7
*FRAME
*MESH DIST ORI=0 DE=1
*FRAME
*MESH DIST ORI=1 DE=0 MARGIN=YES LINES=1
*BAND ZONE=DIST VAR=AEP OUTPUT=ALL COLORMAX=5
```

*

NLINE REACT

19

87

22

101

109

117

125

133

141

149

157

165

173

181

189

197

24

211

214

219

227

235

243

251

259

267

275

283

291

299

307

26

321

30

*

*LIST NLINE

```
*LLIST REACT TSTART=17 TEND=17 VAR=Y-REACTION
*LLIST REACT VAR=Z-REACTION
*
NPOINT VERSPRI NODE=41
PLIST VERSPRI VAR=Y-REACTION Z-REACTION
NPOINT LATSPRI NODE=51
PLIST LATSPRI VAR=Y-REACTION Z-REACTION
*ELINE
END
```

Chapter 3

Plate under Combined Bending and Tension at Hard-point Support

3.1 Introduction to Chapter 3

For structures composed of thin shells such as oil tankers, shear failure can occur along boundaries of the shell [Duffey, 1989]. These boundary conditions can be rigid supports or stiffening members such as the longitudinal and transverse bulkheads in oil tankers. Bulkheads of an oil tanker provide constraint to the plastic flow along the support and cause a rather clean break off of the plates at the bulkheads. A study by McClintock, Zhou, and Wierzbicki (1993) shows that the plate near the clamp revealed necking followed by tearing. Necking occurs around the rim of the clamp as the plate is being pulled with an increasing bending under nearly constant load [McClintock, Zhou, and Wierzbicki, 1993]. The experiments conducted in 1993 suggested that necking, often a precursor to plate fracture, is accelerated by bending superimposed on tension.

The fracture and deformation of plates under combined bending and tension at rigid supports which are called hard-point supports, has not been studied extensively. In 1948

Swift studied the subject for plane strain by considering the final state of a plate under combined bending and tension. He used a deformation theory of non-linear elasticity to get a closed form solution. However, the effect of the local unloading process that occurs on initial bending was ignored. In 1993, McClintock et. al. studied the effect of bending on the tensile necking. They found that for plate under constant tension smaller than the necking force in pure tension: rotational instability occurs under applied bending moments, stable localized kinking occurs under applied bending angles, and tensile necking occurs under applied bending curvatures [McClintock, et.al, 1993].

This chapter discusses the preliminary study of the effect of combined bending and tension on a plate at the hard-point support using finite element analysis. The bottom shell of a single-hull oil tanker without any stiffeners was modeled.

3.2 Finite Element Model and Method Used

The plate at hard-point support study model was based on the 2-D single-hull stranding work discussed in chapter 2. To study the behavior of the plates at hard-point support, only the bottom plate of the structure is needed. Therefore, the longitudinal stiffener and the fillet welds on the 2-D single-hull model were omitted in this analysis. The same grounding incident scenario as in Chapter 2 was assumed in the analysis. The rock was penetrating to the bottom plate of a single-hull oil tanker between two longitudinal stiffeners. Figure 3.1 on p. 71 shows the bottom plate of the ship, without longitudinal stiffeners, stranded on a rock. Both ends of the plate are fixed to simulate longitudinal bulkheads reinforcement. A plate element of unit width (plane-strain analysis) was modeled as 1/4 of symmetry. The finite element model is shown in Figure 3.2 on p. 72. Boundary condition for the left end of the model is fixed in the y- and z-direction to simulate the bulkhead

reinforcement.

The mesh used near the clamped edge and that used near the line of symmetry were refined in order to get more accurate results. The size of the mesh was tested on the same plate dimension under pure tension where the analytical solution is available. The maximum load at necking in pure tension for plane strain can be found by equating the tension in uni-axial case. The necking criterion for uni-axial case (e.g. McClintock and Argon, 1966, p.319) is $dP = 0$. The equivalent uniform plane strain $(\epsilon_u)_p$ and tensile strength $(TS)_p$ in plane strain in terms of P_{max} and initial thickness of the plate t_0 are:

$$(\epsilon_u)_p = n - \epsilon_0 \quad (3.1)$$

$$(TS)_p = \frac{P_{max}}{t_0} = \frac{2}{\sqrt{3}} \left(\left(1 - \frac{2}{\sqrt{3}} \right) \epsilon_0 + \frac{2}{\sqrt{3}} n \right)^n e^{-\epsilon_u} \quad (3.2)$$

The tensile strength obtained from the finite element analysis is compared to the analytical solution obtained from Eq. 3.2. The finite element model with refined mesh for plate under pure tension gives tensile strength per unit width, $(TS)_p$, of 516.5 N/mm while the theoretical solution using Equation 3.2 gives tensile strength of 515.9 N/mm. The error is about 0.12%, therefore, the mesh size is assumed to give reliable results for plate under combined loading. However, the mesh near the clamped edge was refined further to capture necking and to get more accurate stress and strain on that area.

A hybrid displacement/pressure element is used to avoid locking and instability due to almost incompressible elasticity behavior of the elastic-material. The finite element model consists of 6 layers of 9/3-displacement-pressure unknown elements across the thickness of the plate (see Figure 3.2 on p. 72)

To simulate the force imposed on the plate by the rock, a displacement boundary condition was prescribed at the edge of the 1/4 symmetry line. The displacement was applied at one node halfway along the thickness (point A in Figure 3.2). The rest of the nodes were free in the y- and z-direction to allow rotation and elongation. To avoid thinning of the plate due to the constant tension, an end cap with a much harder material was modeled at the symmetry line of the plate.

An automatic time stepping (automatic ATS) method was used in this analysis. By using the automatic ATS method, the user only needs to define the loads by time function or load distribution, without having to worry about the incremental time step. The computer program automatically subdivides the user-selected time step if the user-selected time step cannot reach the convergence.

3.3 Material and Assumptions

Due to lack of information on the actual stress-strain curve of the steel used in oil tankers, material used in this analysis is based on the work of Amdahl and Kavlie in 1992 which is reported on “Experimental and Numerical Simulation of Double Hull Stranding.” Amdahl and Kavlie used plates of ship quality grade A and the stress strain curve from tension coupon test of a 3 mm plate were given in Figure 6 and 7 of their paper [Amdahl & Kavlie, 1992].

The power-law plastic stress-strain relations are fitted to the stress-strain curve given for model 2 of Amdahl and Kavlie (see Figure 3.3 on p. 73). Curves of true stress σ vs. integrated equivalent plastic strain ϵ^p are represented by

$$\sigma = \sigma_1 \left(\epsilon_0 + \epsilon^p \right)^n \quad (3.3)$$

The three constants σ_1 , ϵ_0 , and n are fitted to the yield strength YS, the tensile strength TS and the load maximum at that point, and the logarithmic (uniform) strain at the tensile strength, ϵ_u . From the yield strength, tensile strength, and uniform strain of Figure 3.3 and Eq. 2.3, the constant values turned out to be:

- $\sigma_1 = 705.5 \text{ N/mm}^2$
- $\epsilon_0 = 0.01$
- $n = 0.184$.

The fitted curve is shown in Figure 3.4 and the detailed calculations of the constants can be found in Appendix 3.A.

A piecewise linear, kinematic strain hardening material was assumed, based on the fitted stress-strain curve calculated above for the analysis. The end cap at the line of symmetry is an elastic material with modulus of elasticity of $4.2 \times 10^6 \text{ N/mm}^2$.

3.4 Finite Element Results for Plate at the Hard-point Support

The deformed configuration of the plate under combined bending and tension is illustrated in the lower part of Figure 3.5 on p. 75. Figure 3.5a shows a plate under pure tension, while Figure 3.5b shows a plate under combined bending and tension. In both figures, the dashed line indicates the original structure while the solid line indicates the deformed configuration. It appears that the necking occurs near the clamped edge where the longitudinal bulkhead is located instead of the middle of the plate as in pure tension. Of course, the clamped boundary conditions are not realistic. In real structure, there is some compliance from the longitudinal bulkhead.

The plot of the force-deflection curve for a plate in pure tension and a plate near bulk-head/hard-point is presented in Figure 3.6 on p. 76. In Figure 3.6, the dashed line shows the force-deflection curve of a plate under pure tension while the solid line shows the force-deflection curve of a plate under combined bending and tension load. It appears that the maximum load the plate can carry under combined bending and tension is comparable to maximum load for pure tension. The load is only 2.5% less than that of pure tension. However, the bending action reduces the elongation of the plate significantly. The elongation at the maximum load for plate under combined loading is 40% less than that of pure tension.

Figure 3.7 shows the plot of the accumulative effective plastic strain of the plate for both under pure tension and combined bending and tension (Figure 3.7a and Figure 3.7b respectively). The maximum plastic strain for a plate under pure tension is located at the middle of the plate and the value is 0.1965. On the other hand, the maximum plastic strain of a plate under combined bending and tension is located near the clamped edge with a value of 1.059. Strain at necking area is shown in Figure 3.8 on p. 79 which shows more detail values of accumulative plastic strain in that area. The maximum strain for the plate under combined bending and tension is about 82% higher than the maximum strain for pure tension. The high strain near the edge indicates that the fracture is accelerated by the existence of the reinforcement. With a strain of 1.059, as shown in Figure 3.8, necking and fracture are potential problems for a plate under combined bending and tension near bulkheads.

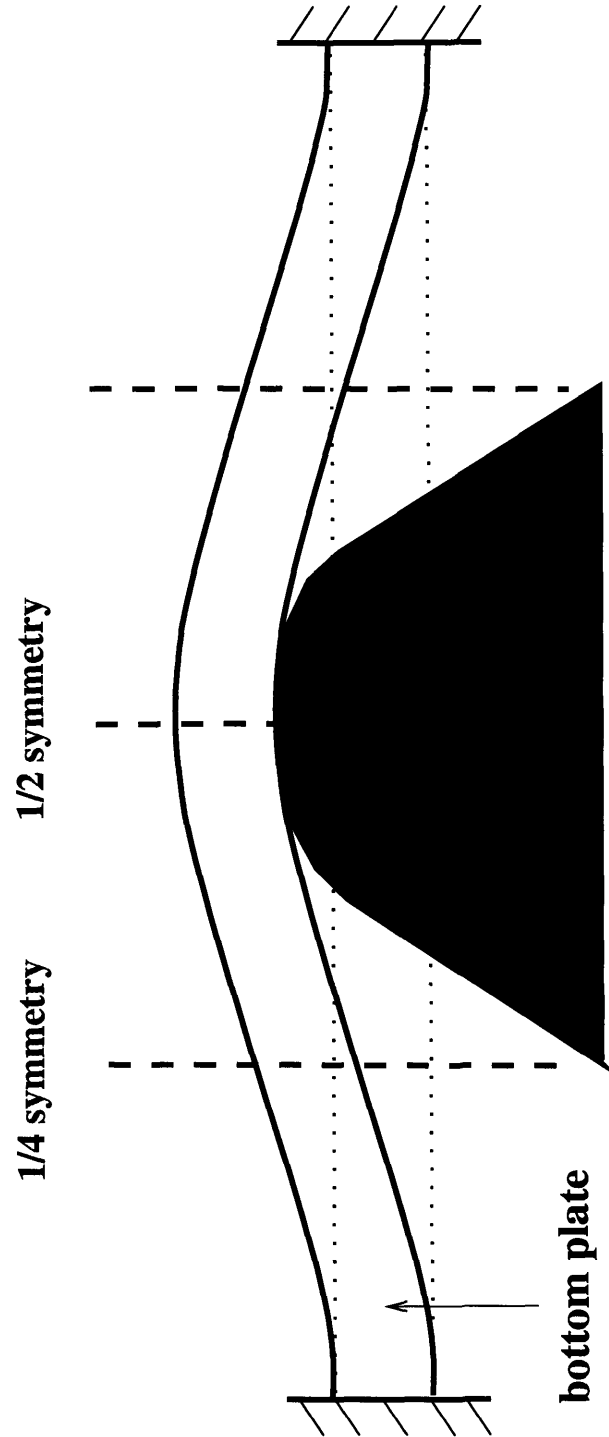


Figure 3.1 Bottom plate without stiffener

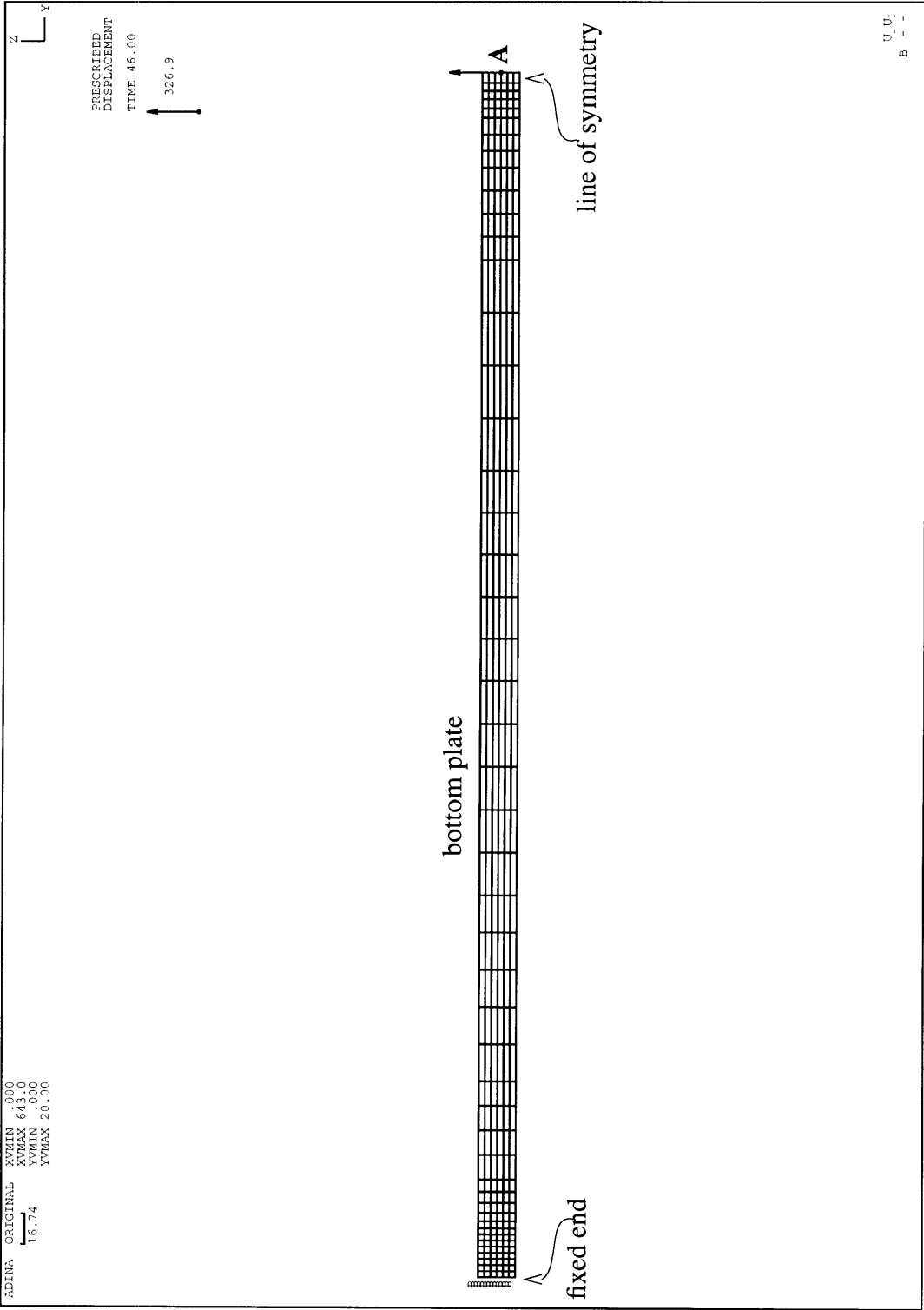


Figure 3.2 Finite element model and boundary conditions

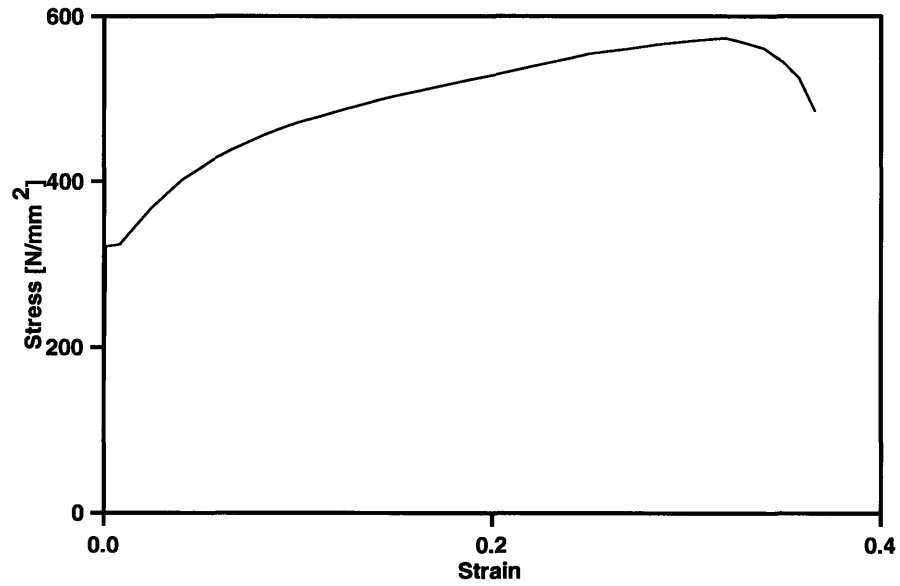


Figure 3.3 Amdahl and Kavlie stress-strain curve

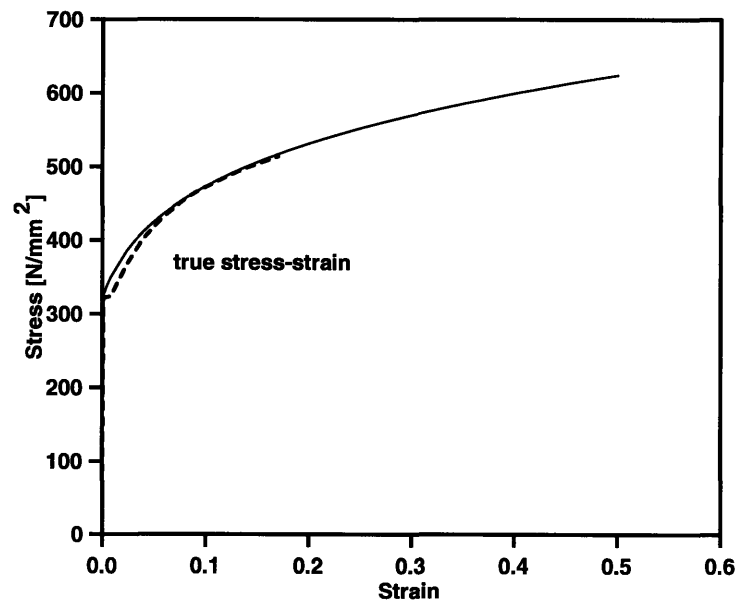


Figure 3.4 Fitted power-law stress-strain curve

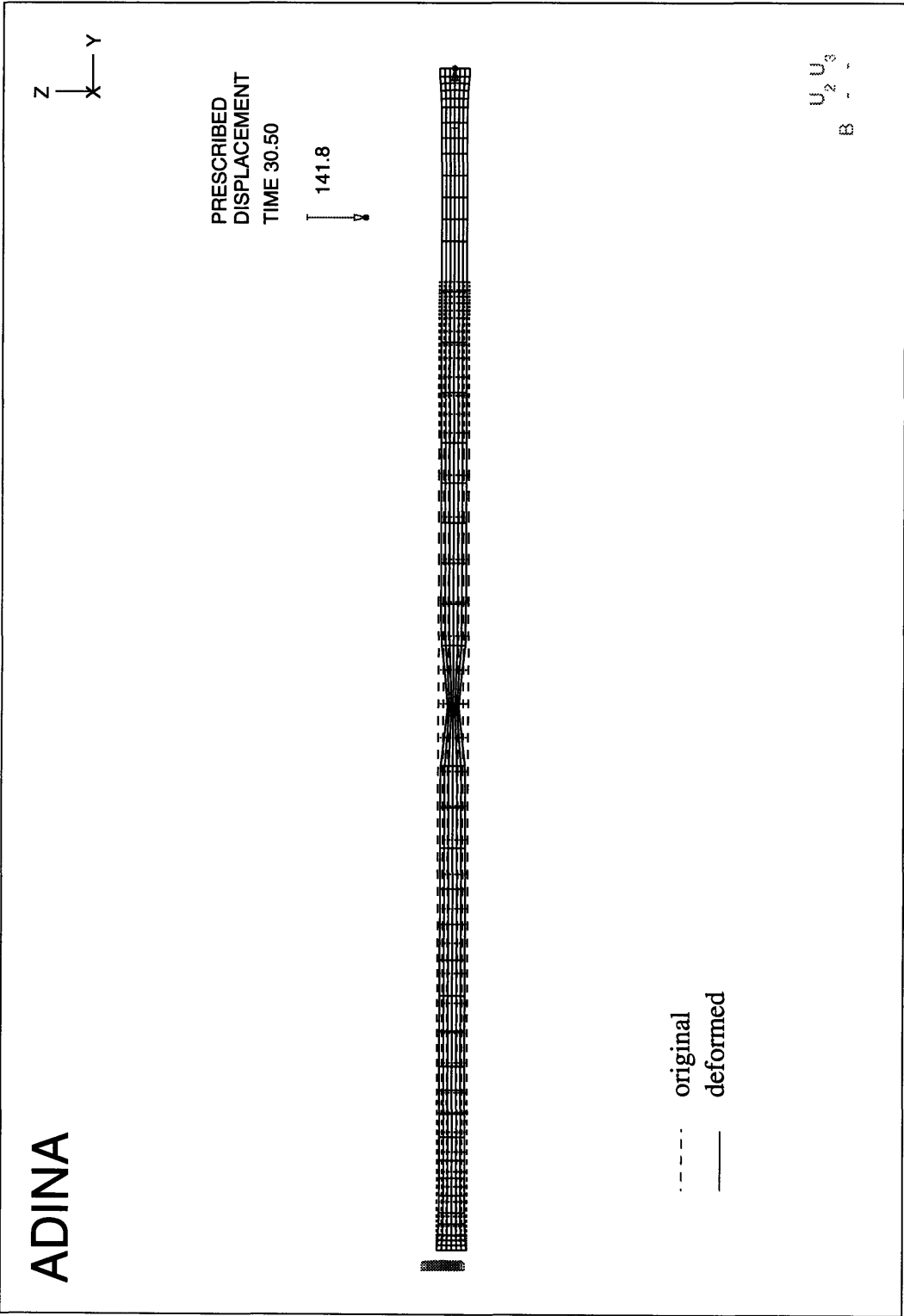


Figure 3.5 a. plate under pure tension

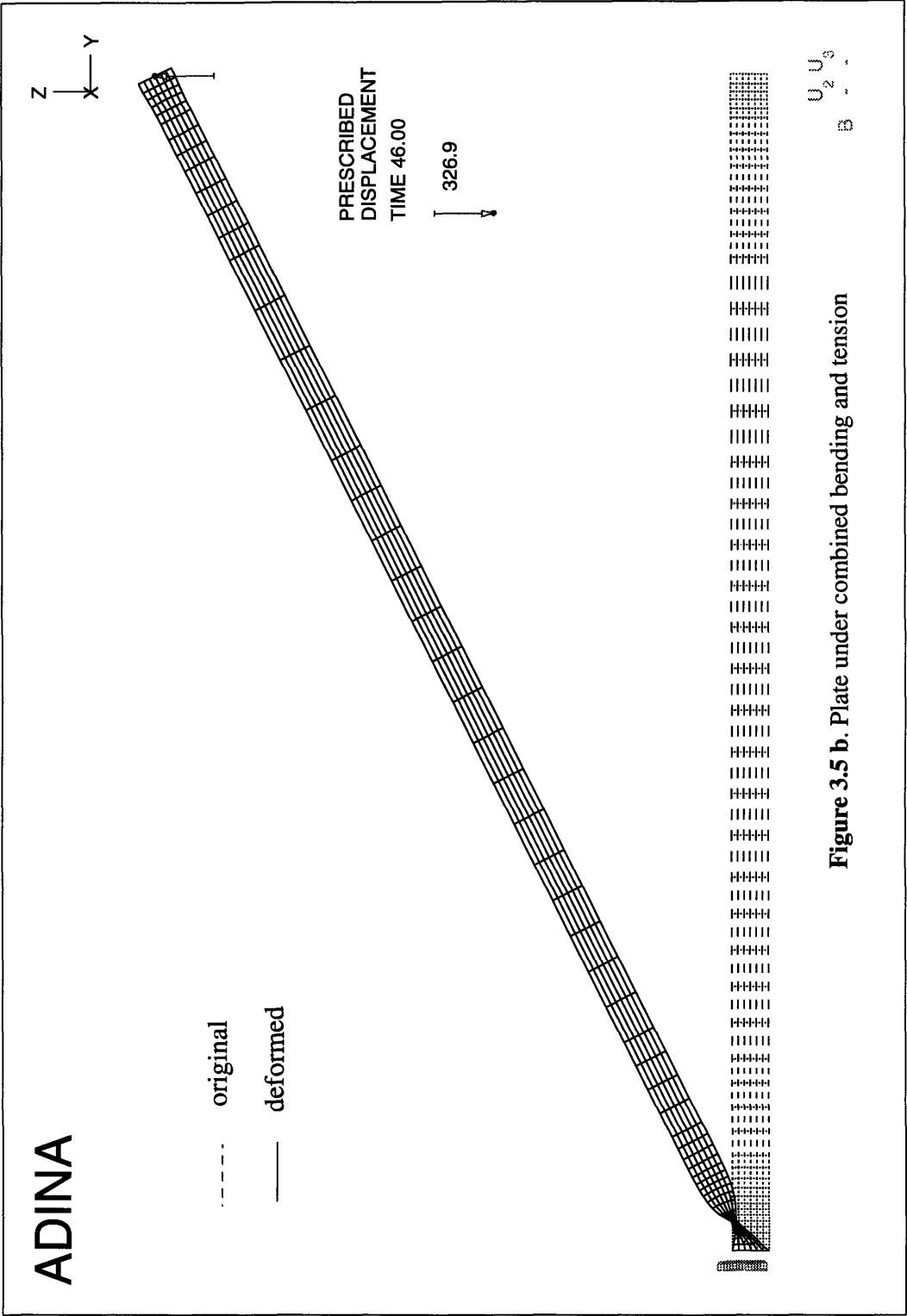


Figure 3.5 Deformed configurations

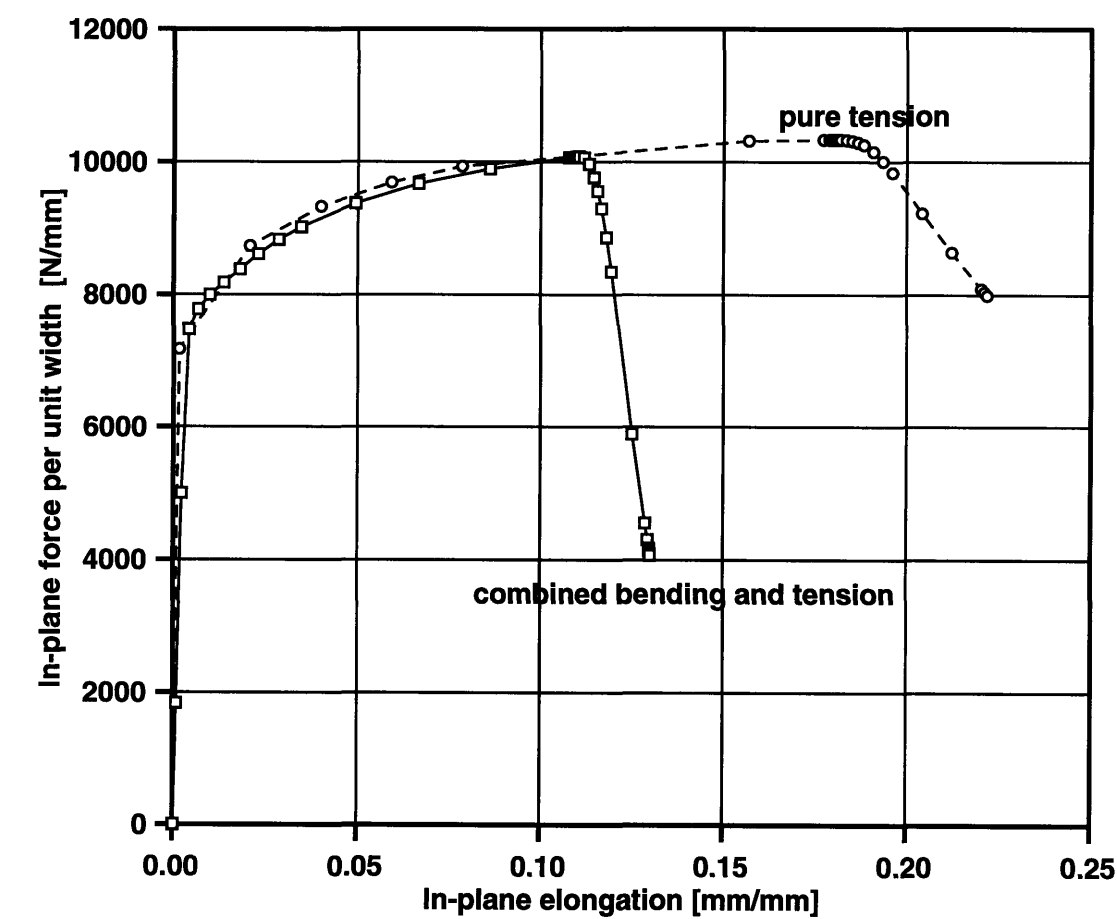


Figure 3.6 Comparison of load-elongation curve

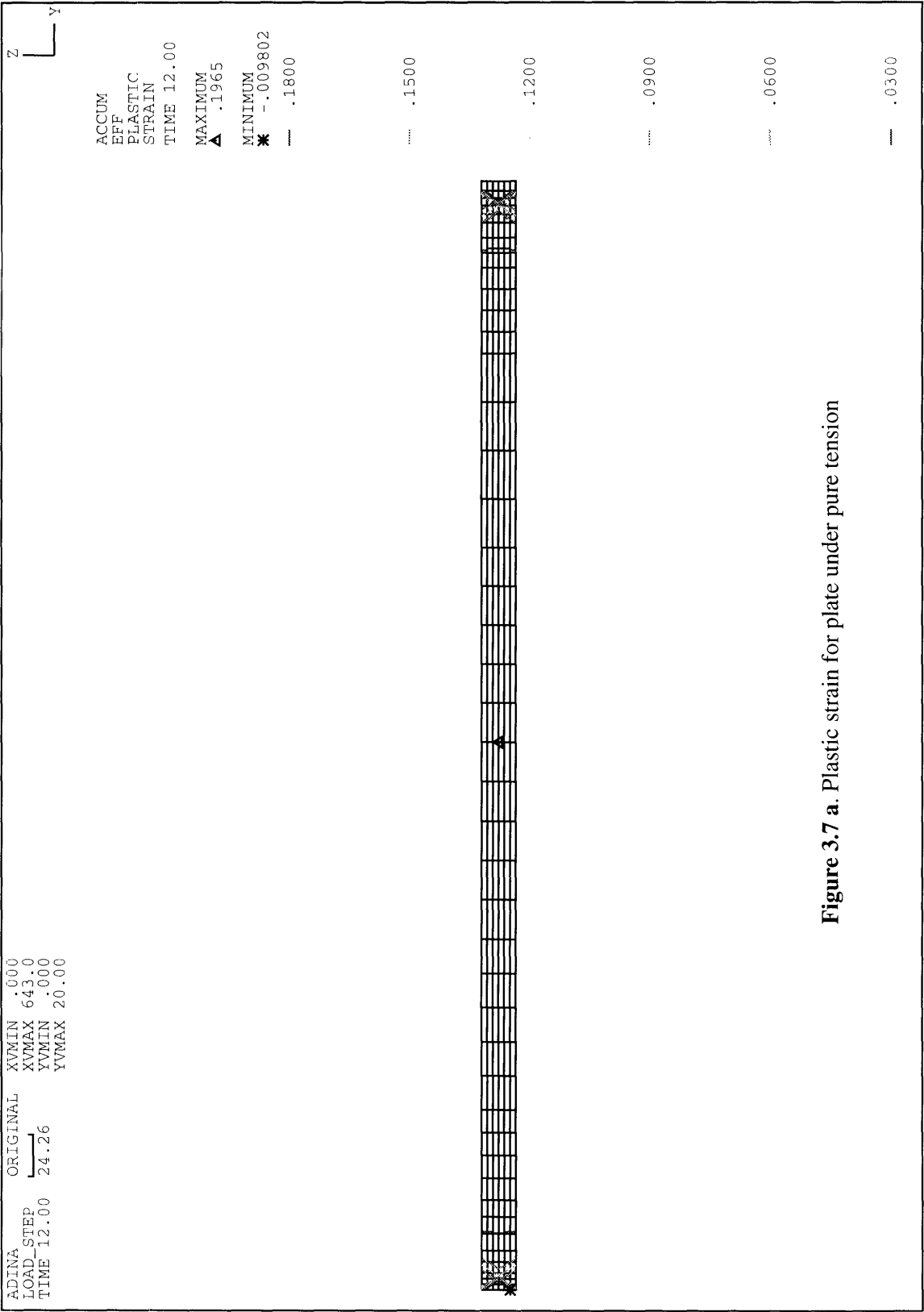


Figure 3.7 a. Plastic strain for plate under pure tension

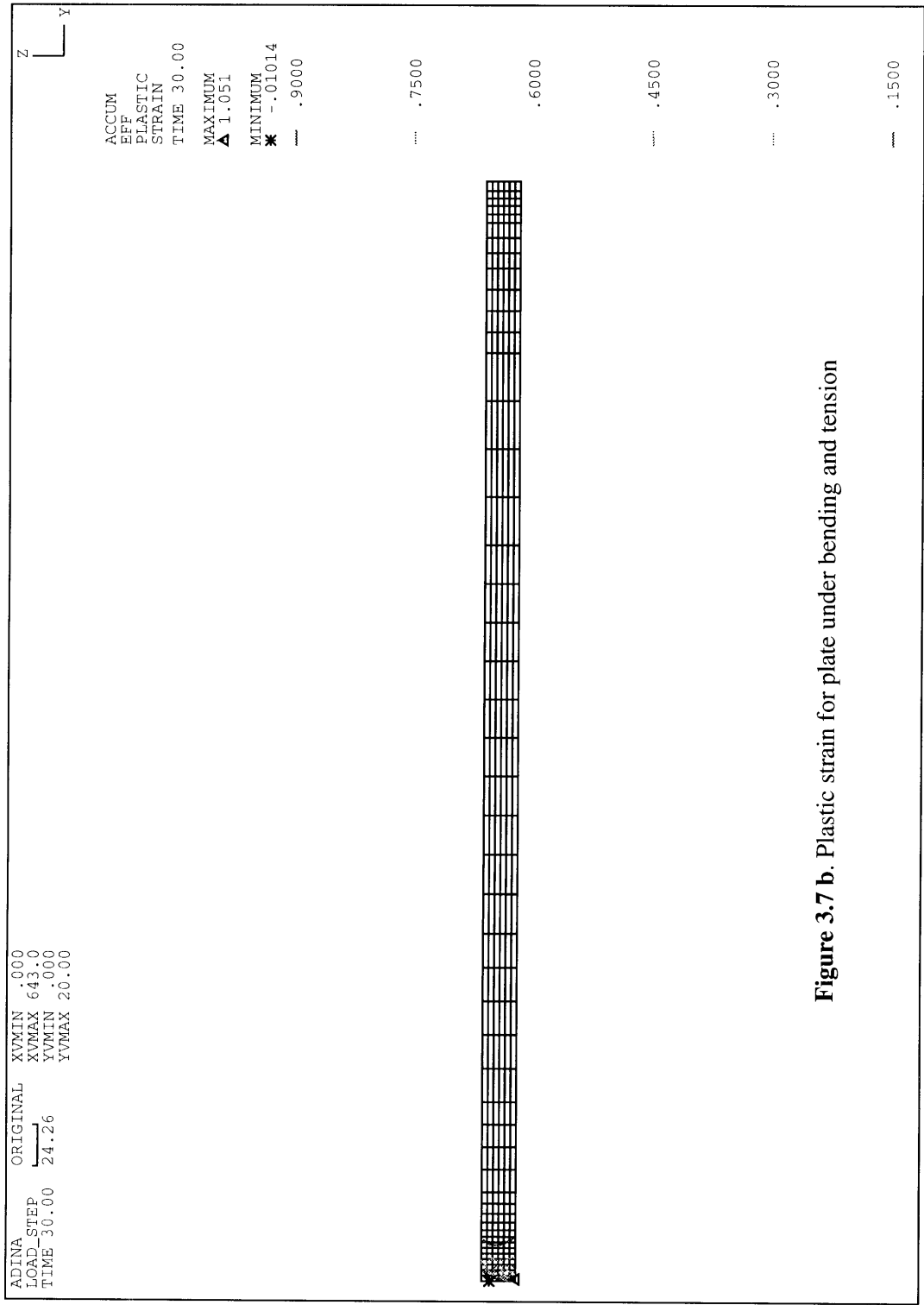
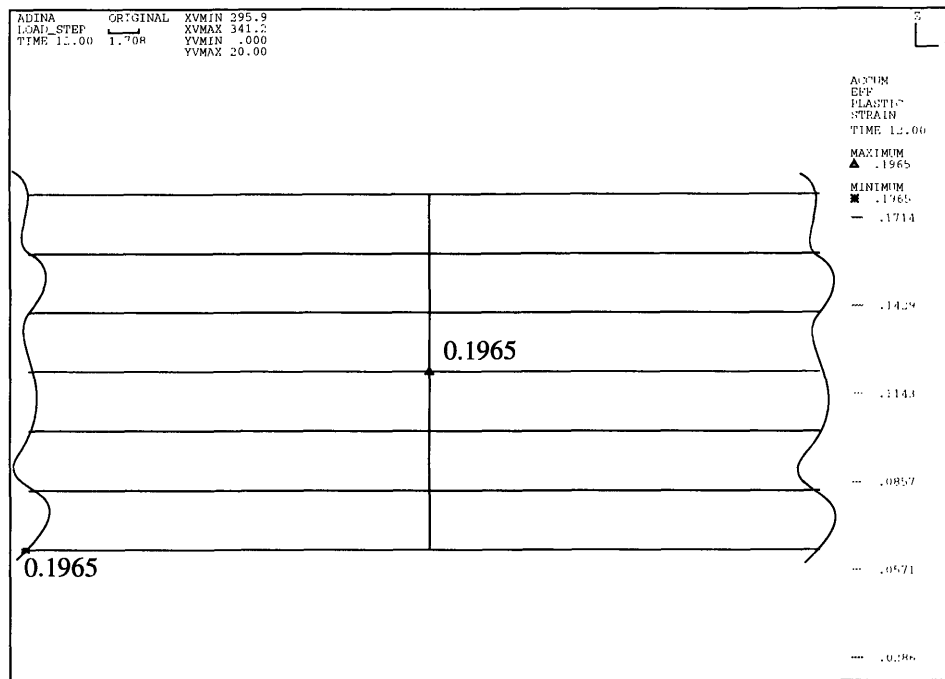


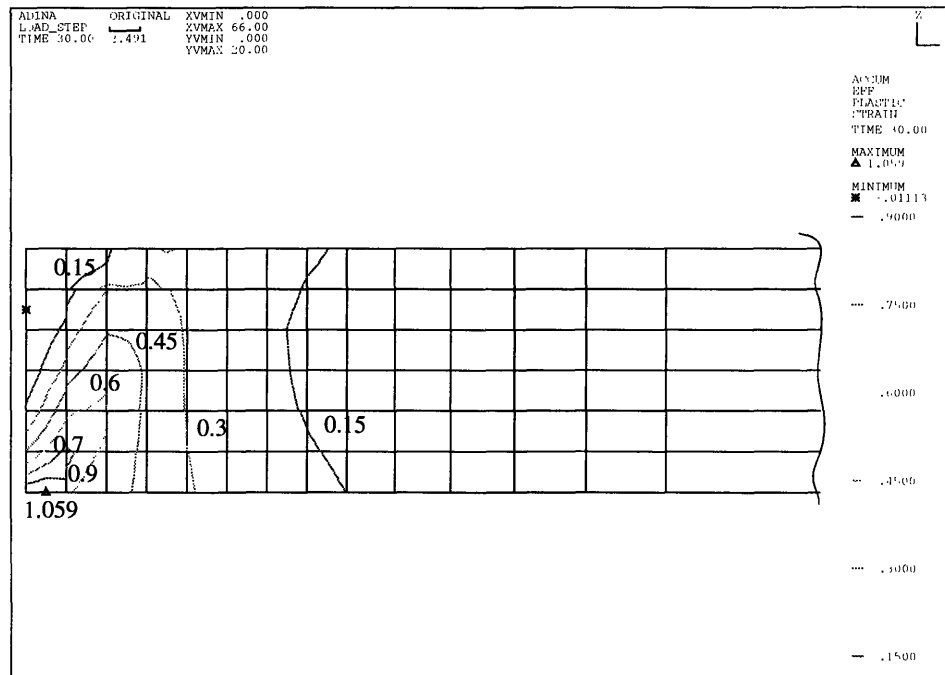
Figure 3.7 b. Plastic strain for plate under bending and tension

Figure 3.7 Plot of accumulative effective plastic strain

Plate under Combined Bending and Tension at Hard-point Support



a. Plate under pure tension



b. Plate under combined bending and tension

Figure 3.8 Strain near the necking area

Chapter 3 References

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- ADINA R&D, Inc., 1992, “**ADINA-PLOT** User’s Manual,” Report ARD 92-7, Watertown, Massachusetts.
- ADINA R&D, Inc., 1992, “ADINA Theory and Modeling Guide,” Report ARD 92-8, Watertown, Massachusetts.
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- Bathe, K.J., 1982, “Finite Element Procedures in Engineering Analysis,” New Jersey: Prentice-Hall, Inc.
- Duffey, T. A., 1989, “Dynamic Rupture of Shells,” *Structural Failure*, edited by Wierzbicki, T. and Jones, N., pp. 161-192, New York: John Wiley and Sons.
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- McClintock, F.A., Zhou, Q., and Wierzbicki, T., 1993, “Necking in Plane Strain Under Bending with Constant Tension,” Joint MIT-Industry Program on Tanker Safety, Report No. 11, Department of Ocean Engineering, Massachusetts Institute of Technology.
- Swift, H.W., 1948, “Plastic Bending under Tension,” *Engineering*, Vol. 166, pp. 333-357.

Appendix 3.A

Power-law Stress-Strain Calculations

This appendix describes the calculations of fitting power-law stress-strain relations to the stress-strain curve from Amdahl and Kavlie experiments. The power law used is based on the Swift power-law

$$\sigma = \sigma_1 \left(\epsilon_0 + \epsilon^p \right)^n . \quad (3.A.1)$$

From the stress-strain curve given in Amdahl and Kavlie report, we can read off the yield strength **YS**, tensile strength **TS**, and the uniform strain at the tensile strength ϵ_u . We also know that the yield strength is

$$YS = \sigma_1 \epsilon_0^n \quad (3.A.2)$$

From necking criterion, $dP = 0$, the tensile strength is

$$\frac{d\sigma}{d\epsilon} = \sigma \quad (3.A.3)$$

Plugging Equation 3.A.1 into Equation 3.A.3, we obtain

$$n = \epsilon_u + \epsilon_0 \quad (3.A.4)$$

Tensile strength is also the force divided by the original area

$$TS = \frac{P}{A_0} = \frac{P}{A} \times \frac{A}{A_0} \quad (3.A.5)$$

where $\log\left(\frac{A}{A_0}\right)$ is the uniform strain at the tensile strength. Therefore, the tensile strength becomes

$$TS = \sigma_1 (\epsilon_u + \epsilon_0)^n e^{-\epsilon_u} \quad (3.A.6)$$

Taking the ratio of tensile strength to the yield strength, we can solve for ϵ_0

$$\frac{TS}{YS} = \left(\frac{\epsilon_u + \epsilon_0}{\epsilon_0} \right)^{\epsilon_u + \epsilon_0} e^{-\epsilon_u} \quad (3.A.7)$$

Once ϵ_0 is solved, we can solve for n and σ_1 using Equation 3.A.4 and Equation 3.A.6.

Appendix 3.B

Tensile Strength for Plane Strain Calculations

This appendix discusses the calculation of tensile strength for plane strain plate. For the necking of a plate in plane strain under pure tension, the tensile strength can be expressed in terms of the corresponding uni-axial case.

Both the elastic and plastic parts of the strain are assumed to be incompressible for simplicity. For a thin plate ($\sigma_y = 0$) under transverse plane strain ($d\epsilon_z = 0$), all the shear stresses and strain increments are zero until a deep neck has formed. So $d\epsilon_y = -d\epsilon_x$ and $\sigma_z = 1/2 \sigma_x$. From von Mises yield criterion and the definitions above, we have

$$\bar{\sigma} = \frac{\sqrt{3}}{2} |\sigma_x| ; \quad d\bar{\epsilon} = \frac{2}{\sqrt{3}} |d\epsilon_x| \quad (3.B.1)$$

In terms of equivalent stress and strain, monotonic loading Eq. A.1 becomes

$$\frac{\sqrt{3}}{2} \sigma_x = \sigma_1 \left(\frac{2}{\sqrt{3}} \epsilon_x + \epsilon_0 \right)^n \text{sign}(\epsilon_x) \quad (3.B.2)$$

From the necking criterion $dP = 0$ such as in uni-axial case, the uniform strain for plane strain case is

$$(\epsilon_u)_p = n - \epsilon_0 \quad (3.B.3)$$

and the tensile strength in terms of $P_{\max}$ and the initial plate thickness, t_0 is

$$(TS)_p = \frac{P_{\max}}{t_0} = \frac{2}{\sqrt{3}} \left(\left(1 - \frac{2}{\sqrt{3}} \right) \epsilon_0 + \frac{2}{\sqrt{3}} n \right)^n e^{-\epsilon_u} \quad (3.B.4)$$

Appendix 3.C

Finite Element Program Input Files

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***** A D I N A - I N INPUT FILE *****
**      Program: hard point bending in plate
**          (was:Tankers Stranding on a Rock)
**          Plastic Analysis, Applied displacement
**          Using power law Stress-Strain Curve
**          9/3 element, fine mesh at both ends
**          BY: JULIANA ATMADJA
**
*****
*
HEAD ' - Plastic, strain hardening'
*
FILEUNIT LIST=8 LOG=7
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
DATABASE CREATE MEMORY=6000
MASTER IDOF=100111 NSTEP=46 REACTION=NO MTOTK=6000
*MASTER IDOF=100111 NSTEP=10 REACTION=YES MTOTK=6000 RESTART=41
MODEX=RESTART
ITERATION METHOD=FULL-NEWTON LINE-SEARCH=YES
KINEMATIC DISPLACEMENT=LARGE STRAINS=LARGE
*AUTOMATIC-LDC NODE=1120 DIR=3 DISPL=10 DISPM=1000.0 CONT=YES
AUTOMATIC-ATS
PRINTOUT VOLUME=MIN
PORTHOLE FORMATTED=YES
*****
*****
**      POSTSCRIPT OUTPUT HEADER FILE FOR ADINA-IN      **
*****
*****
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*ECHO=7
*
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*CONTROL PLOTUNIT=CM HEIGHT=0.25
*FCONTROL SIZE=ISO ISO=-4.5 XSF=2 YSF=1.5
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COLORS ORI=INVERSE EL=INVERSE BC=INVERSE XYA=INVERSE
XYL=INVERSE VE=INVERSE
*
** HEADING OPTIONS:
FCONTROL HEADING=UPPER
*FCONTROL HEADING=LOWER
*
** FOR LANDSCAPE ORIENTATION, UNCOMMENT THE NEXT LINE:
FCONTROL ORIGIN=UPPERLEFT
*****
****
*
COORDINATES
ENTRIES NODE Y Z
1 0.00 0.00
2 9.90 0.00
3 23.10 0.00
4 52.80 0.00
5 105.60 0.00
6 204.60 0.00
7 318.75 0.00
8 430.95 0.00
9 543.15 0.00
10 592.65 0.00
11 619.05 0.00
12 628.95 0.00
13 637.50 0.00
14 643.00 0.00
15 0.00 20.00
16 9.90 20.00
17 23.10 20.00
18 52.80 20.00
19 105.60 20.00
20 204.60 20.00
21 318.75 20.00

```

Plate under Combined Bending and Tension at Hard-point Support

22	430.95	20.00
23	543.15	20.00
24	592.65	20.00
25	619.05	20.00
26	628.95	20.00
27	637.50	20.00
28	643.00	20.00

*

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15	295.0
16	296.0
17	297.0
18	298.0
19	298.1
22	298.2
23	298.21
24	298.22
26	298.25
30	299.0
33	305.0
35	308.0
36	310.0
37	312.0
38	320.0
39	325.0
40	326.0
41	326.5
42	326.55
43	326.6
44	326.75
45	326.8
46	326.85

* Material properties *****

*

* Material properties for base plate

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0.0039920213	336.86536
0.0079681696	349.47146
0.023716527	386.01437
0.031498667	399.57048
0.039413002	411.53681
0.048790164	423.96861
0.056380333	432.96489
0.063913326	441.14179
0.071389996	448.64262
0.07881118	455.57522
0.086177696	462.02291
0.09531018	469.49956
0.10436002	476.42151
0.11332869	482.86761
0.12221763	488.9006
0.13102826	494.57132
0.13976194	499.92152
0.15529288	508.85162
0.1705863	517.01405
0.18232156	522.91097
0.19885086	530.74696
0.20701417	534.43506
0.21511138	537.98507
0.22314355	541.40682
0.2390169	547.89982
0.25153663	552.79046
0.26236426	556.87062
0.27763174	562.40768
0.28367405	564.53384
0.29266961	567.63486
0.30010459	570.14236
0.30601303	572.10071
0.31188676	574.01854
0.32	576.62171
0.35	585.82014

0.4	599.85972
0.45	612.57737
0.46	614.98547
0.47	617.35247
0.485	620.82921
0.49	621.96917
0.5	624.22169
0.7	663.13525
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0.9	693.96208
1	707.34718
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* Base plate formulation

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GSURFACE 2 3 17 16 EL1=4 EL2=6 NO=9

GSURFACE 3 4 18 17 EL1=6 EL2=6 NO=9 RATIO1=2

GSURFACE 4 5 19 18 EL1=4 EL2=6 NO=9

GSURFACE 5 6 20 19 EL1=5 EL2=6 NO=9

GSURFACE 6 7 21 20 EL1=5 EL2=6 NO=9

GSURFACE 7 8 22 21 EL1=5 EL2=6 NO=9

GSURFACE 8 9 23 22 EL1=4 EL2=6 NO=9

GSURFACE 9 10 24 23 EL1=4 EL2=6 NO=9

GSURFACE 10 11 25 24 EL1=3 EL2=6 NO=9

GSURFACE 11 12 26 25 EL1=2 EL2=6 NO=9

GSURFACE 12 13 27 26 EL1=2 EL2=6 NO=9

*

***** Harder material ***

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* elastic material at the end of the plate formulation
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TION=1 MAT=2 ,
      RESULTS=FORCE
GSURFACE 13 14 28 27 EL1=1 EL2=6 NO=9
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* Loading conditions
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      1250 2 0.0
*
*
FIXB DIR=23 TYPE=LINE
      1 15
*
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*MESH FORCE EL=1 SUBFRAME=1122 MARGIN=YES
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ADINA
END
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***** A D I N A - P L O T INPUT FILE *****
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**      (was:Tankers Stranding on a Rock)
**      Plastic Analysis, Applied displacement
**      Using power law Stress-Strain Curve
**      9/3 element, fine mesh at both ends
**      BY: JULIANA ATMADJA
FILEUNITS LIST=8 LOG=7
FCONTROL HEADING=UPPER ORIGIN=UPPERLEFT
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
DATABASE CREATE FORMATTED=YES MEMORY=1000
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*****
* POSTSCRIPT OUTPUT HEADER FILE
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FILEUNITS LIST=8
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FCONTROL SIZE=ISO ISO=-4.5 XSF=10 YSF=5
WORKSTATION SYS=12 COLORS=RGB BACKGROUND=WHITE
COLORS ORI=INVERSE EL=INVERSE BC=INVERSE XYA=INVERSE
XYL=INVERSE
COLORS DEF=INVERSE VE=INVERSE ST=INVERSE
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*
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Chapter 4

Finite Element Analysis of Fillet Welds for Lazy-L Test

4.1 Introduction to Chapter 4

The goal for ship designers or fillet welded T-joints designers is to have sufficiently large fillet welds in order that their surrounding plates will deform under ‘normal’ and ‘accidental’ service instead of the welds themselves. From previous studies of fillet weld - plate interactions, it appears that with the current rules set by the classification societies, some weld - plate size combinations allow deformation on the welds. There is also some evidence of welds failure during grounding incidents such as the Exxon Valdez. The type of failures observed in the Exxon Valdez incident was ‘peeling’ or ‘tearing’ of the fillet welds. This subject was studied by Kirkov in 1994 and Wilcox in 1995. Fracture of fillets due to folding or tripping of the longitudinal stiffeners or frames is another type of failure which has not been studied extensively.

A Lazy-L test was proposed by Brooks as a tool for ship designers and fabricators to design a sound fillet weld and to get quantitative results of fillet welds fracture due to folding or tripping. The Lazy-L test is a modification of the existing ABS tack welder qualifi-

cation test No. 3 [Brooks, 1995]. As mentioned in Brooks' report, the proposed test is flexible, where three different experiments are available from the same general setup. Bending of fillet welds can be studied by considering the Lazy-L test configuration with a single fillet weld in the upper position (see Figure 4.1 on p. 111). When the fillet weld is in the lower position (Figure 4.2 on p. 111) the fillet weld under predominant shear on the weld leg, which is similar to pure tension, can be studied. Finally, the web folding failure case can be analyzed by taking into account a double fillet welded Lazy-L test (Figure 4.25 on p. 134).

In conjunction with the Lazy-L test, finite element analysis was also performed to study the limit moment, slip-line field, and local stress of the single fillet weld, both under predominant opening bending and under predominant transverse shear of the fillet leg. This chapter of the thesis reports the study of the deformation and strength of fillet welds using finite element analysis for the Lazy-L test. Section 4.2 discusses the single fillet weld Lazy-L test under the predominantly opening bending case. The upper bound analysis, finite element method which leads to slip-line field, and slip-line field analysis are also reported in this section. Section 4.3 reports the upper bound, finite element analysis, and slip-line field study on the predominant leg shear of single fillet weld Lazy-L test. Finally, Section 4.4 presents the upper bound analysis on web folding of the double fillet welds.

4.2 Predominantly Opening Bending of Single Fillet Weld Lazy-L Test

When the fillet weld is in the upper position of Lazy-L configuration (Figure 4.1 on p. 111), the weld is in a predominantly opening bending mode. The exact solutions for this problem were unknown prior to this study. To obtain the solutions, an upper bound to limit load theory, finite element method, and finally slip-line field theory were utilized.

4.2.1 Least upper bound

Analyzing fillet welded T-joints is not an easy task due to their geometry and the complexity of the materials. Exact solutions for limit loads are difficult to obtain since they have to satisfy five conditions of mechanics, namely: (i) the partial differential equations of equilibrium of stress gradients, (ii) the definitions of components of strain in terms of displacement gradients, (iii) boundary conditions in terms of displacements of tractions (boundary forces per unit surface area), (iv) a yield locus which limits the magnitudes of the stress components, (v) linear functions relating only the increments of strain components to current stress components [McClintock, 1994]. Fortunately, bounds to limit load can be found by satisfying some of the five conditions above. For practical purposes, the exact solutions are not needed if the bounds are close enough. The least upper bound of the limit load is of particular importance for the designers.

To find an upper bound to the limit load, it is necessary to have a complete field of displacement increments $u_i(x_j)$ which satisfy any displacement boundary conditions, give no change in volume anywhere, and give an integral of the plastic work increment throughout the body which is the upper bound load P_{ub} times the corresponding displacement component in the direction of the load δu_p :

$$P \times \delta u_p \leq P_{ub} \times \delta u_p = \delta W^p = \int (Y \times \delta \epsilon^p) dV \quad (4.1)$$

Least upper bound can be found from the plastic work of incompressible displacement fields which satisfy any displacement boundary conditions.

Useful upper bounds to the limit moment can be constructed from kinematically admissible deformation fields which take the form of circular arcs of sliding. These arcs represent the path of maximum shear stress in the material arising from the corresponding

far-field loading conditions [Kim, 1993]. Kim (1993) demonstrates that the arc which yields the least upper bound, called the LUB arc, may be chosen to be consistent with the three global equilibrium conditions, i.e.: (a) the Hencky equation for equilibrium and yield condition in the deforming region, (b) the Geiringer equations for incompressibility in the deforming region, and (c) equilibrium and the yield inequality in the rigid region, and therefore, applicable to fully plastic deformation and crack growth analysis.

The least upper bound (LUB) moment for the predominant opening bending single fillet weld is the minimum work done against the shear strength of the fillet weld metal. Because the hardness distribution within the fillet welds is roughly uniform and is less than that of the surrounding heat affected zone [Middaugh, 1994], as a first approximation the plastic flow fields for the fillet welds and the surrounding web metal can be modeled as arcs of maximum shear through the weld metal. With an applied moment M as shown in Figure 4.3 on p. 112, the stiffener's web is assumed to be rotating about the center of rotation O . The limit moment for fillet under predominant opening bending is independent of the web thickness. The angle and radius of the circular arc are related to the weld leg, d .

The arc on the fillet weld is characterized by the radius of sliding, R_C , angles ϕ_C and ϕ_D which are measured from a tangent to the arc of sliding clockwise to the face of the weld (Figure 4.3 on p. 112). The applied moment multiplied by the rotation increment, $\delta\phi$, will give the incremental work along the sliding arc needed against the shear strength of the fillet weld metal, k_f .

$$\delta W = M \times \delta\phi = ((k_f \times R_C \times \theta_c) \times R_C) \times \delta\phi \quad (4.2)$$

where θ_c is the angle difference ($\phi_D - \phi_C$) in radians. The bending moment is then:

$$M = (k_f \times R_C \times \theta_c) \times R_C \quad (4.3)$$

The minimum or the least upper bound moment can be found by iterative method for a series of different R_C . Minimization methods are described in Appendix 4.A. The normalizing moment in the single-fillet opening case is the moment of a bar of fillet weld metal of throat thickness, $d/\sqrt{2}$ is

$$M_{nom} = \frac{2k_f \left[\frac{d}{\sqrt{2}} \right]^2}{4} = \frac{k_f d^2}{4} \quad (4.4)$$

The minimum value of M/M_{nom} is the same for all single fillets in predominant bending since it is a function of weld leg length with which the arcs of sliding scale.

The stress and deformation fields at a crack tip under loadings are very useful in characterizing the fully plastic growth in structures. The normal stress across the LUB arc at the crack tip, σ_s , can be approximated from Hencky's equation

$$d\sigma = 2kd\psi \text{ or } \sigma = \sigma_r + 2k\psi \quad (4.5)$$

4.2.2 Finite element analysis

The finite element method can be used to test the validity of simple LUB arc-sliding models for stress and strain fields around a growing crack in full-size welds. The results from finite element analysis are influenced by the assumptions relevant to model extension, boundary condition, load modeling and the type of mesh and element used. With careful assumptions relevant to the model and boundary conditions, finite element analysis gives exact solutions except for errors due to mesh size. Therefore, choosing the correct mesh size is the critical point in using the finite element method to obtain good accuracy. In this study, the finite element mesh size was tested on a known slip-line field for a singly-

grooved symmetry crack under pure shear [McClintock & Clerico, 1980]. Three different mesh sizes of fillet weld were studied and the slip-line fields were compared to the analytical solution. The comparison of the principal plastic strain obtained from the finite element results to the known analytical solution can be seen in Figure 4.4 on p. 114. The coarse mesh size cannot capture the fan of the slip-line field near the face of the weld. The medium and fine mesh size gives comparable detail of the fan near the face of the weld. Therefore, medium mesh size with 16 elements across the fillet weld surface (Figure 4.4c) was chosen to model the single fillet Lazy-L test in order to obtain reliable results. Calculations on fillet weld mesh size and geometry can be found in Appendix 4.B.

4.2.2.1 Finite element model and method

A perfect triangular fillet weld was modeled to study the characteristics of the weld under predominant leg shear. No gap between the base plate and the stiffener was modeled. The base plate was assumed to be rigid, therefore the boundary conditions for the weld near the base plate are fixed in the y- and z-directions (see Figure 4.6 on p. 116). To simulate web folding, bending moment M was applied at the web (see Fig. Figure 4.6 on p. 116). On the finite element model, this was done by assigning displacement boundary conditions along the leg of the weld near the stiffener's web. The boundary conditions were modeled as a set of displacement, with the center of rotation at O. The amount of prescribed displacement was linear, zero at the center of the arc, to the maximum values at the weld toe and weld surface as shown in Figure 4.6 on p. 116. The calculation of displacement boundary conditions can be found in Appendix 4.C. For convenience, the finite element fillet weld model was rotated 45° clockwise.

The mesh for the weld was modeled to be square elements for more accurate results. The calculation of the mesh size and geometry can be found in Appendix 4.B. To avoid locking and instability due to almost incompressible elasticity behavior of the elastic-plastic material, a mixed finite element formulation is used. Regular pure displacement formulation element generally locks in almost incompressible analysis. In the analysis of almost incompressible behavior, using a formulation that 'locks', the displacements are not necessarily to a large extent in error but the stresses (pressure) are very inaccurate [Bathe, 1995]. Since accurate stress and strain on the weld are important aspects in this analysis, a 9/3 mixed element was used. A 9/3 element means there are 9 displacement points with 3 pressure points in each element. By interpolating displacement and pressure, the finite element formulation for almost incompressible behavior do not lock. A rounded bottom near the weld toe was modeled to avoid high stress concentration near the toe of the weld.

An automatic-time-stepping (ATS) method was used to analyze the problem. In this method, the user defines the loads by time functions, load distributions, etc. The incremental solution is then attempted with the user-selected time step and the only effect of the ATS method is that, if iteration convergence is not reached in the maximum number of allowed iterations, the program automatically subdivides the user-selected time step to reach convergence.

The material used for the analysis was a non-strain hardening steel for simplicity. Another reason to use non-strain hardening material was that so that one can compare the finite element analysis results to the theoretical calculations. Modulus of elasticity of the material is $2.0 \times 10^5 \text{ N/mm}^2$ with yield stress of 500 N/mm^2 . Automatic Dynamic Incre-

mental Nonlinear Analysis (ADINA) was the finite element program used to study the strength and deformation of the fillet weld.

4.2.2.2 Finite element results

The deformed configuration of the predominant opening bending single fillet weld can be seen in Figure 4.6 on p. 116. The original configuration is shown in dashed lines while the deformed configuration is shown in solid lines. The slip-line field path of the fillet weld can be seen by plotting the principal plastic strain. The plot of principal plastic strain is shown in Figure 4.7 on p. 117. It appears that from Figure 4.7, the slip-line field for single fillet weld under predominant opening bending is not a single circular arc. One can see that the slip-line coming out 45° from the toe of the weld at point A in Figure 4.7 as an arc and then the slip-line continues with a straight line with a fan near the face of the weld. The slip-line field solution is a modified Green and Hundy slip-line field for bending of a single edge notch beam and it will be discussed in Section 4.2.3.

Finite Element Radius of Slip-line Field

The radius of the slip-line field for the single fillet Lazy-L test under predominant opening bending was determined by calculating the equilibrium of the Lazy-L test in the 1- direction of the 1-2 coordinate system shown in Figure 4.8 on p. 118. The Lazy-L configuration is in equilibrium when the value of F_{Rb} and F_{Rt} from the finite element results are the same (see Figure 4.8). The radius of the slip-line field obtained from finite element analysis is about 25% lower than the radius obtained from the LUB analysis. The value can be seen in Table 4.1. However, the radius of the slip-line field is in good agreement with the Green and Hundy solution for the bending of a single edge notch beam.

Limit Moment

The limit moment was calculated by summing the moment of each nodal point along the prescribed displacement boundary at about the middle of the weld, point O in Figure 4.5 on p. 115. Because the sliding arc is independent of the web thickness, the limit moment is the same for 6- and 9-mm weld size. The limit moment from finite element analysis is 12% lower than that of the LUB analysis. This indicates that the LUB analysis is a good method for first approximation.

Mean Normal Stress

The mean normal stress across the weld is also plotted in Figure 4.9 on p. 119. Figure 4.9 shows that the value of mean normal stress near the crack tip of the predominantly opening bending single fillet is 1.2. This value is in a good agreement with the LUB analysis value which is 1.198 (see Table 4.1).

4.2.3 Slip-line field theory

The slip-line field for predominant opening bending was obtained from the finite element results. From the plot of principal plastic strain, one can see that there is a 45° fan near the face of the weld. This means that the slip-line field for single fillet weld under predominant opening bending is not a single circular arc as assumed in the LUB analysis. The proposed slip-line field is presented in this section.

For the pure opening bending of a single V-groove specimen, Green and Hundy (1956) found the slip-line field as shown in Figure 4.10 on p. 120 which shows a circular arc from point A at the toe of the weld up to point B. The slip-line path is continued from point B to point C and D as straight lines with 45° rigid region. The field near the tip of the groove consists of two circular arcs. The single fillet weld under predominant opening bending has a similar situation except the region is restricted by the rigid regions from the web

stiffener and the base plate. Therefore, the proposed slip-line is a modified Green and Hundy slip-line for the pure opening bending of a single V-groove specimen. The proposed slip-line field can be seen in Figure 4.11 on p. 120. The radius of the slip-line field can be found by equilibrating the weld in the 2-direction of the 1-2 local coordinate system Figure 4.11 on p. 120. Detailed calculations can be found in Appendix 4.D. The radius of the center arc is a function of the weld leg length, d

$$R = \frac{d}{\pi} \quad (4.6)$$

The radius of the center arc from LUB analysis, FEA, slip-line field solution, and single edge notch solution are compared in Table 4.1. The radius obtained from the finite element analysis is about 4% higher than the radius obtained from the slip-line field theory.

The aspect of the stress distribution that is important is the normal stress σ on the active slip surfaces. At the tip of the crack, the normal stress reaches:

$$\frac{\sigma_s}{2k} = 1.07 \quad (4.7)$$

The finite element analysis also gives good accuracy for the normal stress near the crack tip, which is 12% higher than the slip-line field solution. The error in the finite element analysis might be due to high stress concentration near the tip of the crack. Table 4.1 lists the comparison of mean normal stress obtained LUB analysis, FEA, slip-line field theory, and single edge notch bar solution.

We can also obtain the limit moment from LUB analysis, FEA, slip-line field theory, and single edge notch bar solution. The slip-line field, which is the modified Green and Hundy solution for single edge notch bar under pure bending, gives the limit moment as:

$$\frac{M}{\left(2k_f a^2\right)/4} = 1.36 \quad (4.8)$$

Again, the comparison of the values obtained can be seen in Table 4.1. The finite element result is about 5% lower than that of slip-line field theory.

Table 4.1 Comparison of predominant opening bending solutions

	Least Upper Bound		FEM	Slip-line Solution	
	SEN Plate	Fillet	Fillet	SEN Plate	Fillet
Limit Moment $M/(2ka^2/4)$	1.38	1.48	1.30	1.26	1.36
Angle, θ_s	66.8°	45°	45°	75°	45°
Mean Normal Stress, $\sigma_s/2k$	1.166	1.198	1.2	1.543	1.071
Radius, R_C/a	0.544	0.619	0.465	0.389	0.449

4.3 Predominantly Leg Shear of Single Fillet Weld Lazy-L Test

The weld is under a predominant transverse shear along the fillet leg close to the web when the fillet weld is in the lower position of the Lazy-L configuration (Figure 4.2 on p. 111). The upper bound limit moment of this single fillet weld can be calculated by assuming a single circular arc with an arc focus at O (Figure 4.12 on p. 121). The upper bound limit moments, the assumed single arc slip-line, and the mean normal stresses will be compared to the finite element results. In addition, a proposed slip-line field solution is presented.

4.3.1 Least upper bound

As in the predominant opening bending case, a single circular arc was assumed to be the slip-line field for the weld (see Figure 4.12 on p. 121). The arc is characterized by the radius of curvature R_A . Other variables are the center of rotation, O, the height of the center rotation from the base plate, R_C , and the angles ϕ_A and ϕ_B which are the angles from the tangent of the arc to the horizontal line. The incremental work required in sliding along the arc of sliding against the shear strength of the fillet metal is equal to the bending moment, M , multiplied by the increment rotation, $\delta\phi$

$$\delta W = M \times \delta\phi = ((k_f \times R_A \times \theta_t) \times R_A) \times \delta\phi \quad (4.9)$$

where θ_t is the angle difference ($\phi_B - \phi_A$) in radians and k_f is the shear strength of the fillet weld metal, which is $(YS) / (\sqrt{3})$. The moment can be found by rearranging Eq. 7 and obtain

$$M = (k_f \times R_A \times \theta_t) \times R_A \quad (4.10)$$

The bending moment is normalized by the moment of a bar of web metal of thickness, t_w

$$M_{nom} = \frac{2k_w t_w^2}{4} = \frac{k_w t_w^2}{2} \quad (4.11)$$

The minimum bending moment which obtained by iterative method is:

$$\frac{M}{M_{nom}} = \frac{2(k \times R_A \times \theta_l) \times R_A}{k_w t_w^2} \quad (4.12)$$

Detailed calculation in obtaining the minimum bending moment can be found in Appendix 4.A. It turns out that the minimum normalized bending moment for the single fillet in predominant transverse shear is a function of the ratio of the weld leg length (d) to the web thickness (t_w). The value of minimum bending moment for different d/t_w ratios can be seen in Table 4.2.

Table 4.2 Minimum bending moment values

Leg length, d	Web thickness, t_w	Ratio, d/t_w	Minimum Moment
6	20	0.3	0.869
6	13.3	0.45	0.894
6	11	0.54	0.911
6	9	0.67	0.934

4.3.2 Finite element analysis

The same mesh size which was used for the single fillet weld under predominant opening bending was used in this analysis. To simulate bending, the fillet weld is at the lower position of the base plate stiffener configuration (Figure 4.2 on p. 111). The method used was also the same as for the predominant opening bending. The only difference in the analysis was the boundary conditions which were prescribed on the fillet weld.

4.3.2.1 Finite element model and method

The boundary conditions for this model were different because the bending moment applied to the web was different from the one for predominant opening bending. Similar to the predominant opening bending case, the displacements were applied along the leg of the weld near the stiffener web. The difference in this case is that the center of rotation was on the web stiffener instead of on the leg length (see Figure 4.12 on p. 121). The value of the applied displacement can be found in Appendix 4.C. The finite element model can be seen in Figure 4.13 on p. 122.

4.3.2.2 Finite element results

Figure 4.14 on p. 123 shows the deformed configuration of the fillet weld under a predominant transverse shear. The deformed configuration is shown in solid lines while the original configuration is shown in dashed lines. The slip-line field from finite element analysis can be seen by plotting the principal plastic strains on the weld. From Figure 4.15 on p. 124, one can see that the slip-line field from the finite element corresponds well with the assumed single circular arc through the weld. From the finite element results, it appears that the actual slip-line is not a single arc. Looking closer at the face of the fillet

weld, one can see that the mean normal stresses change from positive at point A to negative (compression) at point B of Figure 4.16 on p. 125. This indicates that the actual slip-line might be similar to the single crack under pure shear developed by McClintock and Clerico in 1980. Therefore, the mesh near the face of the weld was refined (see Figure 4.17 on p. 126).

Finite Element Radius of Slip-Line Field

The radius of slip-line field was obtained by running the finite element analysis and checking the equilibrium of the structure in 1-direction of the 1-2 coordinate system (see Figure 4.18 on p. 127). To find R_C , we assume an infinite moment arm (infinitely long web stiffener) so the reaction force, N_w , is zero. To obtain an equilibrium in the 1-direction, the magnitude of force N should be equal to the magnitude of force F_{Rf} , which is the resultant of F_{yf} and F_{zf} obtained from the finite element analysis. Comparisons of different radii for different d/t_w s can be found in Figure 4.19 on p. 128. The radii obtained from finite element method are indicated by the dashed line and the LUB radii are indicated by the solid line on Figure 4.19. The upper bound method gives lower arc radius. However, the error is within 10%.

Limit Moment

Figure 4.20 on p. 129 shows that the limit moments from the finite element analysis (dashed line) are lower than that of LUB calculations (solid line) as expected. The limit moment was calculated by taking the moment of each local nodal point along the applied displacement boundary about the middle of the weld, point O in Figure 4.13 on p. 122. The finite element limit moments were about 5% lower than the least upper bound

moment. This indicates that the least upper bound approximation is a good first estimation in designing the fillet welds of the ship.

Effects of Friction

The effects of friction were also studied. Different values of frictions for the interface between stiffener web and base plate (f_i in Figure 4.21) were applied. Different friction values were also applied at the support point (f_s in Figure 4.21). The effect of friction to the support load and the radius of sliding were examined. The results show that the effect of friction is negligible. Figure 4.22 on p. 131 shows the effect of friction on the radius of sliding. By taking into account friction of 0.2, the radius of sliding was reduced by 3%. Similarly, friction does not effect the support load. The support load is increased by only about 5% due to friction (see Figure 4.21 on p. 130).

4.3.3 Slip-line field theory

For single fillet Lazy-L test where the weld is under predominant shear, the slip-line field is obtained from the finite element analysis (FEA). From FEA results, the assumed circular arc gives good accuracy for the radius of sliding. However, as mentioned earlier in the finite element results section, the mean normal stress plot across the surface of the weld indicates that the stresses change from positive (tension) at point A to negative (compressive) at point B of Figure 4.16 on p. 125. In addition, from the plot of principal plastic strain, one can see an abrupt change in the direction of the principal plastic strain near the face of the weld. This indicates that the actual slip-line is not a single arc. The actual slip-line is predicted to be similar to the slip-line field or a crack under pure shear.

To verify this prediction, the existing mesh was refined at the location where the fan should be located. The FEA with a refined mesh model shows that the slip-line field

indeed looks like the slip-line field for a crack under pure shear. The plot of principal plastic strain near the face of the refined mesh model can be seen in Figure 4.22 on p. 131. Unfortunately, there is no closed-form solution for this type of slip-line field. Only the shape of the slip-line field can be compared. There is no theoretical solution on the radius of slip-line field. Therefore, the limit moment from the FEA cannot be compared with the limit moment from the slip-line field theory solution. Figure 4.24 on p. 133 shows the proposed slip-line field which consists of a circular arc with a fan near the face of the weld.

4.4 Web Folding of Double Fillet Welds

Slip-line fields for double fillet welded T-joints are not available. McClintock (1994) proposed kinematically admissible flow fields, each consisting a single circular arc, $\delta\phi$ (see Figure 4.26 on p. 135). The minimum bending moment for a double fillet weld in bending is an extension of the single fillet in predominant weld leg shear to include the influence of the additional fillet.

The web was considered to be rotating about the focus of the arc (point O in Figure 4.26 on p. 135). Assume the left-hand fillet weld will be subject to a constant shear strain to accommodate the rotation of the web. The right-hand fillet weld will undergo the same shear strain, plus shear along the bond line to accommodate the swing of the web, $t_w\delta\theta$ [McClintock, 1994]. The product of the rotation and the applied moment will give the work done in sliding of the arcs in terms of the shear strength of the fillet weld, k_f

$$\delta W = M \times \delta\phi = [(k_f \times R_A \times \theta_i) \times R_A]_i \delta\phi + [(k_f \times R_C \times \theta_e) \times R_C]_e \delta\phi \quad (4.13)$$

To get the minimum limit moment, the arc focus (O) needs to be adjusted. Calculations of this limit moments for 6 mm and 9 mm double fillet welds can be found in Appen-

dix 4.E and the values for different d/t_w configurations are listed in Table 4.3. The normalizing moment is the moment of a bar of web metal with thickness of t_w (Equation 4.11). So the normalized limit moment is:

$$\frac{M}{M_{nom}} = \frac{2k_f \left[\left(R_A^2 \times \theta_t \right) + \left(R_C^2 \times \theta_c \right) \right]}{k_w \times t_w^2} \quad (4.14)$$

The crack growth information can be obtained from the normal stress σ_s across the slip-line, especially near the crack tip. In the double fillet weld case, due to the existence of two welds, the normal stress cannot be found from overall equilibrium. For the arcs AB and DC, it is plausible to assume that the mean normal stresses at the surfaces of the welds are of a form that goes to the right limit when the arcs are at 45° to the weld surface, and is zero when the arc is normal:

$$\frac{\sigma_D}{2k_f} = \frac{(\phi_D + \pi/4)}{\pi/2}, \quad \frac{\sigma_B}{2k_f} = \frac{(\phi_B + \pi/4)}{\pi/2} \quad (4.15)$$

Along the α -lines, the Hencky equations of equilibrium give $d\sigma = 2kd\phi$, so, with angles in radians,

$$\frac{\sigma_C}{2k_f} = \frac{\phi_D}{\pi/2} + \frac{1}{2} + \phi_C - \phi_D, \quad \frac{\sigma_A}{2k_f} = \frac{\phi_B}{\pi/2} + \frac{1}{2} + \phi_A - \phi_B \quad (4.16)$$

Table 4.3 Least upper bounds for double fillet weld

d, mm	t _w , mm	d/t _w , mm	Mome nt	R _C , mm	R _A , mm	φ _D , °	φ _C , °	φ _A , °	φ _B , °	σ _C / 2k _f	σ _A / 2k _f
6	16.4	0.366	0.844	4.00	16.88	-65.7	0	76.3	95.4	0.917	0.216
9	19	0.474	1.144	5.71	19.84	-68.9	0	73.3	97.6	0.937	0.160
9	18	0.500	1.222	5.73	18.89	-68.8	0	72.3	97.8	0.936	0.143
6	11	0.545	1.358	3.78	11.63	-69.5	0	71.0	98.4	0.941	0.116
6	10	0.600	1.528	3.66	10.65	-71.2	0	69.9	99.5	0.951	0.089
6	9	0.667	1.748	3.63	9.70	-72.5	0	68.0	101.5	0.96	0.044

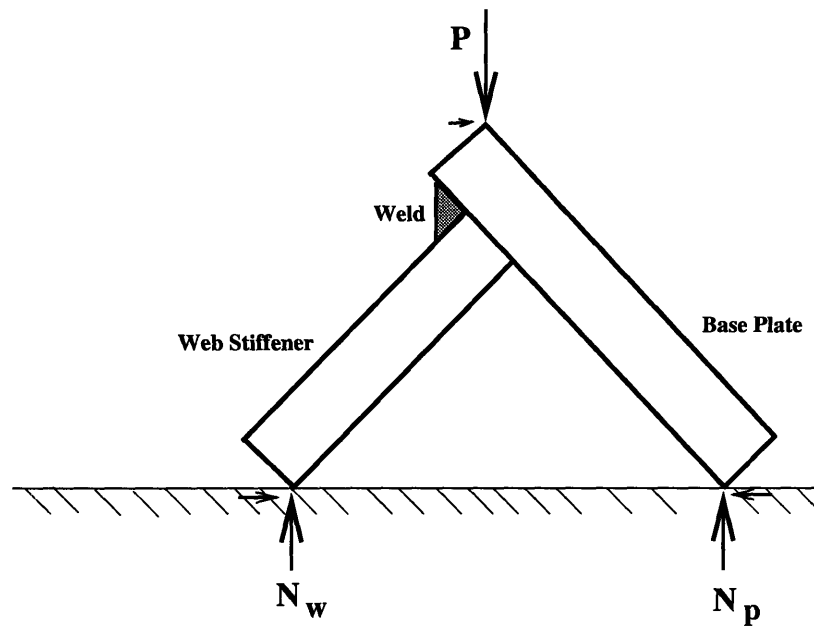


Figure 4.1 Predominant opening bending of single fillet lazy-l test

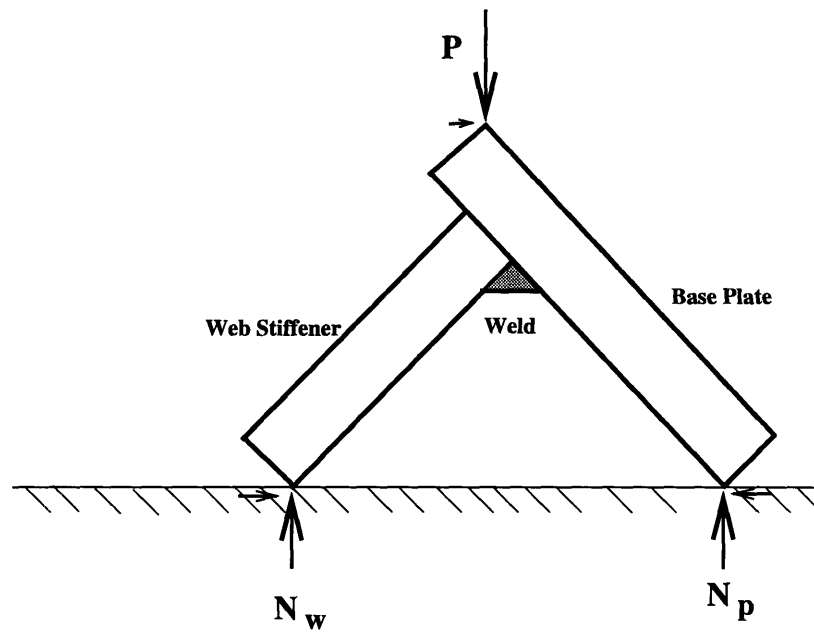


Figure 4.2 Predominant leg shear of single fillet lazy-l test

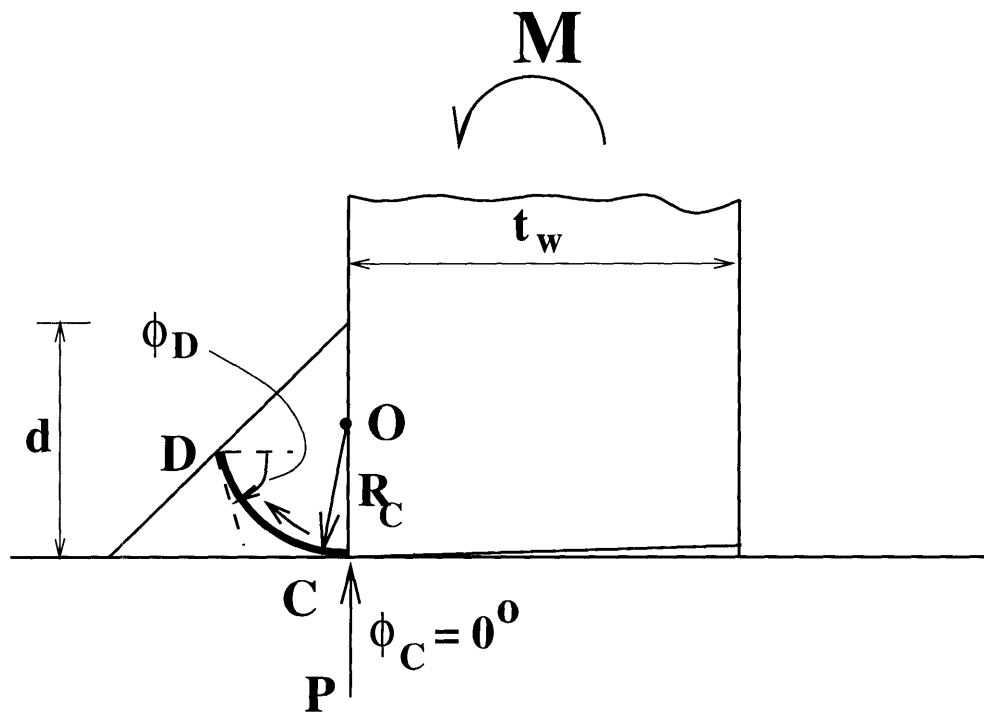
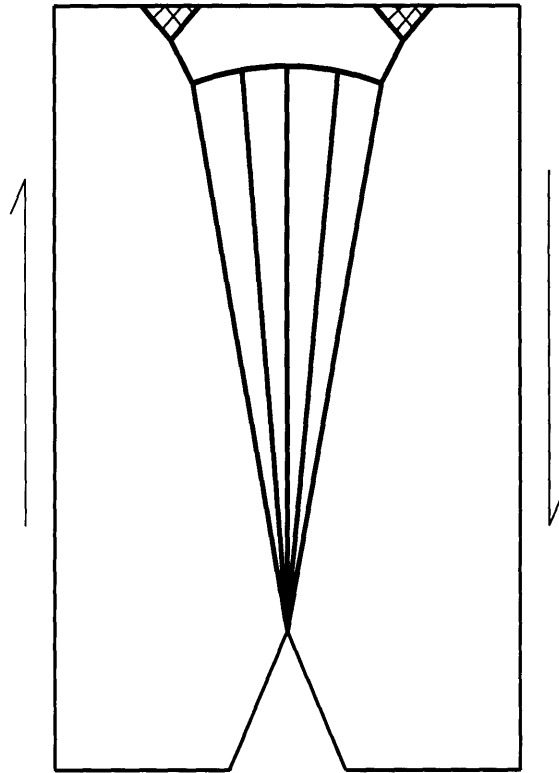
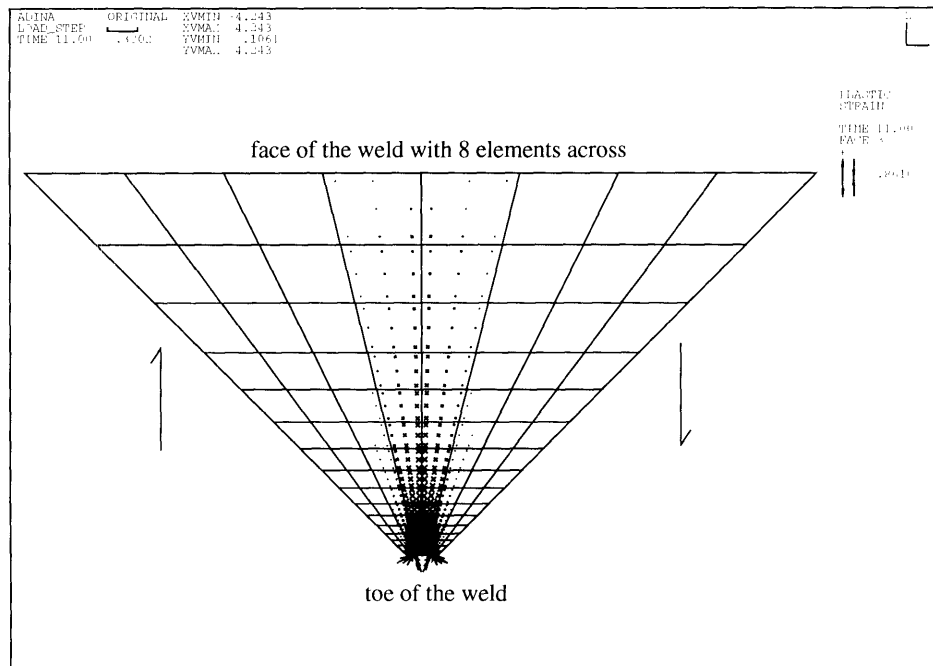


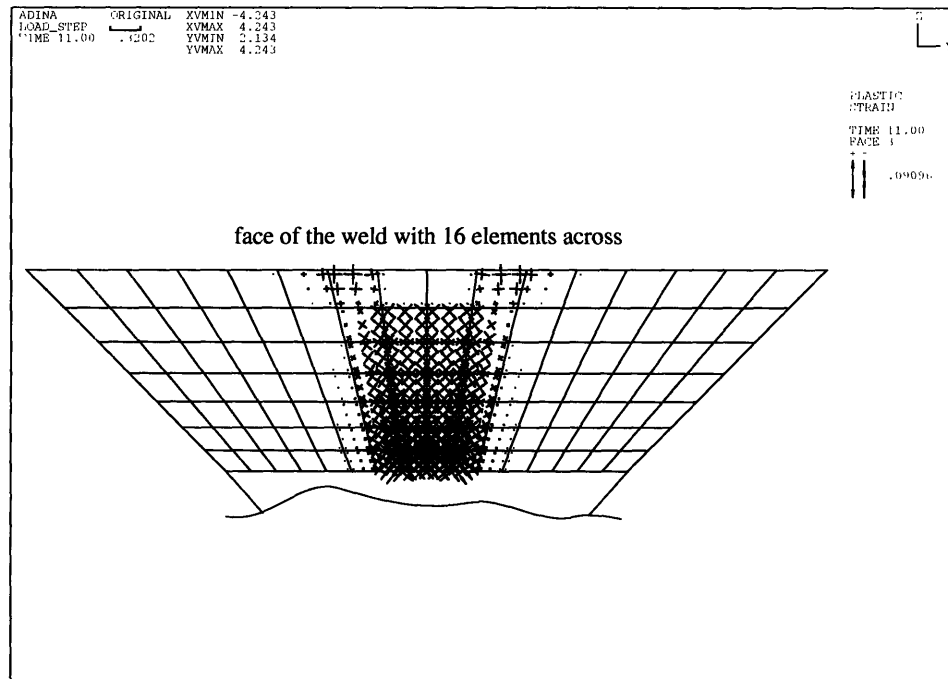
Figure 4.3 LUB single arc for predominant opening bending



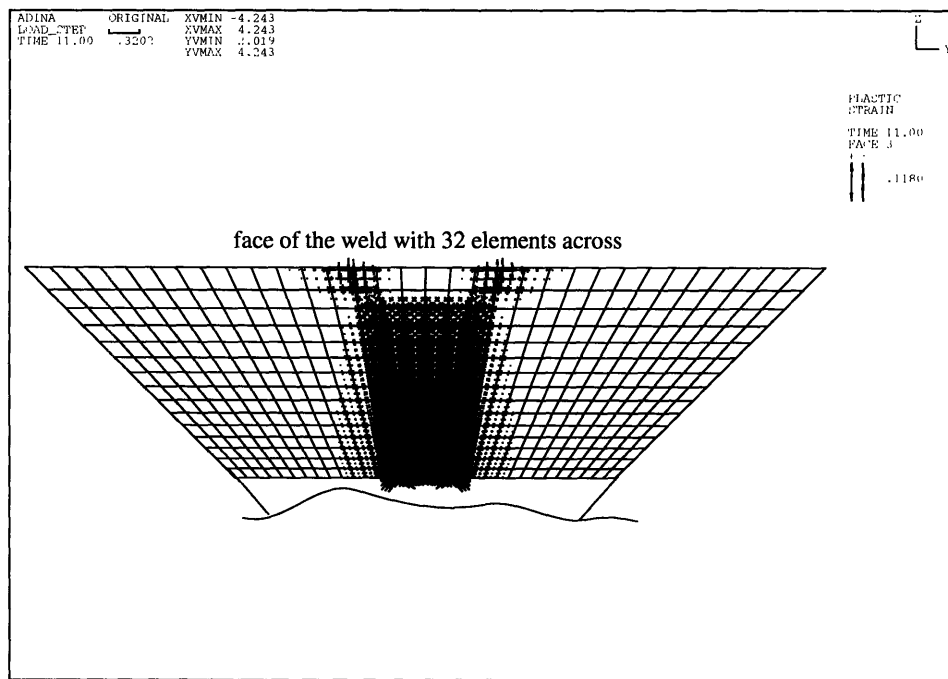
a. Analytical solution slip-line field



b. Coarse size mesh



c. Medium size mesh



d. Fine size mesh

Figure 4.4 Principal plastic strains for three different mesh sizing

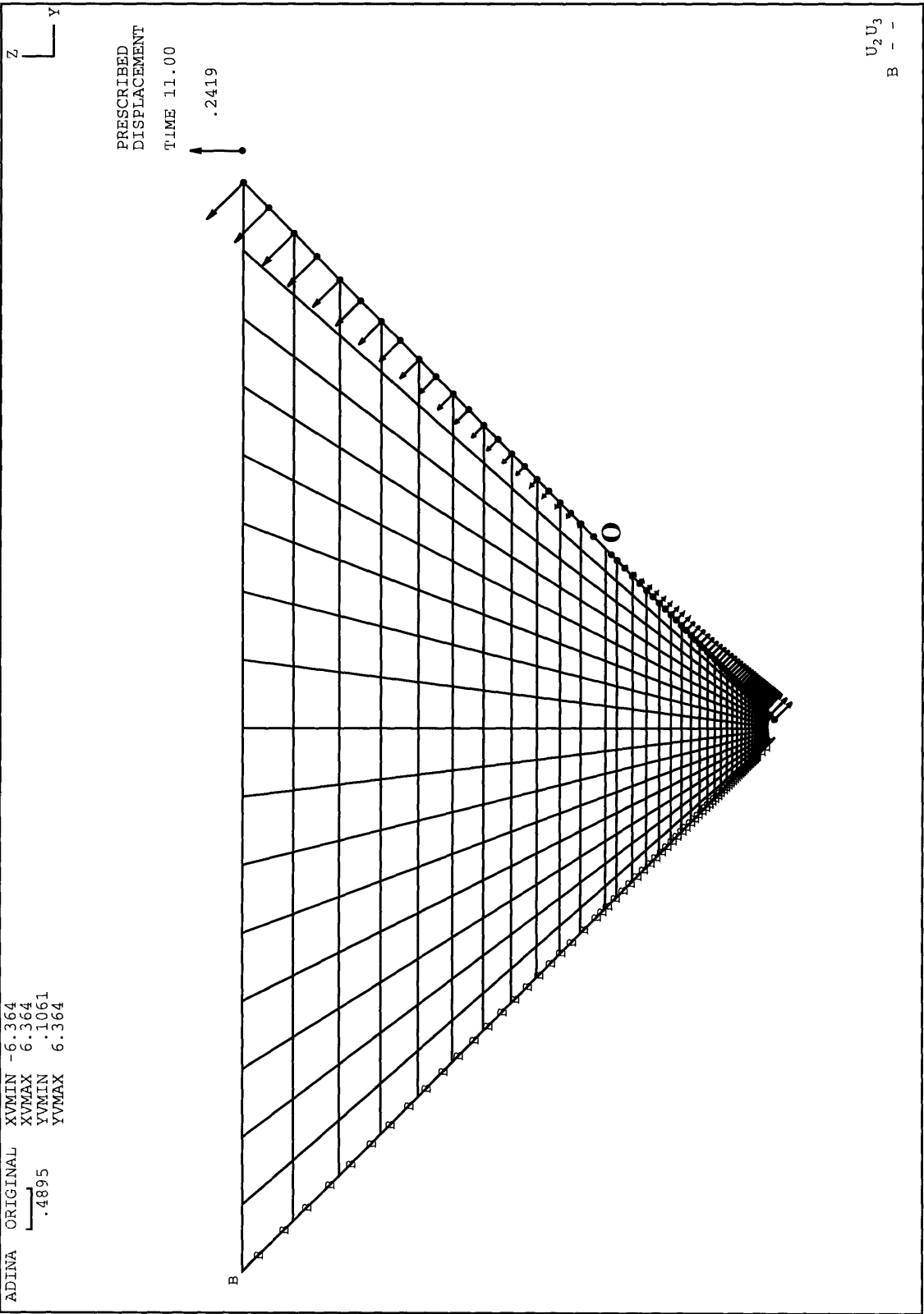


Figure 4.5 Finite element model for predominant opening bending

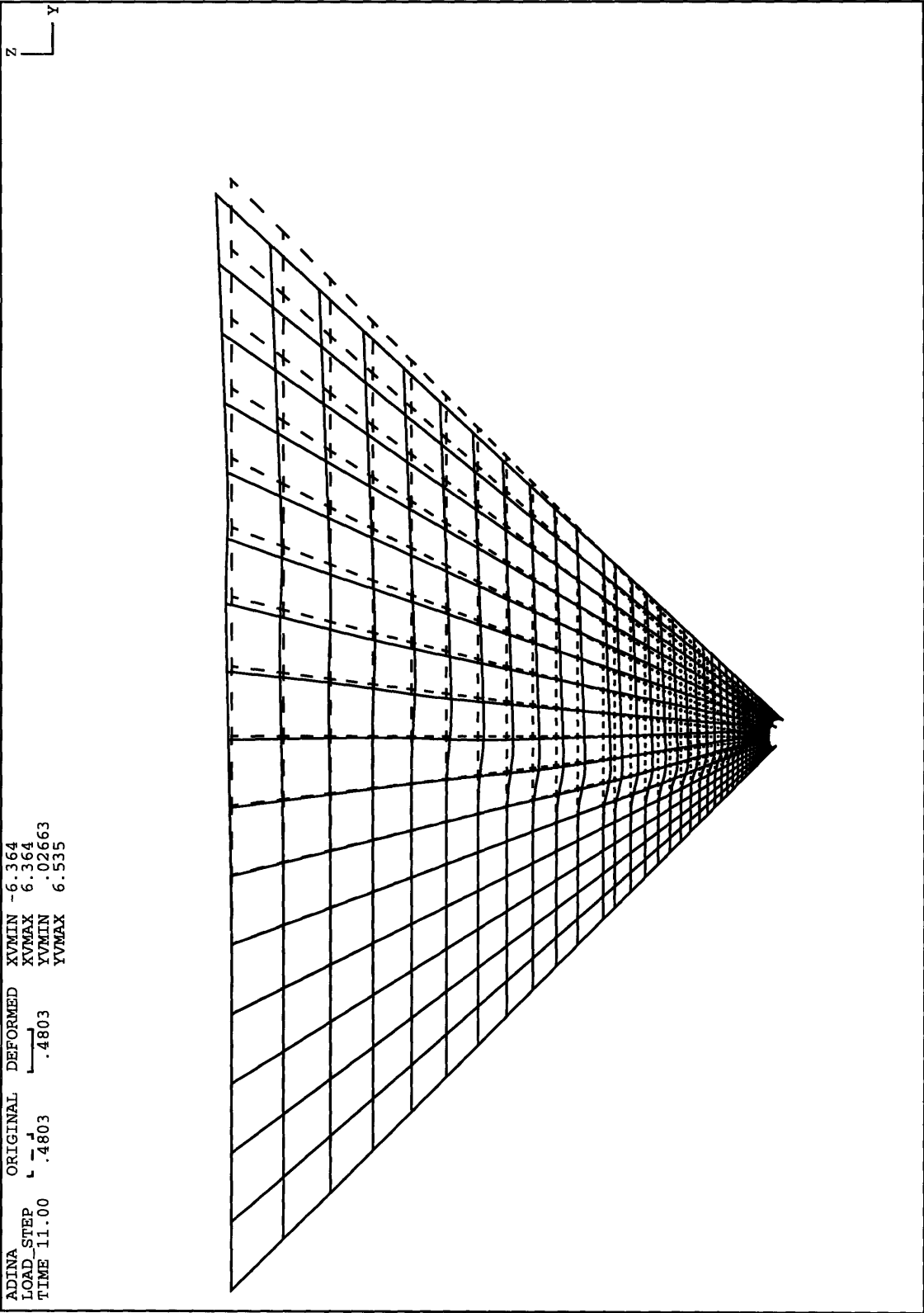


Figure 4.6 Deformed configuration of predominant opening bending case

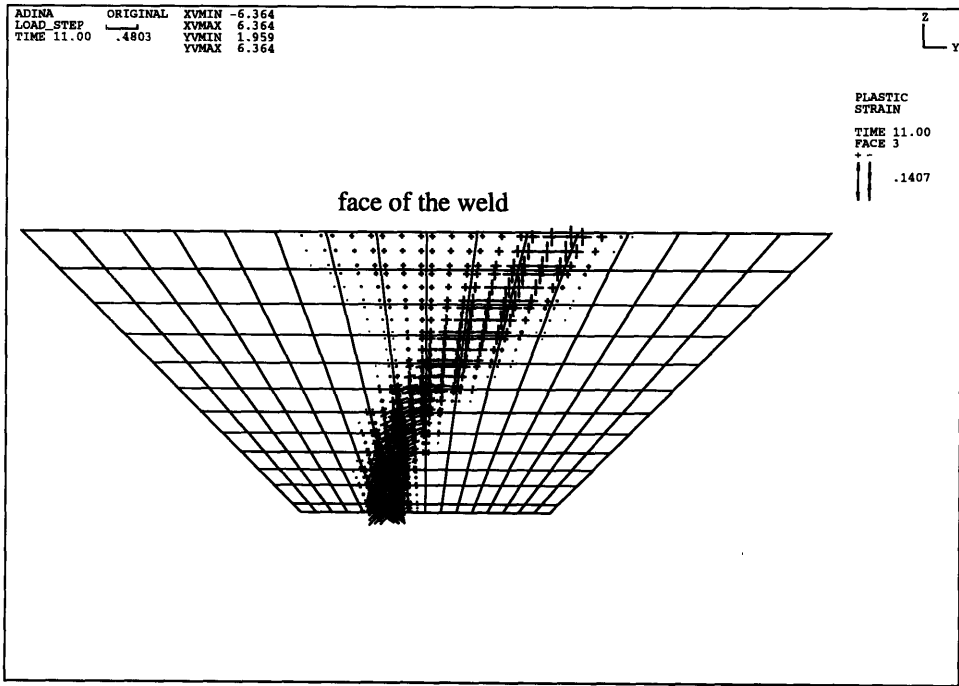
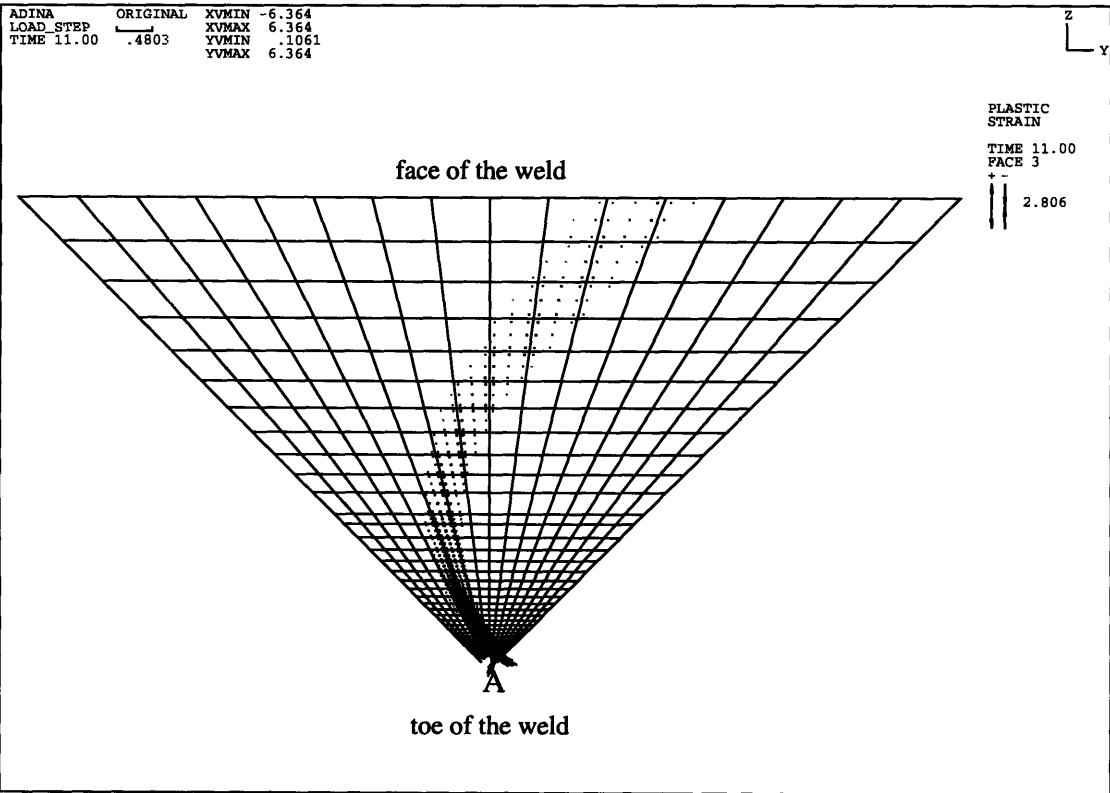


Figure 4.7 Principal plastic strain of predominant opening bending

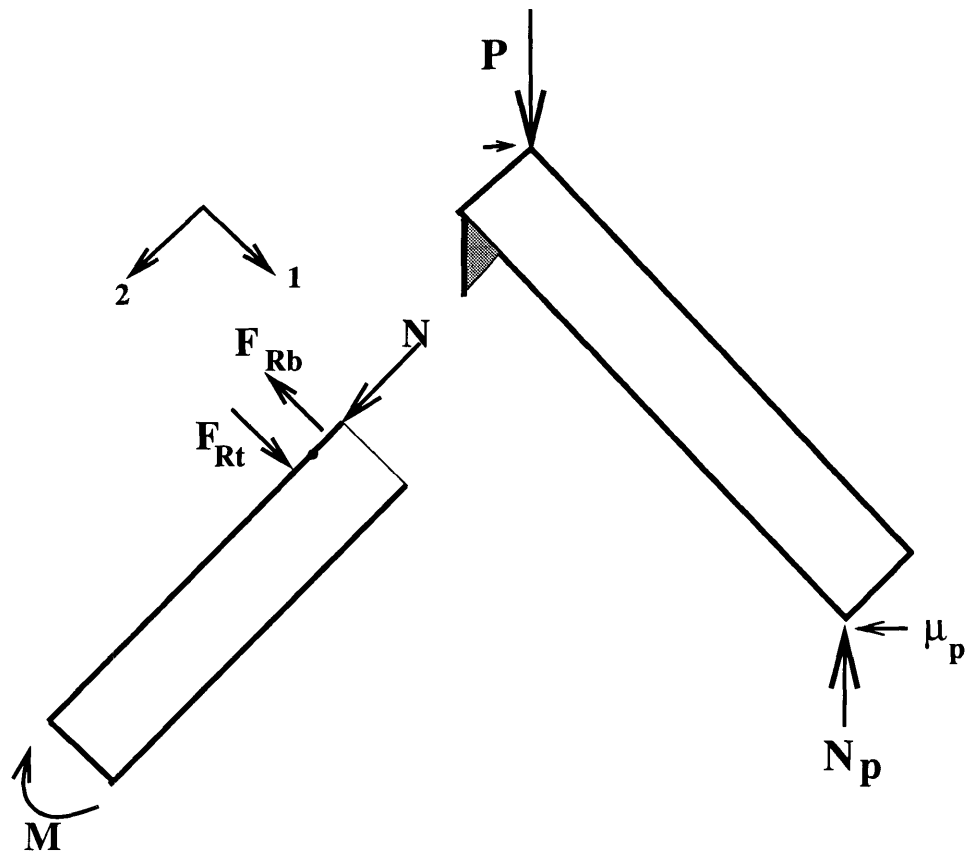


Figure 4.8 Equilibrium conditions

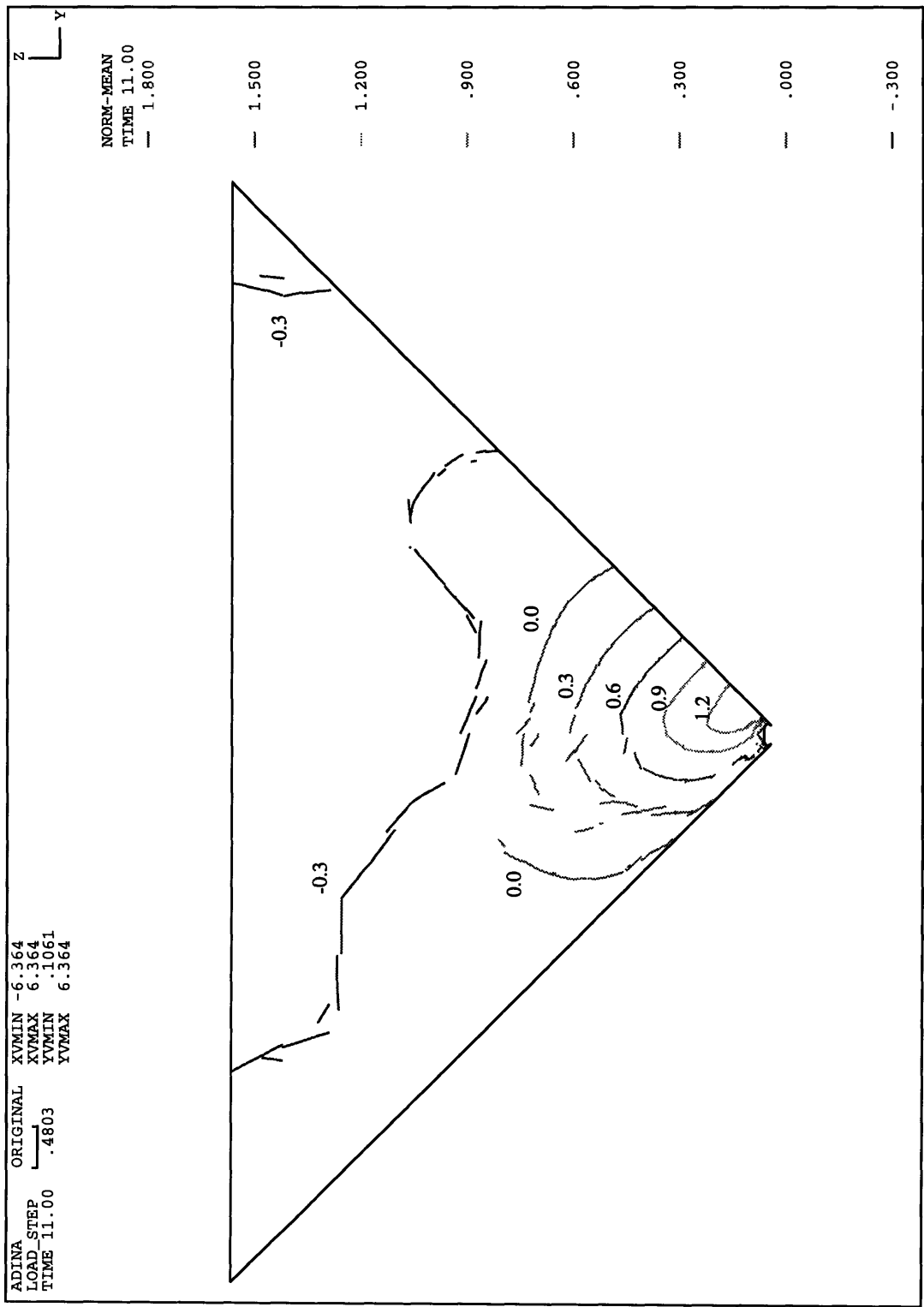
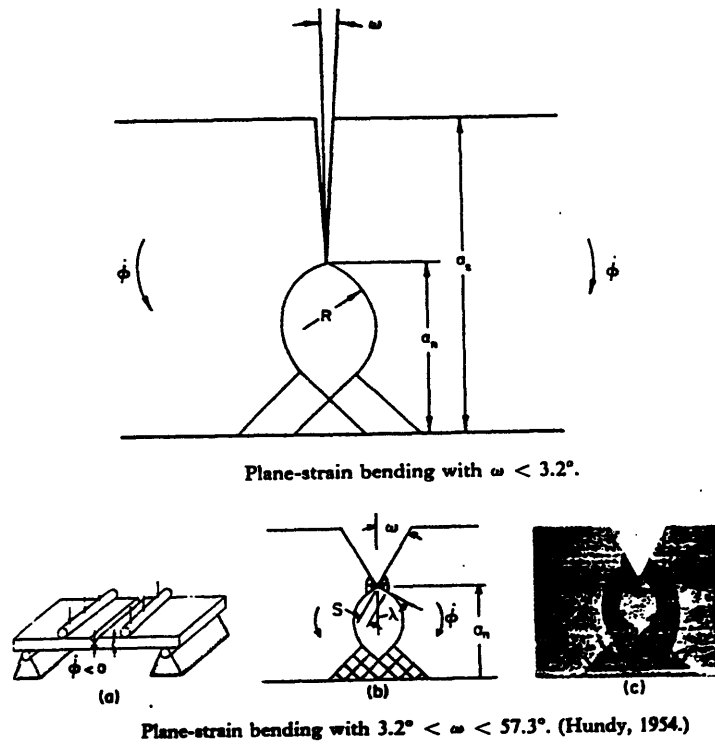


Figure 4.9 Mean normal stress across the weld



source: McClintock, 1971

Figure 4.10 Green and Hundy slip-line field for single edge notch

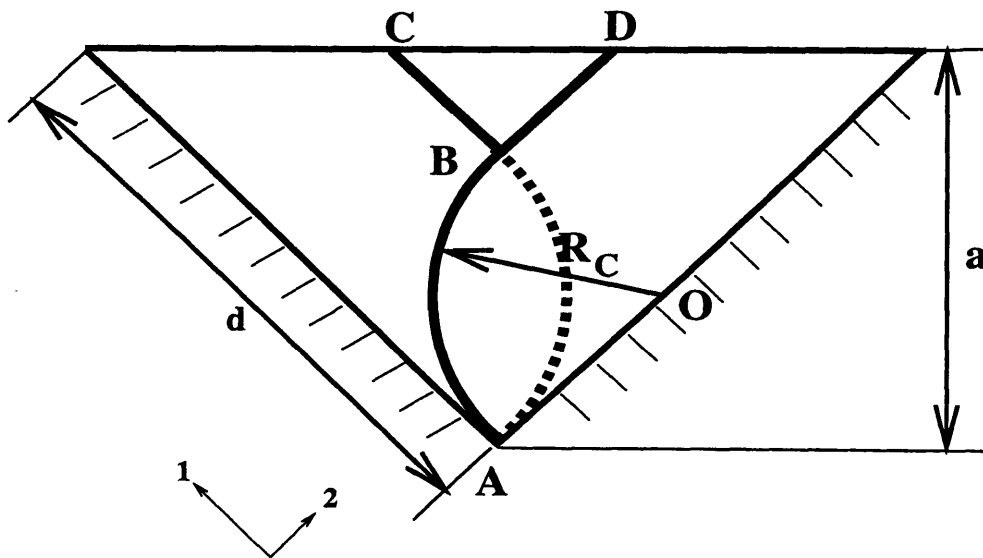


Figure 4.11 Proposed slip-line field for predominant opening bending

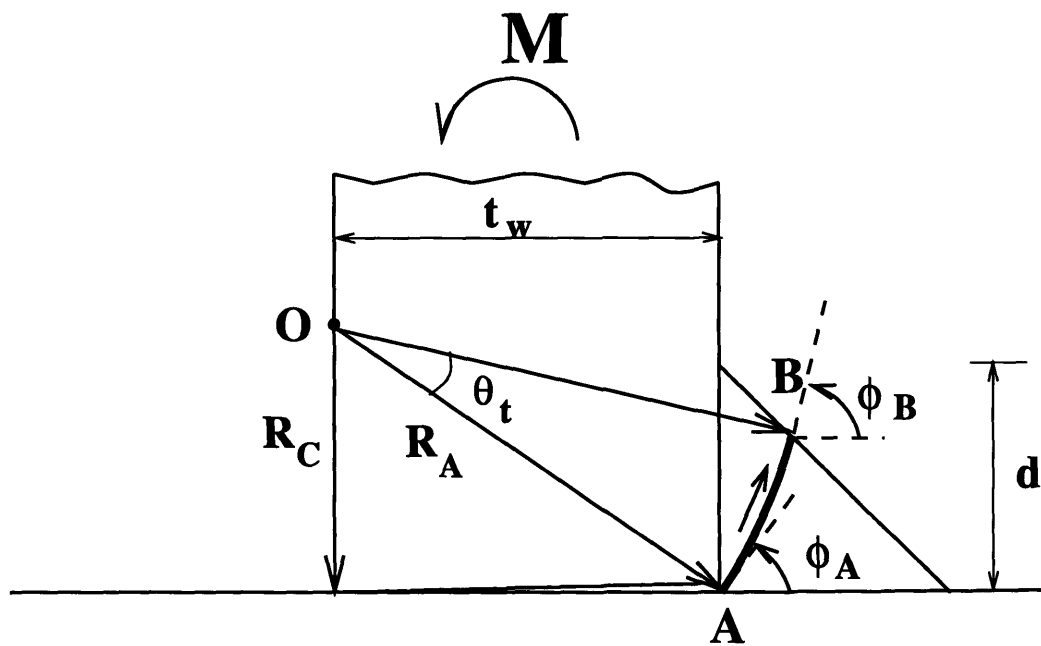


Figure 4.12 LUB single arc for predominant weld leg shear

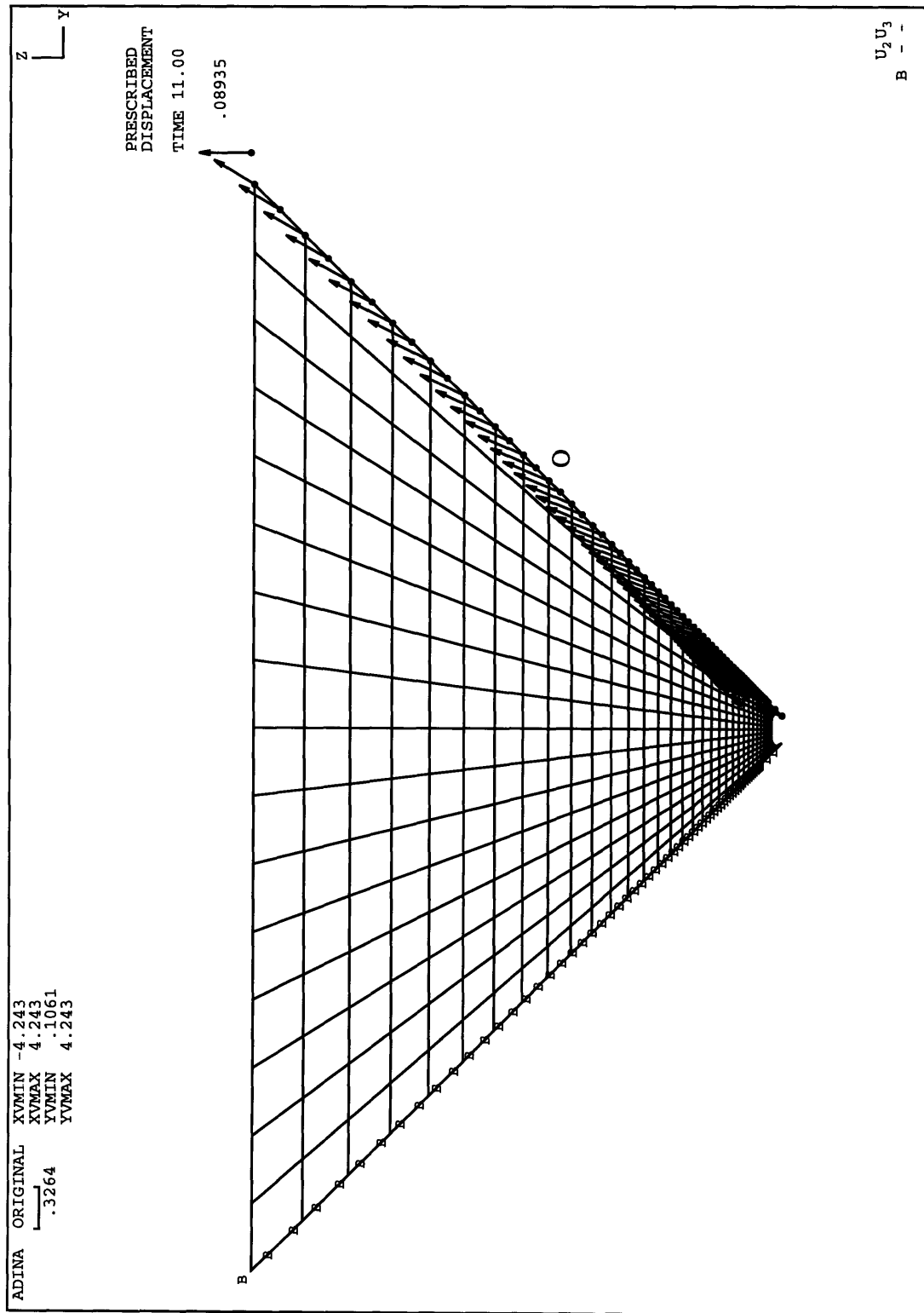


Figure 4.13 Finite element model of predominant weld leg shear

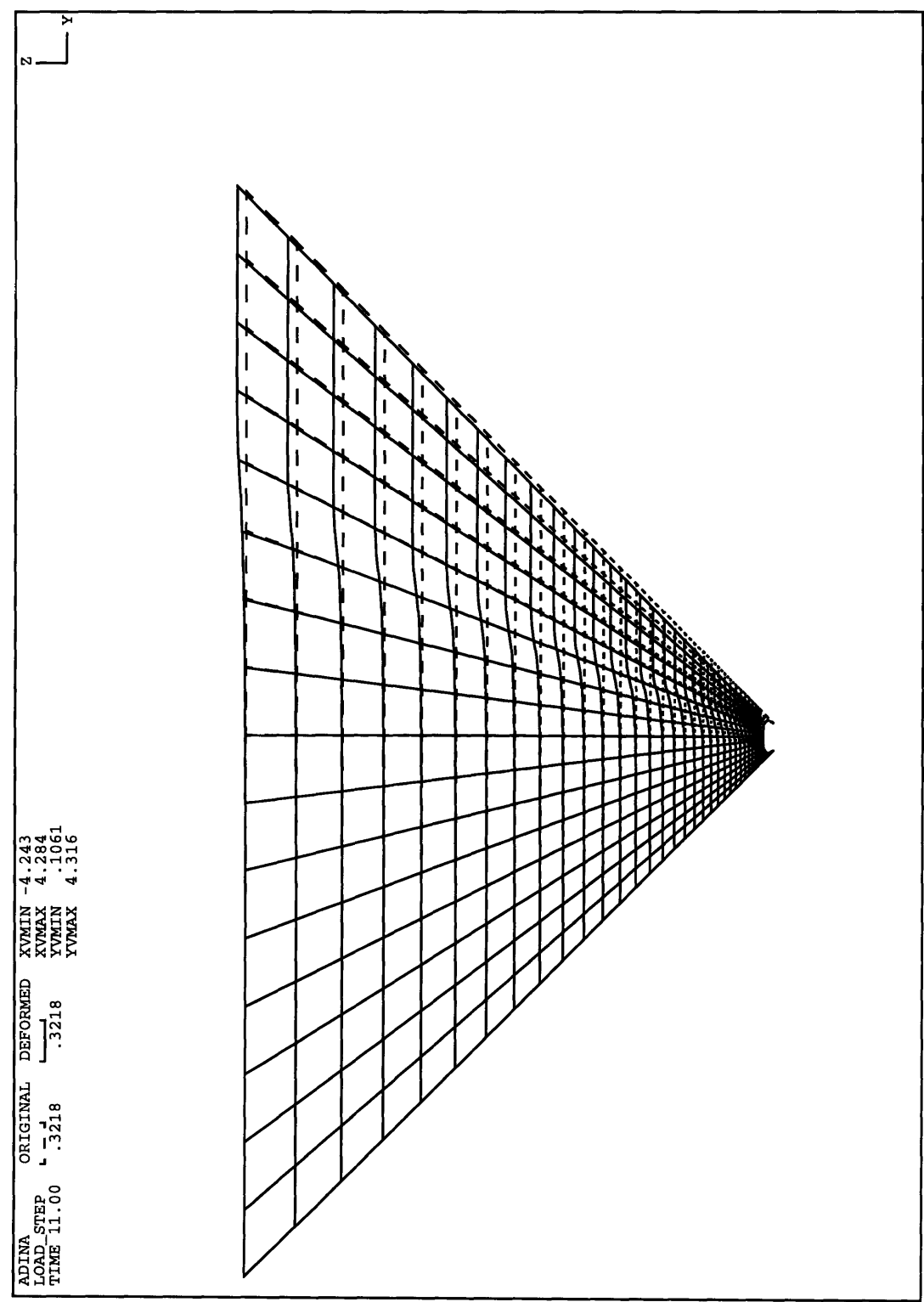


Figure 4.14 Deformed configuration of predominant weld leg shear

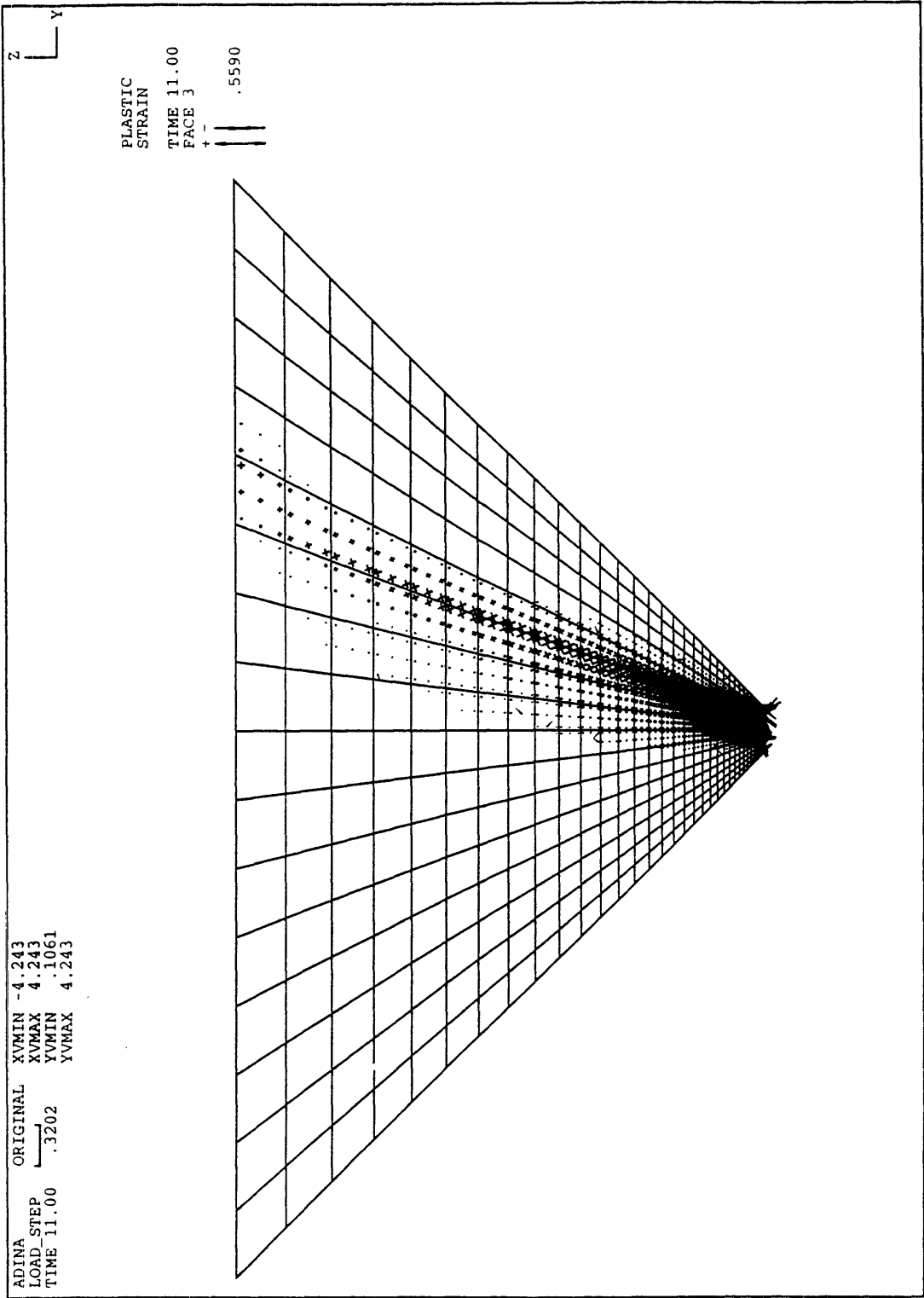
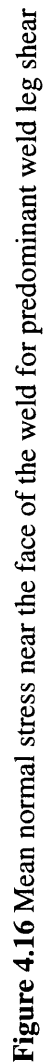


Figure 4.15 Principal plastic strain across the weld for predominant weld leg shear



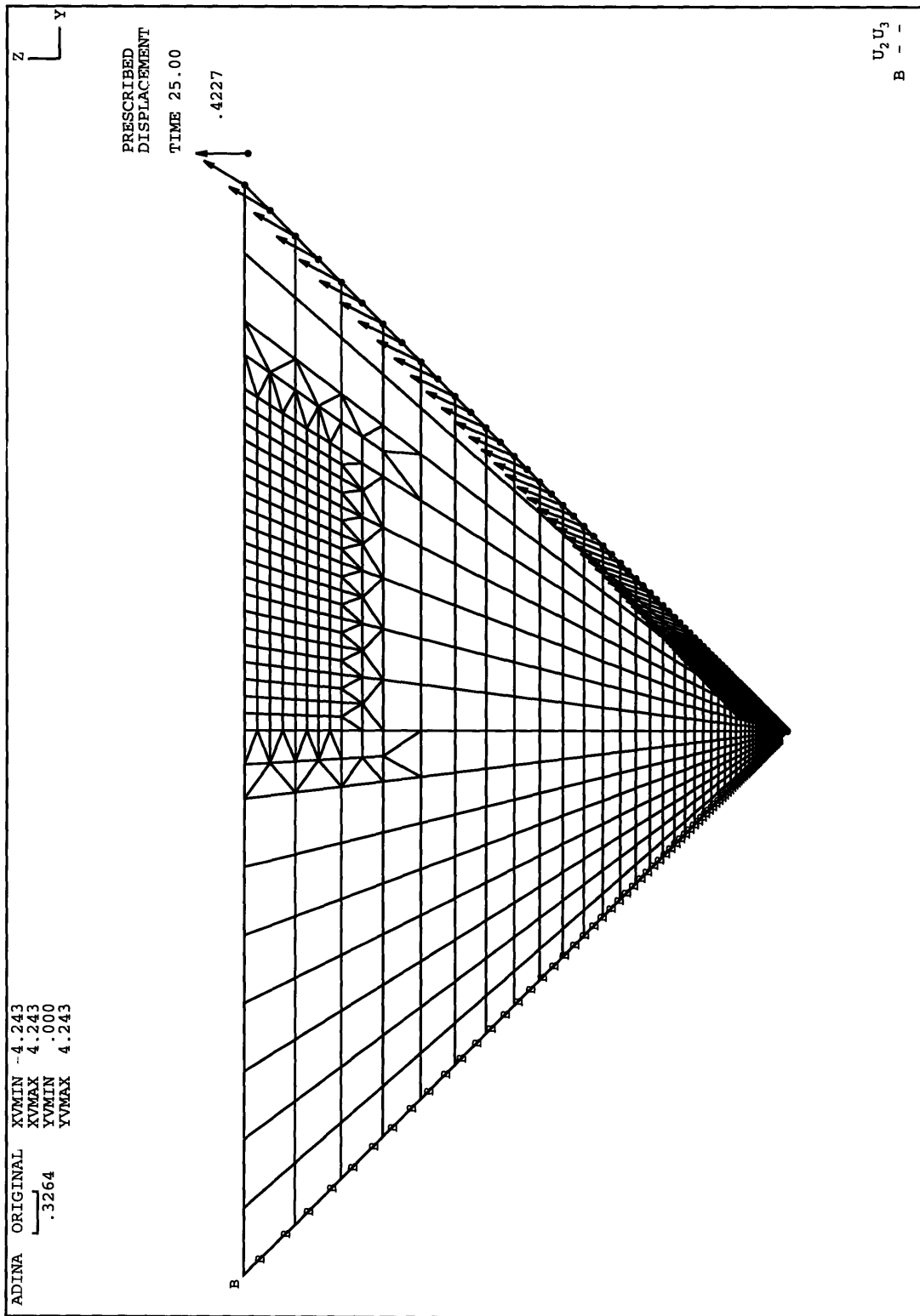


Figure 4.17 Refined mesh for predominant weld leg shear

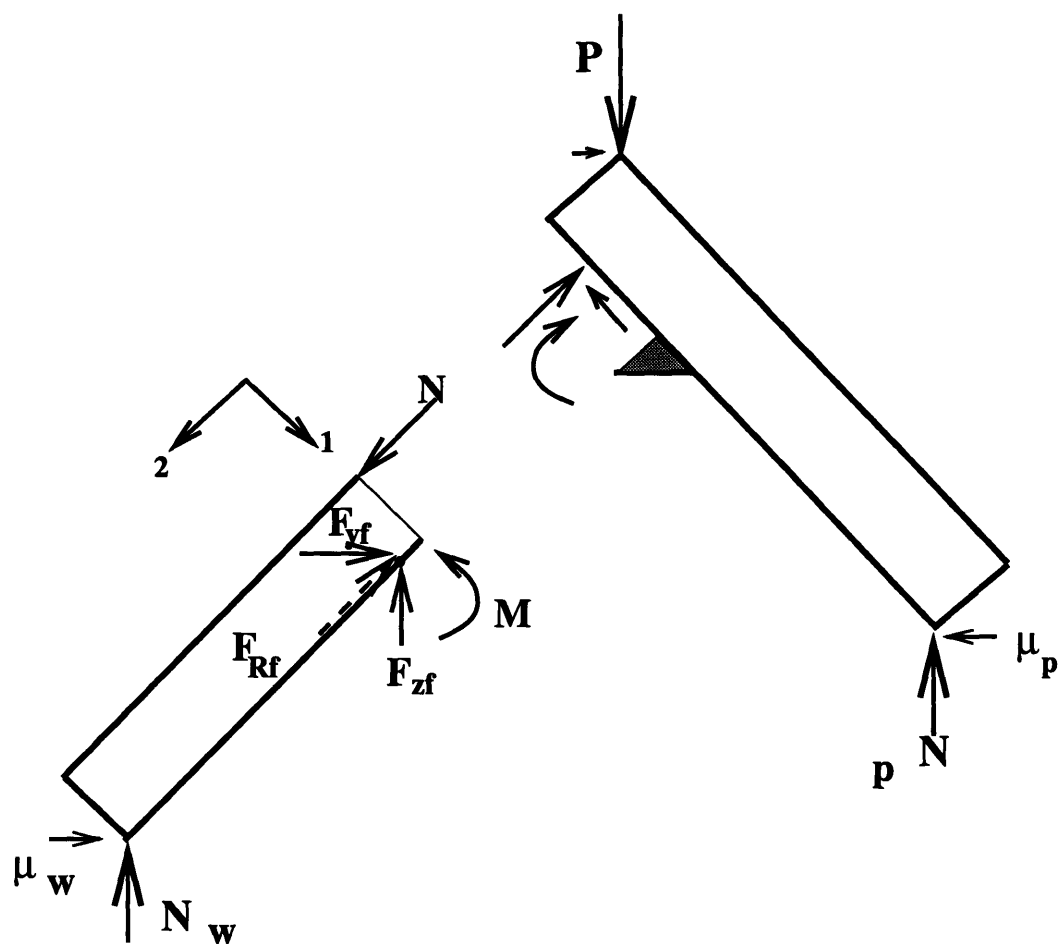


Figure 4.18 Equilibrium conditions for predominant weld leg shear

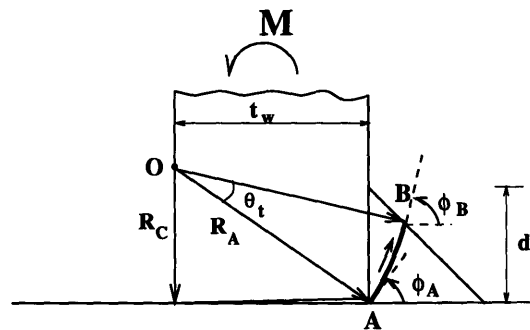
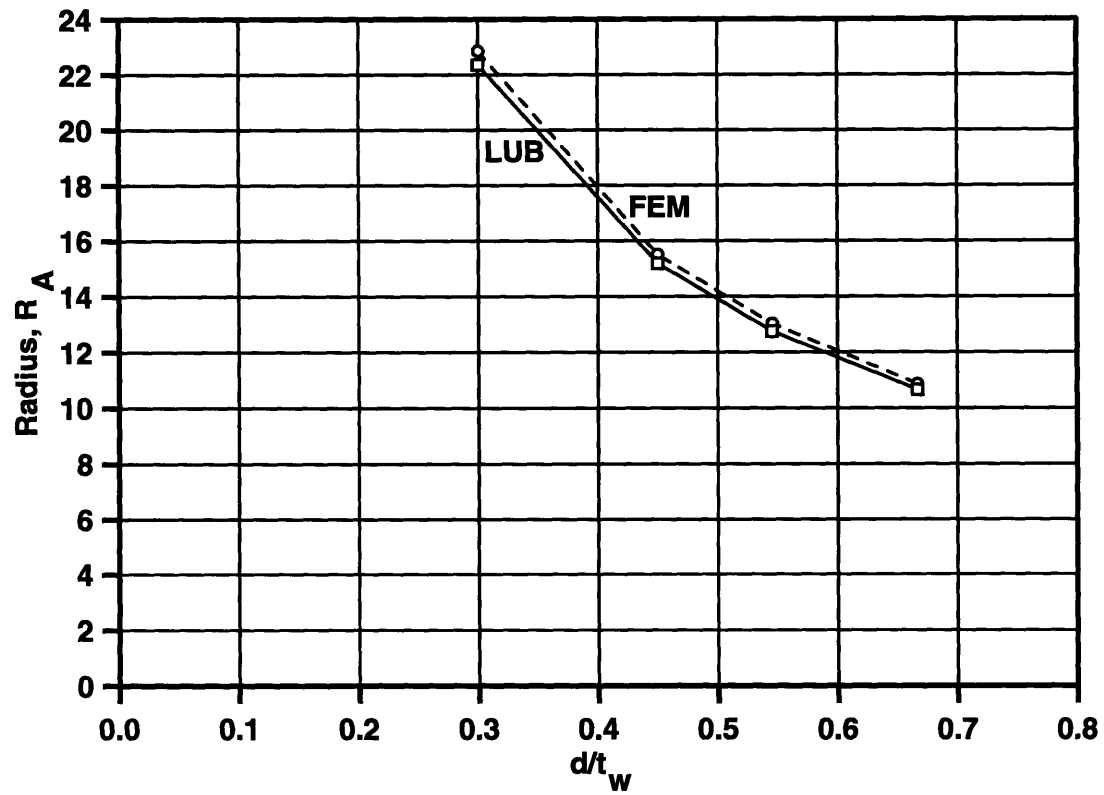


Figure 4.19 Comparison of LUB crc with FEM radius

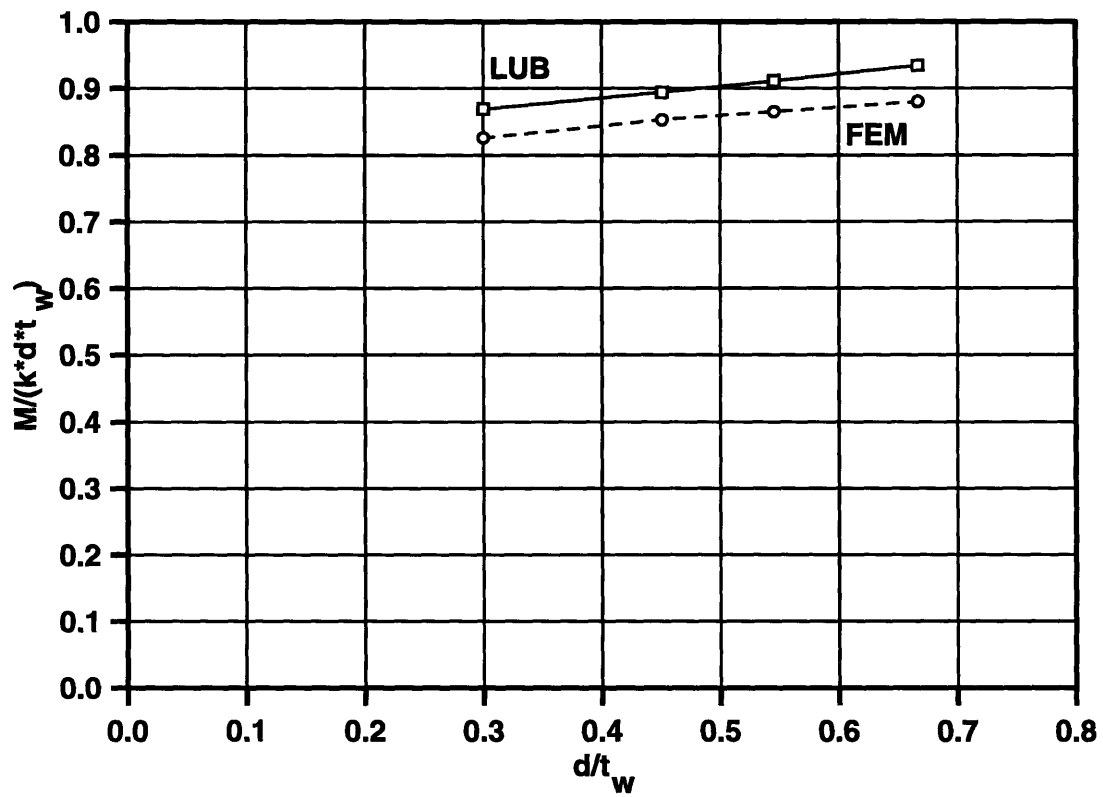


Figure 4.20 Comparison of LUB limit moment with FEM limit moment

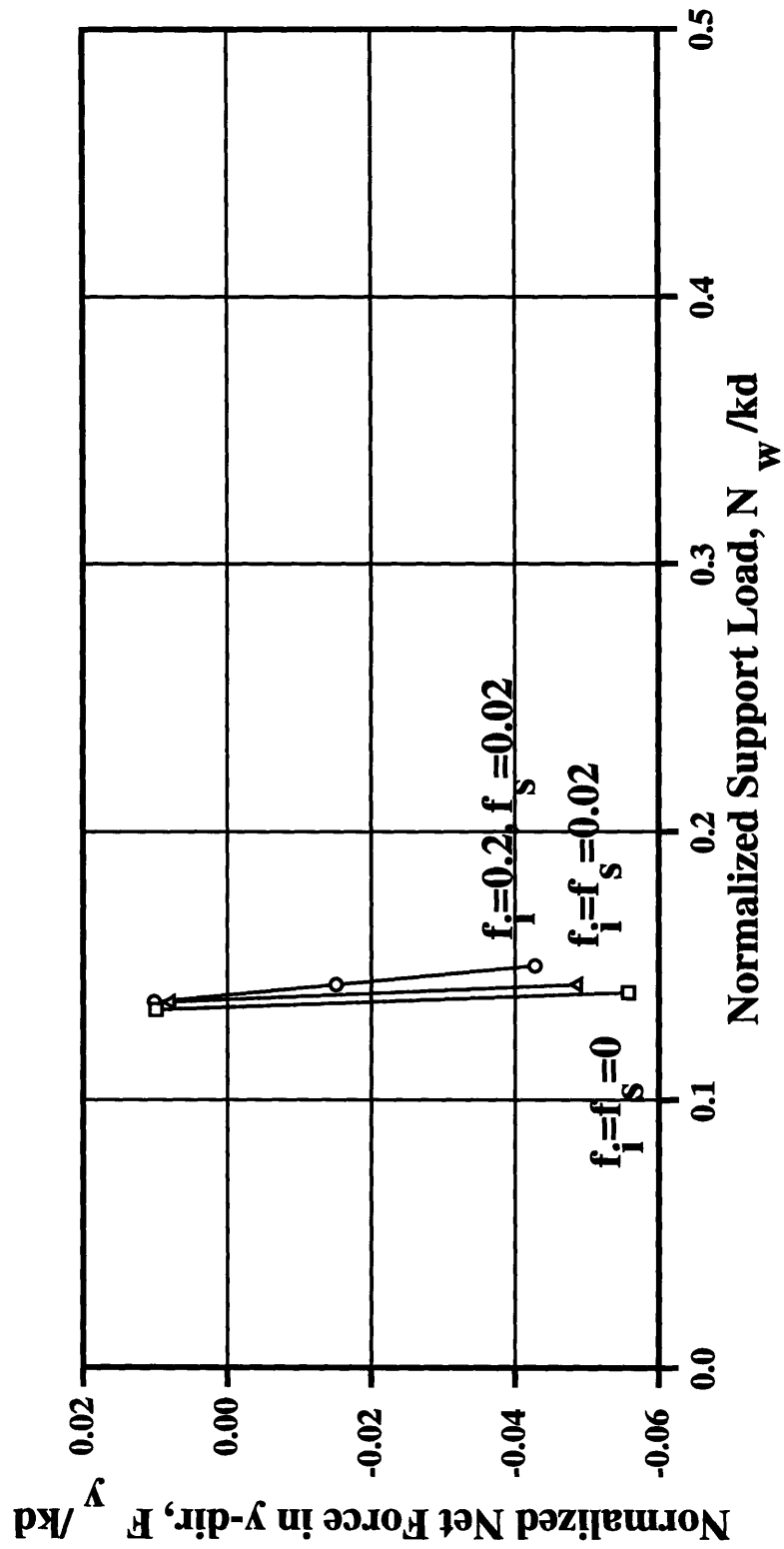


Figure 4.21 Effect of support and interface friction on support load

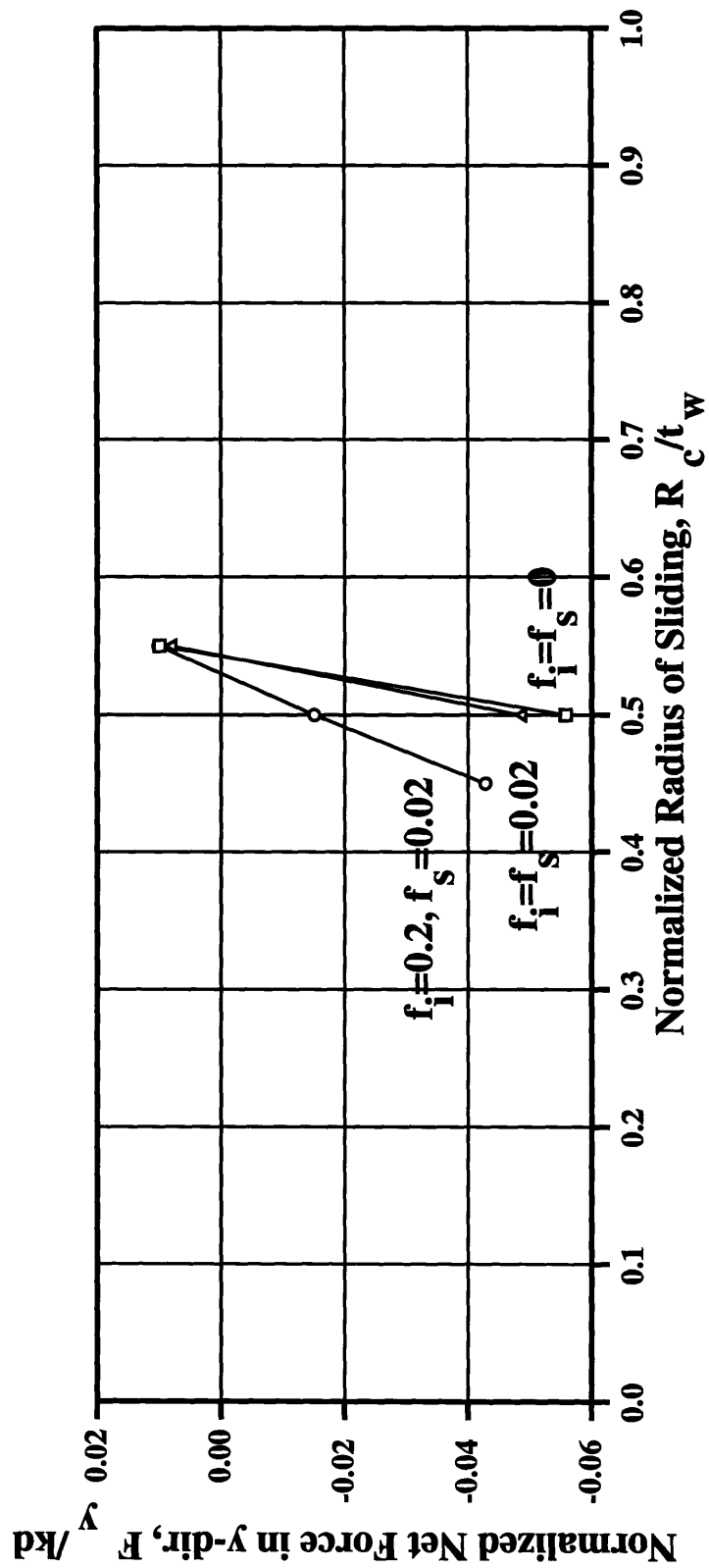


Figure 4.22 Effects of support and interface friction on radius of sliding

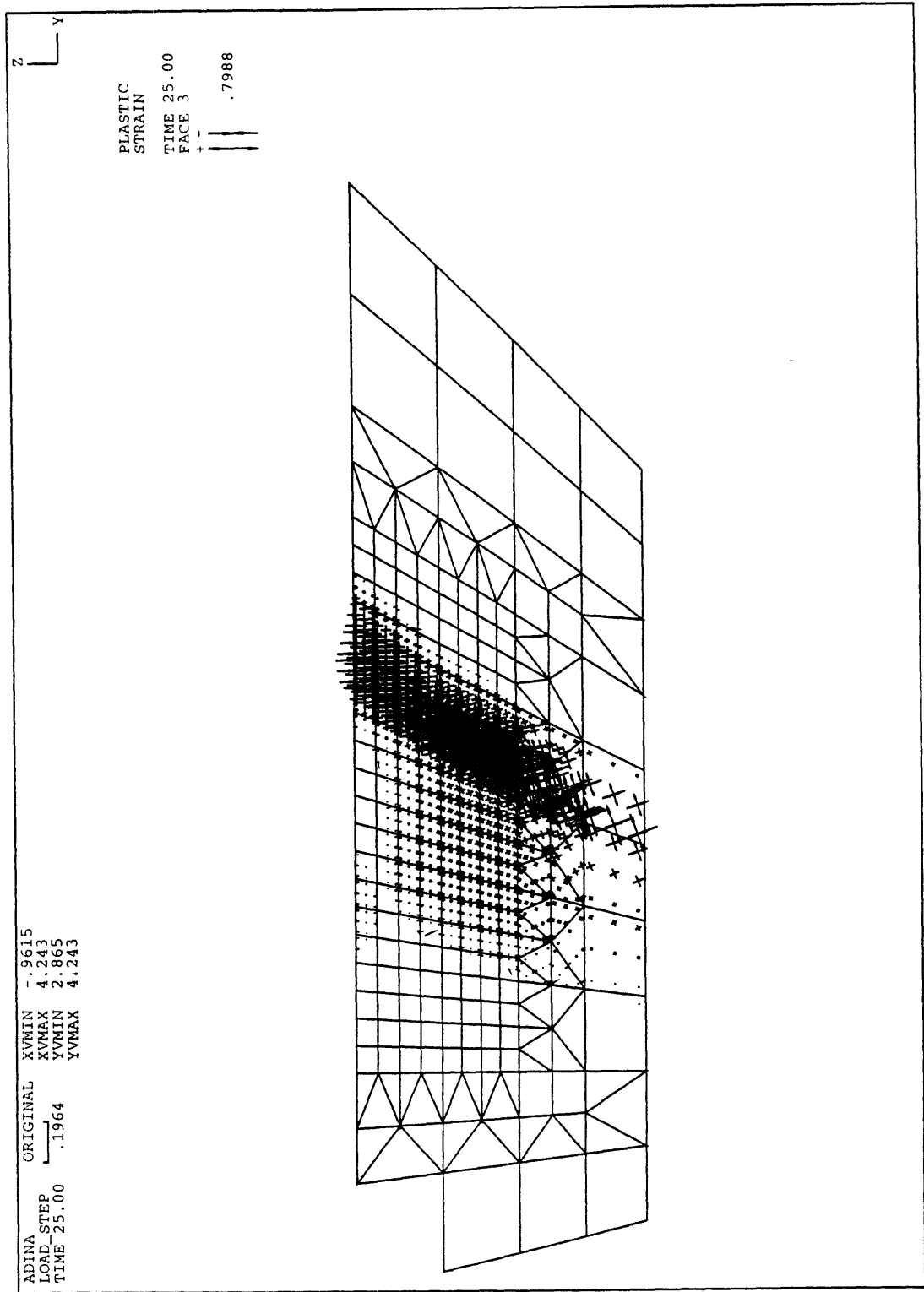


Figure 4.23 Plastic strain on the face of the refined mesh

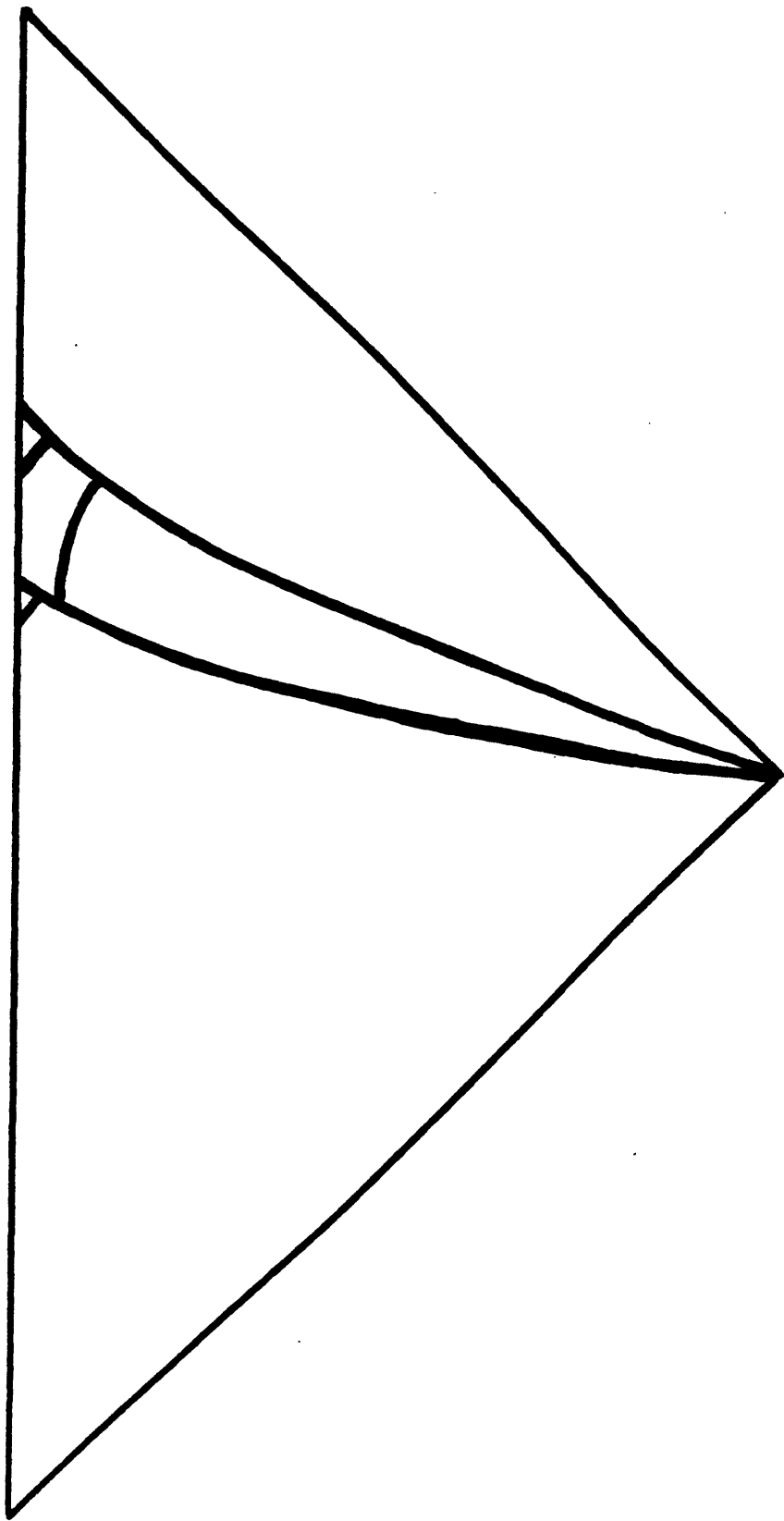


Figure 4.24 Proposed slip-line field

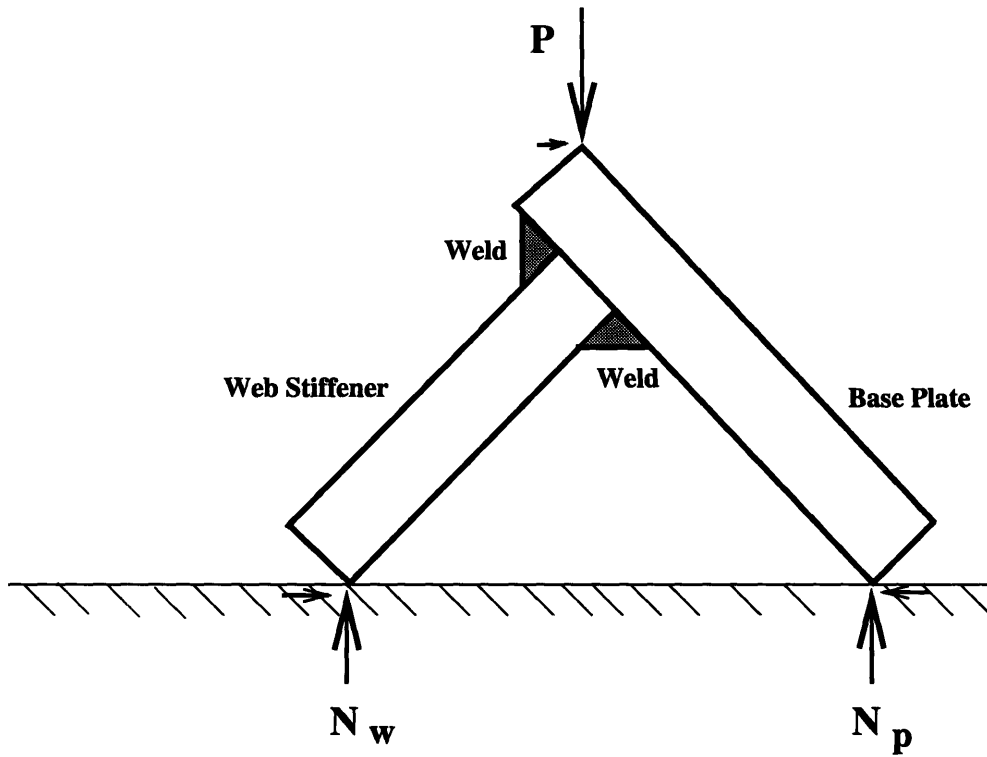


Figure 4.25 Web folding double fillet welds

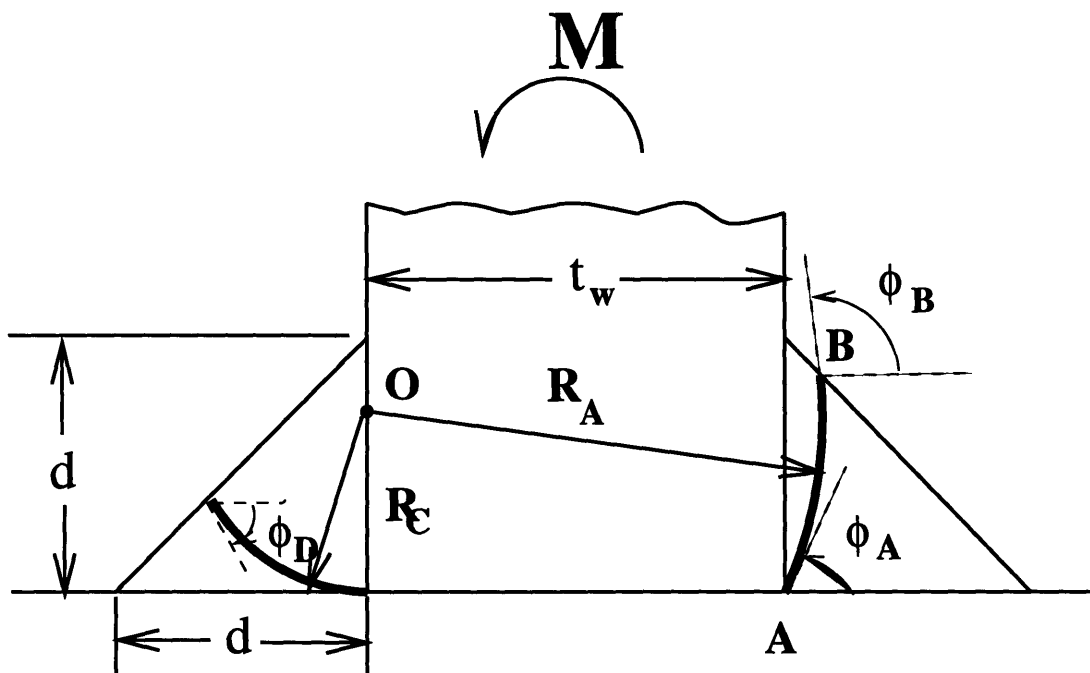


Figure 4.26 LUB arc for web folding double fillet welds

Chapter 4 References

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Appendix 4.A

Least Upper Bound (LUB) Limit Moment Calculations

This Appendix describes the calculations of the least upper bound (LUB) limit moment for both predominant opening bending mode and predominant leg shear of single fillet weld Lazy-L test. The LUB limit moment can be found by iterative method for a series of different radius of the sliding arc using Equation 4.3 and Equation 4.10. The solutions were done using MathCad program.

4.A.1 LUB Limit Moment Calculations for Predominant Opening Bending Single Fillet Lazy-L Test

Weld leg length	$d := 9$
Stiffener web thickness	$t_w := 20$
Ratio of leg length to thickness	$\frac{d}{t_w} = 0.45$
Assumption: $k_f = k_w$	
Guess values:	$x := 1$
	$y := 1$

Equations to get x and y positions where the sliding arc intersects with the face of the weld

Given	$x=y$
	$(x-d)^2 + (y-h)^2 = h^2$
	$x \geq 0 \quad y \geq 0$
	$F(h) := \text{Find}(x, y)$
	$h := 3.9, 3.91 \dots 4.0$
	$x(h) := F(h)_0 \quad y(h) := F(h)_1$

h	x(h)	y(h)
3.9	5.4	5.4
3.91	5.375	5.375
3.92	5.35	5.35
3.93	5.326	5.326
3.94	5.303	5.303
3.95	5.281	5.281
3.96	5.259	5.259
3.97	5.238	5.238
3.98	5.217	5.217
3.99	5.197	5.197
4	5.177	5.177

Length of the sliding arc chord $c(h) := \sqrt{(d - x(h))^2 + y(h)^2}$

Angle of the sliding arc $\theta c(h) := 2 \cdot \arcsin\left(\frac{c(h)}{2 \cdot \sqrt{h^2}}\right)$

angle in radians angle in degrees

h	$\theta c(h)$	$\theta c(h) \cdot \left(\frac{180}{\pi}\right)$
3.9	1.966	112.62
3.91	1.955	112
3.92	1.944	111.399
3.93	1.934	110.814
3.94	1.924	110.246
3.95	1.914	109.692
3.96	1.905	109.152
3.97	1.896	108.625
3.98	1.887	108.11
3.99	1.878	107.607
4	1.869	107.114

Normalized Bending Moments Calculations

Radius of sliding arc $R_c(h) := \sqrt{h^2}$

Bending moments normalized by Equation 4.4

$R_c(h)$	$\frac{R_c(h) \cdot \theta_c(h) \cdot R_c(h)}{\left(\frac{d^2}{4}\right)}$
3.9	1.476375
3.91	1.475787
3.92	1.475381
3.93	1.475139
3.94	1.475049
3.95	1.4751
3.96	1.47528
3.97	1.475582
3.98	1.475997
3.99	1.476517
4	1.477135

Least upper bound (LUB) limit moment from the above calculations is 1.4751

The LUB limit moment value is the same for any weld leg length.

4.A.2 LUB Limit Moment Calculations for Predominant Leg Shear Single Fillet Weld Lazy-L Test

Weld leg length $d := 6$

Stiffener web thickness $t_w := 20$

Ratio of leg length to thickness $\frac{d}{t_w} = 0.3$

Assumption: $k_f = k_w$

Guess values: $x := 1$

$y := 1$

Equations to get x and y positions where the sliding arc intersects with the face of the weld

Given $x=y$

$$\left[x - (d + t_w) \right]^2 + (y - h)^2 = h^2 + t_w^2$$

$$x \geq 0 \quad y \geq 0$$

$$F(h) := \text{Find}(x, y)$$

$$h := 9.5, 9.6.. 11$$

$$x(h) := F(h)_0$$

$$y(h) := F(h)_1$$

Length of the sliding arc chord $c(h) := \sqrt{(d - x(h))^2 + y(h)^2}$

Angle of the sliding arc $\theta_t(h) := 2 \cdot \text{asin} \left(\frac{c(h)}{2 \cdot \sqrt{h^2 + t_w^2}} \right)$

h	x(h)	y(h)	angle in	angle in
			radians	degress
			$\theta t(h)$	$\theta t(h) \cdot \left(\frac{180}{\pi} \right)$
9.5	4.444	4.444	0.213	
9.6	4.427	4.427	0.212	12.207
9.7	4.41	4.41	0.211	12.156
9.8	4.394	4.394	0.21	12.107
9.9	4.378	4.378	0.21	12.058
10	4.362	4.362	0.209	12.009
10.1	4.346	4.346	0.208	11.96
10.2	4.33	4.33	0.207	11.913
10.3	4.314	4.314	0.206	11.865
10.4	4.299	4.299	0.205	11.818
10.5	4.284	4.284	0.205	11.772
10.6	4.268	4.268	0.204	11.725
10.7	4.253	4.253	0.203	11.68
10.8	4.238	4.238	0.202	11.634
10.9	4.223	4.223	0.201	11.589
11	4.208	4.208	0.201	11.545
				11.501

Normalized Bending Moments Calculations

Radius of sliding $R_A(h) := \sqrt{h^2 + t_w^2}$

Bending moments normalized by Equation 4.11

h	$R_A(h)$	$\frac{R_A(h) \cdot \theta t(h) \cdot R_A(h)}{(t_w \cdot d)}$
9.5	22.142	0.8703769
9.6	22.185	0.87017799
9.7	22.228	0.87002022
9.8	22.272	0.86990302
9.9	22.316	0.86982584
10	22.361	0.86978812
10.1	22.406	0.86978934
10.2	22.451	0.86982898
10.3	22.496	0.86990652
10.4	22.542	0.87002145
10.5	22.589	0.8701733
10.6	22.635	0.87036158
10.7	22.682	0.8705858
10.8	22.73	0.87084552
10.9	22.777	0.87114028
11	22.825	0.87146962

Least upper bound (LUB) limit moment from the above calculations is 0.86978812.

LUB limit moment value is different for different ratios of weld leg length to web stiffener thickness.

Appendix 4.B

Mesh Size and Geometry

The mesh size and shape of the finite element models are critical in obtaining good accuracy. To ensure good accuracy in analyzing the single fillet weld Lazy-L test, the mesh is designed to be as square as possible. The mesh is finer at the weld's toe compared to the one near the surface of the weld.

To get 'square' element, the following calculations are used:

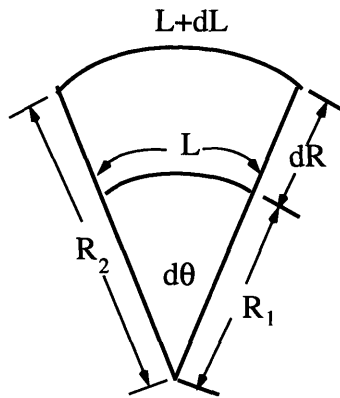


Figure 4.B.1 Square element

For a square element,

$$dR = L \quad (4.B.1)$$

and we know that

$$L = R_1 \times \sin \theta \quad (4.B.2)$$

for small angle, $\sin \theta = \theta$, hence

$$dR = R_1 \times d\theta \quad (4.B.3)$$

rearrange and integrate both sides of the above equation:

$$\int_{R_n}^{R_{n+1}} \frac{dR}{R} = \int_{\theta_n}^{\theta_{n+1}} d\theta \quad (4.B.4)$$

therefore,

$$\Delta\theta = \ln\left(\frac{R_{n+1}}{R_n}\right) \quad (4.B.5)$$

and

$$R_{n+1} = R_n + dR \quad (4.B.6)$$

In modeling the single fillet weld, the number of elements across the surface of the weld is fixed, i.e., $\delta\theta$ is fixed. With a given $\delta\theta$ dR can be calculated and coordinates for R along the fillet weld leg can be obtained (see Figure 4.A.2).

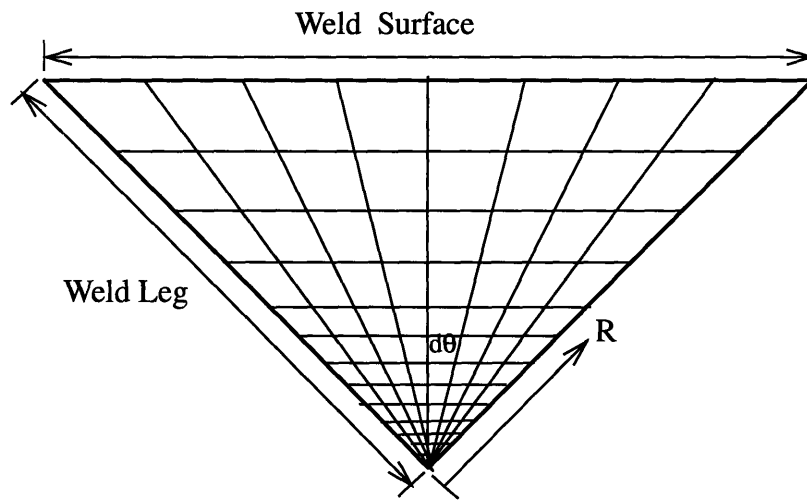


Figure 4.B.2 Finite element model with square elements

Appendix 4.C

Prescribed Displacements for Single Fillet Weld Finite Element Model Calculations

This Appendix discusses the calculations of the displacements prescribed along the weld leg of a single fillet weld for both predominant opening bending and predominant leg shear cases.

4.C.1 Prescribed Displacements for Predominant Opening Bending Mode

Displacements were applied at the weld leg close to the stiffener web to simulate bending caused by the applied bending moment on the stiffener web of the Lazy-L test configuration. The displacements were applied at the nodal points of the finite element model. To apply the displacements, the center of rotation needs to be found. The center of rotation for the weld under predominant opening bending mode is located along the leg of the weld, point O of Figure 4.C.1. This point can be found from the least upper bound limit moment calculations (see Appendix 4.A.1). Once the center of rotation was found, the displacements could be applied. The displacements are linear and they are functions of the radius of rotation R_C , the distance between the center of rotation to the nodal point r , and the maximum displacement at the toe of the weld, u_c . For each nodal point, the magnitude of the displacement is

$$u = \frac{u_c}{R_C} r \quad (4.C.1)$$

In the finite element model, the displacement consists of displacement in the y- and z-direction. This displacement can be found by assigning displacement in the z-direction,

u_z , fixed, for example u_z is always 1. The displacement in the y direction can then be found by using

$$u_y = \frac{u_z}{\tan(45^\circ)} \quad (4.C.2)$$

4.C.2 Prescribed Displacements for Predominant Leg Shear of Single Fillet Weld

Similar to the weld under predominant opening bending, the prescribed displacements for weld under predominant leg shear were also applied to the weld leg near the stiffener web. The difference is that the center of the rotation for this case was not along the weld leg but along the web stiffener, point O in Figure 4.C.2. The center of rotation can be found from the least upper bound limit moment calculations for the first approximation. Once the center of rotation was found, the displacements can be prescribed. The direction of the displacements are perpendicular to the radius from the center of rotation (see Figure 4.C.1). The magnitude of the displacements can be calculated by first calculating the angle of the nodal point from the horizontal, θ , which is a function of the height of the nodal point, h_1 , to the center of rotation and the thickness of the web, t_w

$$\theta = \tan^{-1}\left(\frac{h_1}{t_w}\right) \quad (4.C.3)$$

For the applied displacement, the angle θ is also

$$\theta = \tan^{-1}\left(\frac{z}{y}\right) \quad (4.C.4)$$

where z and y are the magnitude of the prescribed displacement. Choose z as always 1 and calculate y

$$y = z \sin \theta \quad (4.C.5)$$

The displacement is maximum at the toe of the weld. The magnitude of the displacement is smaller near the face of the weld due to the angle, θ , decreases.

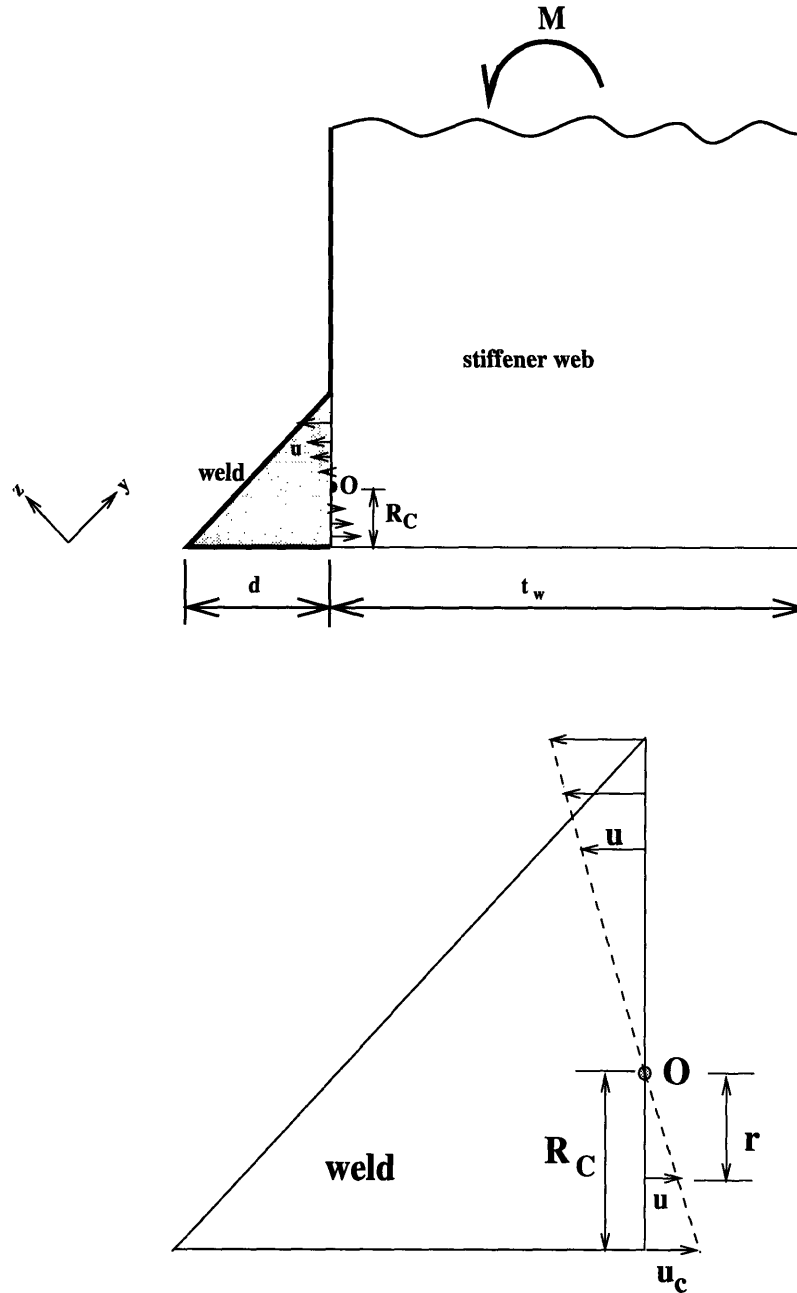


Figure 4.C.1 Prescribed displacements for predominant opening bending mode

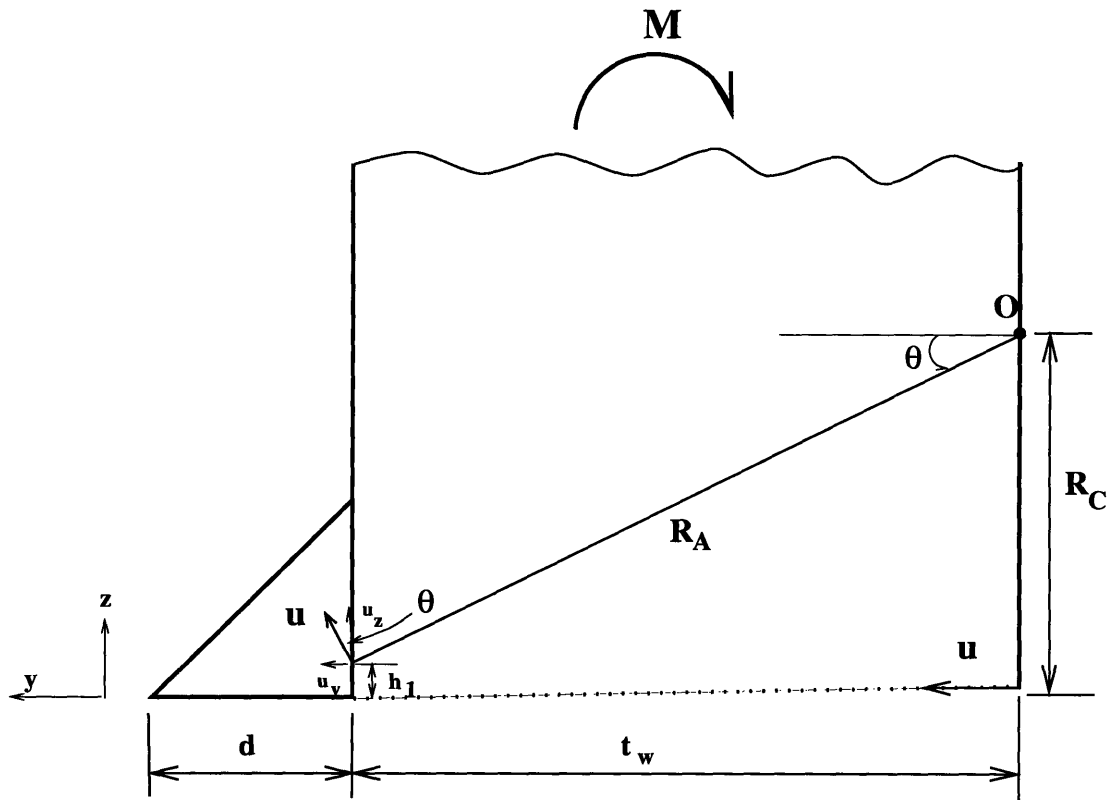


Figure 4.C.2 Prescribed displacements for predominant weld leg shear

Appendix 4.D

Modified Green and Hundy Slip-Line Field for Predominantly Opening Bending Fillet Welds

This appendix explains the proposed slip-line field solution for single fillet welds under predominant opening bending. The proposed slip-line is a modified Green and Hundy slip-line field for single edge notch V-groove specimen. Consider a triangular weld and assume that the crack is at the toe of the weld (point A of Figure 4.D.1). The proposed slip-line consists of a circular arc with a radius of R_C from point A to point B, with a fan of 45° near the face of the weld (lines BC and BD).

The radius of the slip-line field can be found by equilibrating the structure in the 1-direction of the 1-2 coordinate system.

$$\sum F_1 = 0 = OA(\sigma_{OA}) - k(OC) \quad (4.D.1)$$

From slip-line field solutions, the magnitude of the stress near the face of the weld equals the compressive shear strength, $-k$. Hence, the magnitude of the stress along the leg of the weld is

$$(\sigma_{OA} - k) = 2k(\phi_{OA} - \phi_D) \quad (4.D.2)$$

Plugging ϕ_{OA} and ϕ_D values, which is $3\pi/4$ and $\pi/4$ respectively, into Equation 4.D.2 the magnitude of σ_{OA} becomes $k(\pi)-1$. Distance OA and OC which can be found from the geometry of the triangular weld is R and $\sqrt{2}a - R$ respectively. The radius of slip-line field can be found by applying the information above into the equilibrium equation (Equation 4.D.1)

$$Rk(\pi - 1) = k(\sqrt{2}a - R) \quad (4.D.3)$$

and the radius of slip-line field is

$$R = \frac{\sqrt{2}a}{\pi} \quad (4.D.4)$$

The limit moment can be found by taking the moment of the weld about point O

$$M = R\sigma_{OA}\left(\frac{R}{2}\right) + (R+S)\sigma_B\left(\frac{R+S}{2}\right) \quad (4.D.5)$$

plugging in the values of σ_{OA} and σ_B which equals to σ_D to Equation 4.D.5 and normalized it with Equation 4.4, the limit moment becomes:

$$\frac{M}{M_{nom}} = 1.36 \quad (4.D.6)$$

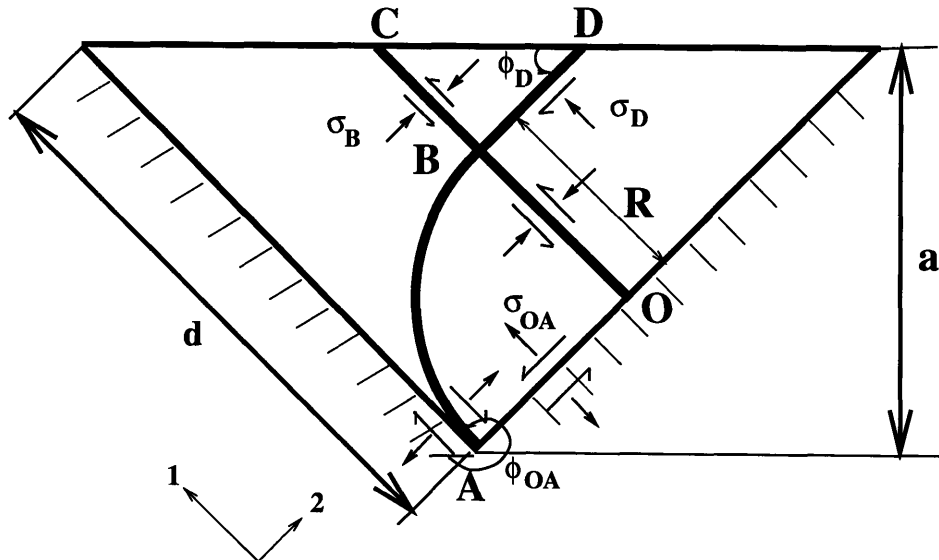


Figure 4.D.1 Proposed slip-line field for predominant opening bending

Appendix 4.E

Least Upper Bound Limit Moment of Double Fillet Welds Calculations

Weld leg length $d := 6$
Stiffener web thickness $t_w := 16.4$
Ratio of leg length to thickness $\frac{d}{t_w} = 0.366$

Right weld

Guess values: $x := 1$
 $y := 1$

Equations to get x and y positions where the sliding arc intersects with the face of the weld

Given $x=y$

$$\left[x - (d + t_w) \right]^2 + (y - h)^2 = h^2 + t_w^2$$

$x \geq 0 \qquad y \geq 0$

$F(h) := \text{Find}(x,y)$

$h := 3, 3.4.. 6$

$x(h) := F(h)_0 \qquad y(h) := F(h)_1$

$x(h)$	$y(h)$
6	6
5.828	5.828
5.67	5.67
5.522	5.522
5.385	5.385
5.257	5.257
5.136	5.136
5.022	5.022

$$c(h) := \sqrt{(d - x(h))^2 + y(h)^2}$$

$$\theta t(h) := 2 \cdot \text{asin} \left(\frac{c(h)}{2 \cdot \sqrt{h^2 + t_w^2}} \right)$$

angle in
radians

angle in
degrees

$\theta t(h)$	$\theta t(h) \cdot \left(\frac{180}{\pi} \right)$
0.362	20.733
0.35	20.049
0.339	19.422
0.329	18.845
0.32	18.31
0.311	17.813
0.303	17.349
0.295	16.913

Left Weld

Guess value $x := 24$ $y := 1$

Given

$$(x - d - t_w) + y = d$$
$$\left[x - (d + t_w) \right]^2 + (y - h)^2 = h^2$$

$$F(h) := \text{Find}(x, y)$$

$$h := 3, 3.4..6$$

$$x(h) := F(h)_0$$

$$y(h) := F(h)_1$$

h	x(h)	y(h)
3	25.4	3
3.4	25.722	2.678
3.8	25.952	2.448
4.2	26.13	2.27
4.6	26.276	2.124
5	26.4	2
5.4	26.507	1.893
5.8	26.6	1.8

Length of the sliding arc chord
for left weld

$$c(h) := \sqrt{[x(h) - (d + t_w)]^2 + y(h)^2}$$

Radius of sliding for left weld

$$R_A(h) := \sqrt{h^2 + t_w^2}$$

Radius of sliding for right weld

$$R_C(h) := \sqrt{h^2}$$

Angle of the sliding arc

$$\theta c(h) := 2 \cdot \arcsin\left(\frac{c(h)}{2 \cdot \sqrt{h^2}}\right)$$

angle in radians	angle in degrees
$\theta_c(h)$	$\theta_c(h) \cdot \left(\frac{180}{\pi}\right)$
1.571	90
1.357	77.733
1.207	69.166
1.093	62.641
1.002	57.428
0.927	53.13
0.864	49.506
0.81	46.397

Bending moments normalized by Equation 4.11

$$\frac{R_A(h) \cdot \theta_t(h) \cdot R_A(h) + R_C(h) \cdot \theta_c(h) \cdot R_C(h)}{\left(\frac{t_w^2}{2}\right)}$$

0.853
0.847
0.844
0.844
0.847
0.852
0.859
0.867

Least upper bound (LUB) limit moment from the above calculations is 0.844.

LUB limit moment value is different for different ratios of weld leg length to web stiffener thickness.

Appendix 4.F

Finite Element Program Input Files

4.F.1 Input Files for Predominantly Opening Bending Mode of Single Fillet Weld

```
*****
**      Program: Fillet Weld Strength and Deformation
**              in Lazy-L  Bend Test
**              BY: JULIANA ATMADJA
*****
*
FILEUNITS LIST=8 LOG=7 ECHO=7
HEAD 'Fillet Weld Strength in Lazy-L Test, 9mm - Bending, Node=58'
* Rc=2.96 = node 58
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
DATABASE CREATE MEMORY=1000
MASTER IDOF=100111 NSTEP=11 MTOTK=1000
AUTOMATIC-ATS
ITERATION FULL-NEWTON LINE-SEARCH=YES
PRINTOUT VOLUME=MIN
PORTHOLE FORMATTED=YES FILE=60
*****
*****
**      POSTSCRIPT OUTPUT HEADER FILE FOR ADINA-IN      **
*****
*****
FILEUNITS LIST=8 LOG=7
*ECHO=7
*
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
FCONTROL SIZE=ISO ISO=-4.5 XSF=10 YSF=5
*CONTROL PLOTUNIT=CM HEIGHT=0.25
*FCONTROL SIZE=ISO ISO=-4.5 XSF=2 YSF=1.5
WORKSTATION SYS=12 COLORS=RGB BACKGROUND=WHITE
```

COLORS ORI=INVERSE EL=INVERSE BC=INVERSE XYA=INVERSE
XYL=INVERSE VE=INVERSE

*

** HEADING OPTIONS:

FCONTROL HEADING=UPPER

*FCONTROL HEADING=LOWER

*

** FOR LANDSCAPE ORIENTATION, UNCOMMENT THE NEXT LINE:

FCONTROL ORIGIN=UPPERLEFT

*

COORDINATES

ENTRIES	NODE	Y	Z
1	0.1061	0.1061	
2	-0.1061	0.1061	
3	0.2121	0.2121	STEP TO
19	-0.2121	0.2121	
20	-0.1291	0.1476	
21	-0.1214	0.1619	
22	-0.1087	0.1739	
23	-0.0918	0.1836	
24	-0.0698	0.1862	
25	-0.0471	0.1882	
26	-0.0236	0.1888	
27	0.0000	0.1888	
28	0.0236	0.1888	
29	0.0471	0.1882	
30	0.0698	0.1862	
31	0.0918	0.1836	
32	0.1087	0.1739	
33	0.1214	0.1619	
34	0.1291	0.1476	
35	0.2340	0.2340	
36	0.2493	0.2493	
37	0.2750	0.2750	
38	0.3034	0.3034	
39	0.3347	0.3347	

40	0.3692	0.3692
41	0.4073	0.4073
42	0.4493	0.4493
43	0.4956	0.4956
44	0.5468	0.5468
45	0.6032	0.6032
46	0.6654	0.6654
47	0.7340	0.7340
48	0.8098	0.8098
49	0.8933	0.8933
50	0.9854	0.9854
51	1.0871	1.0871
52	1.1992	1.1992
53	1.3229	1.3229
54	1.4594	1.4594
55	1.6099	1.6100
56	1.7760	1.7760
57	1.9592	1.9592
58	2.0915	2.0915
59	2.3843	2.3843
60	2.6303	2.6303
61	2.9016	2.9016
62	3.2009	3.2009
63	3.5311	3.5311
64	3.8953	3.8953
65	4.2972	4.2972
66	-0.2340	0.2340
67	-0.2493	0.2493
68	-0.2750	0.2750
69	-0.3034	0.3034
70	-0.3347	0.3347
71	-0.3692	0.3692
72	-0.4073	0.4073
73	-0.4493	0.4493
74	-0.4956	0.4956
75	-0.5468	0.5468
76	-0.6032	0.6032
77	-0.6654	0.6654

78	-0.7340	0.7340
79	-0.8098	0.8098
80	-0.8933	0.8933
81	-0.9854	0.9854
82	-1.0871	1.0871
83	-1.1992	1.1992
84	-1.3229	1.3229
85	-1.4594	1.4594
86	-1.6100	1.6100
87	-1.7760	1.7760
88	-1.9592	1.9592
89	-2.0915	2.0915
90	-2.3843	2.3843
91	-2.6303	2.6303
92	-2.9016	2.9016
93	-3.2009	3.2009
94	-3.5311	3.5311
95	-3.8953	3.8953
96	-4.2972	4.2972
97	-4.7404	4.7404
98	-5.2294	5.2294
99	-5.7689	5.7689
100	-6.3640	6.3640
101	4.7404	4.7404
102	5.2294	5.2294
103	5.7689	5.7689
104	6.3640	6.3640

*

TIMEFUNCTION 1

0 0.0

1 1.0

11 160.0

*

MAT 1 PLASTIC E=2.0E5 NU=0.3 DEN=7.8 YIELD=519.615 ET=0.0

EGROUP 1 TWOSOLID SUBTYPE=STRAIN DISPL=SMALL MATERIAL=1,
FORMULATION=1

*

* Mesh generation

*

GSURFACE 2 20 18 19 NODES=9
GSURFACE 20 21 17 18 NODES=9
GSURFACE 21 22 16 17 NODES=9
GSURFACE 22 23 15 16 NODES=9
GSURFACE 23 24 14 15 NODES=9
GSURFACE 24 25 13 14 NODES=9
GSURFACE 25 26 12 13 NODES=9
GSURFACE 26 27 11 12 NODES=9
GSURFACE 27 28 10 11 NODES=9
GSURFACE 28 29 9 10 NODES=9
GSURFACE 29 30 8 9 NODES=9
GSURFACE 30 31 7 8 NODES=9
GSURFACE 31 32 6 7 NODES=9
GSURFACE 32 33 5 6 NODES=9
GSURFACE 33 34 4 5 NODES=9
GSURFACE 34 1 3 4 NODES=9
GSURFACE 19 3 35 66 EL1=16 NODES=9
GSURFACE 66 35 36 67 EL1=16 NODES=9
GSURFACE 67 36 37 68 EL1=16 NODES=9
GSURFACE 68 37 38 69 EL1=16 NODES=9
GSURFACE 69 38 39 70 EL1=16 NODES=9
GSURFACE 70 39 40 71 EL1=16 NODES=9
GSURFACE 71 40 41 72 EL1=16 NODES=9
GSURFACE 72 41 42 73 EL1=16 NODES=9
GSURFACE 73 42 43 74 EL1=16 NODES=9
GSURFACE 74 43 44 75 EL1=16 NODES=9
GSURFACE 75 44 45 76 EL1=16 NODES=9
GSURFACE 76 45 46 77 EL1=16 NODES=9
GSURFACE 77 46 47 78 EL1=16 NODES=9
GSURFACE 78 47 48 79 EL1=16 NODES=9
GSURFACE 79 48 49 80 EL1=16 NODES=9
GSURFACE 80 49 50 81 EL1=16 NODES=9
GSURFACE 81 50 51 82 EL1=16 NODES=9
GSURFACE 82 51 52 83 EL1=16 NODES=9
GSURFACE 83 52 53 84 EL1=16 NODES=9
GSURFACE 84 53 54 85 EL1=16 NODES=9
GSURFACE 85 54 55 86 EL1=16 NODES=9

GSURFACE 86 55 56 87 EL1=16 NODES=9
GSURFACE 87 56 57 88 EL1=16 NODES=9
GSURFACE 88 57 58 89 EL1=16 NODES=9
GSURFACE 89 58 59 90 EL1=16 NODES=9
GSURFACE 90 59 60 91 EL1=16 NODES=9
GSURFACE 91 60 61 92 EL1=16 NODES=9
GSURFACE 92 61 62 93 EL1=16 NODES=9
GSURFACE 93 62 63 94 EL1=16 NODES=9
GSURFACE 94 63 64 95 EL1=16 NODES=9
GSURFACE 95 64 65 96 EL1=16 NODES=9
GSURFACE 96 65 101 97 EL1=16 NODES=9
GSURFACE 97 101 102 98 EL1=16 NODES=9
GSURFACE 98 102 103 99 EL1=16 NODES=9
GSURFACE 99 103 104 100 EL1=16 NODES=9

*

LIST COORDINATES

*

LINE COMBINED N1=2 N2=100 ,
19 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82,
83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99

*

LIST LINE N1=2 N2=100

*

*

** Fixing the nodes for rigid boundaries along the base plate ***

FIXBOUNDARIES DIR=23 TYPE=LINES

2 100

*

*** PRESCRIBED DISPLACEMENT IN THE Y-DIRECTION

LOADS DISPLACEMENTS TYPE=NODES

1	2	0.0004967
168	2	0.0004835
3	2	0.0004702
202	2	0.0004675
35	2	0.0004647
266	2	0.0004628
36	2	0.0004609
330	2	0.0004577

37	2	0.0004545
394	2	0.0004509
38	2	0.0004474
458	2	0.0004434
39	2	0.0004395
522	2	0.0004352
40	2	0.0004309
586	2	0.0004261
41	2	0.0004214
650	2	0.0004161
42	2	0.0004109
714	2	0.0004051
43	2	0.0003993
778	2	0.0003929
44	2	0.0003865
842	2	0.0003794
45	2	0.0003723
906	2	0.0003646
46	2	0.0003568
970	2	0.0003482
47	2	0.0003396
1034	2	0.0003301
48	2	0.0003207
1098	2	0.0003102
49	2	0.0002998
1162	2	0.0002882
50	2	0.0002767
1226	2	0.0002640
51	2	0.0002513
1290	2	0.0002373
52	2	0.0002232
1354	2	0.0002078
53	2	0.0001923
1418	2	0.0001752
54	2	0.0001581
1482	2	0.0001393
55	2	0.0001205
1546	2	0.0000997

56	2	0.0000789
1610	2	0.0000560
57	2	0.0000331
1674	2	0.0000165
58	2	0.0000000
1738	2	-0.0000366
59	2	-0.0000733
1802	2	-0.0001040
60	2	-0.0001348
1866	2	-0.0001687
61	2	-0.0002027
1930	2	-0.0002401
62	2	-0.0002776
1994	2	-0.0003189
63	2	-0.0003602
2058	2	-0.0004057
64	2	-0.0004513
2122	2	-0.0005016
65	2	-0.0005518
2186	2	-0.0006073
101	2	-0.0006627
2250	2	-0.0007239
102	2	-0.0007851
2314	2	-0.0008525
103	2	-0.0009200
2378	2	-0.0009945
104	2	-0.0010689

*

*** PRESCRIBED DISPLACEMENT IN THE Z-DIRECTION
LOADS DISPLACEMENTS TYPE=NODES

1	3	-0.0004967
168	3	-0.0004835
3	3	-0.0004702
202	3	-0.0004675
35	3	-0.0004647
266	3	-0.0004628
36	3	-0.0004609
330	3	-0.0004577

37	3	-0.0004545
394	3	-0.0004509
38	3	-0.0004474
458	3	-0.0004434
39	3	-0.0004395
522	3	-0.0004352
40	3	-0.0004309
586	3	-0.0004261
41	3	-0.0004214
650	3	-0.0004161
42	3	-0.0004109
714	3	-0.0004051
43	3	-0.0003993
778	3	-0.0003929
44	3	-0.0003865
842	3	-0.0003794
45	3	-0.0003723
906	3	-0.0003646
46	3	-0.0003568
970	3	-0.0003482
47	3	-0.0003396
1034	3	-0.0003301
48	3	-0.0003207
1098	3	-0.0003102
49	3	-0.0002998
1162	3	-0.0002882
50	3	-0.0002767
1226	3	-0.0002640
51	3	-0.0002513
1290	3	-0.0002373
52	3	-0.0002232
1354	3	-0.0002078
53	3	-0.0001923
1418	3	-0.0001752
54	3	-0.0001581
1482	3	-0.0001393
55	3	-0.0001205
1546	3	-0.0000997

56	3	-0.0000789
1610	3	-0.0000560
57	3	-0.0000331
1674	3	-0.0000165
58	3	0.0000000
1738	3	0.0000366
59	3	0.0000733
1802	3	0.0001040
60	3	0.0001348
1866	3	0.0001687
61	3	0.0002027
1930	3	0.0002401
62	3	0.0002776
1994	3	0.0003189
63	3	0.0003602
2058	3	0.0004057
64	3	0.0004513
2122	3	0.0005016
65	3	0.0005518
2186	3	0.0006073
101	3	0.0006627
2250	3	0.0007239
102	3	0.0007850
2314	3	0.0008525
103	3	0.0009200
2378	3	0.0009945
104	3	0.0010689

*

LIST LOADS DISPLACEMENTS

LIST FIXBOUNDARIES 23

*

LIST ENODES FIRST=272 LAST=272

*

*

FRAME HEADING=NONE

MESH BCODE=ALL MARGIN=YES

EVECTOR VAR=PDISP OUTPUT=ALL

*

```
BZONE CORNER ZMAX=0.4
BZONE SUDUT ZMIN=0.3
BZONE RIGHT ZMIN=2.3 ZMAX=4.0 YMIN=0.0
*FRAME
*MESH RIGHT NODES=11
*
*FRAME
*MESH CORNER EL=1
*FRAME
*MESH CORNER NODES=11
*FRAME
*MESH SUDUT NODES=11
*
ADINA
END
```

```
***** A D I N A - P L O T INPUT FILE *****
***** Program: Lazy-L Bend Test, 9mm weld *****
**
**                BY: JULIANA ATMADJA
**
FILEUNITS LIST=8 LOG=7
FCONTROL HEADING=UPPER ORIGIN=UPPERLEFT
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
DATABASE CREATE FORMATTED=YES MEMORY=1000
*****
* POSTSCRIPT OUTPUT HEADER FILE
*****
FILEUNITS LIST=8
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
FCONTROL SIZE=ISO ISO=-4.5 XSF=10 YSF=5
WORKSTATION SYS=12 COLORS=RGB BACKGROUND=WHITE
COLORS ORI=INVERSE EL=INVERSE BC=INVERSE XYA=INVERSE
XYL=INVERSE
COLORS DEF=INVERSE VE=INVERSE ST=INVERSE
** HEADING OPTION
FCONTROL HEADING=UPPER
*****
PLOTAREA 1 5.0 95.0 5.0 85.0
*
*FRAME HEADING=NONE
*MESH ORI=2 DE=1 MARGIN=YES
*
*FRAME HEADING=NONE
*MESH ORI=1 DE=0 MARGIN=YES
*EVECTOR VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
*FRAME
*MESH ORI=1 DE=0 MARGIN=YES LINES=1
*BAND VAR=EFFECTIVE_STRESS COLORMAX=7
*
*FRAME
*MESH ORI=1 DE=0 MARGIN=YES LINES=1
*BAND VAR=EFFECTIVE_STRESS COLORMAX=11 TYPE=LINES
```

```
*
RESULTANT NORM-MEAN '(-1*PRESSURE)/600'
*
FRAME HEADING=NONE
MESH ORI=1 DE=0 MARGIN=YES LINES=1
BAND VAR=NORM-MEAN COLORMAX=9 TYPE=LINES
*
BZONE CORNER ZMAX=0.3
BZONE INT ZMIN=2.6 ZMAX=3.2 YMIN=-2.0 YMAX=-1.3
BZONE ACROSS ZMIN=2.6 ZMAX=3.2
BZONE TOP ZMIN=3.5
BZONE MIDDLE ZMIN=1.8 ZMAX=2.6
BZONE MISESHOLE YMIN=-0.11 YMAX=-0.06 ZMAX=0.22
BZONE NORMAL YMIN=-0.05
*
BZONE TENGAH1 ZMIN=0.5 ZMAX=0.8 YMIN=0.0
BZONE TENGAH2 ZMIN=0.7 ZMAX=1.2 YMIN=0.0
BZONE TENGAH3 ZMIN=1.1 ZMAX=2.0 YMIN=0.0
BZONE ATAS ZMIN=1.8
*
BZONE STRESSES ZMIN=0.5 ZMAX=1.9
*ZLIST VAR=ACCUM_EFF_PLASTIC_STRAIN
*
*FRAME HEADING=NONE
*MESH ATAS ORI=1 DE=0 MARGIN=YES
*EVECTOR ZONE=ATAS VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*FRAME
*MESH TENGAH2 ORI=1 DE=0 NODES=11
*TEXT XP=20 YP=90 STRING='TENGAH2'
*
*
*FRAME
*MESH INT ORI=1 DE=0
*EVECTOR VAR=STRESS POINTS=YES
*TEXT XP=20 YP=85 STRING='INTEGRATION POINTS'
*
*FRAME
*MESH ACROSS ORI=1 DE=0 EL=1
```

```
*EVECTOR ACROSS VAR=STRESS POSITIVE=7 NEGATIVE=4 OUTPUT=ALL
*
*CONTROL PLOTUNITS=PERCENT HEIGHT=0.3
*
*FRAME
*MESH NORMAL ORI=1 DE=0 EL=1
*
*FRAME
*MESH STRESSES ORI=1 DE=0
*BAND ZONE=STRESSES VAR=PRESSURE TYPE=LINES COLORMAX=7 MAX-
LAB=YES
*EVECTOR VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
*FRAME
*MESH CORNER ORI=1 DE=0
*EVECTOR CORNER VAR=STRESS POSITIVE=3 NEGATIVE=4 OUTPUT=ALL
*TEXT XP=20 YP=85 STRING='PLOT OF PRINCIPAL STRESSES'
*
*
END
```

4.F.2 Input Files for Predominantly Leg Shear of Single Fillet Weld

```
*****
**      Program: Fillet Weld Strength and Deformation
**              in Lazy-L Test - Predominantly Leg Shear
**
**              BY: JULIANA ATMADJA
*****
*
FILEUNITS LIST=8 LOG=7 ECHO=7
HEAD 'Fillet Weld Strength in Lazy-L Test, 6mm - Tension, Rc=11.06'
*
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
DATABASE CREATE MEMORY=6000
MASTER IDOF=100111 NSTEP=11 MTOTK=1000
ITERATION FULL-NEWTON LINE-SEARCH=YES
AUTOMATIC-ATS
PRINTOUT VOLUME=MIN
PORTHOLE FORMATTED=YES
*****
*****
**      POSTSCRIPT OUTPUT HEADER FILE FOR ADINA-IN                      **
*****
*****
FILEUNITS LIST=8 LOG=7
*ECHO=7
*
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
FCONTROL SIZE=ISO ISO=-4.5 XSF=10 YSF=5
*CONTROL PLOTUNIT=CM HEIGHT=0.25
*FCONTROL SIZE=ISO ISO=-4.5 XSF=2 YSF=1.5
WORKSTATION SYS=12 COLORS=RGB BACKGROUND=WHITE
COLORS  ORI=INVERSE  EL=INVERSE  BC=INVERSE  XYA=INVERSE
XYL=INVERSE VE=INVERSE
*
**  HEADING OPTIONS:
FCONTROL HEADING=UPPER
```

*FCONTROL HEADING=LOWER

*

** FOR LANDSCAPE ORIENTATION, UNCOMMENT THE NEXT LINE:

FCONTROL ORIGIN=UPPERLEFT

*

COORDINATES

ENTRIES	NODE	Y	Z
1	0.1061	0.1061	
2	-0.1061	0.1061	
3	0.2121	0.2121	STEP TO
19	-0.2121	0.2121	
20	-0.1291	0.1476	
21	-0.1214	0.1619	
22	-0.1087	0.1739	
23	-0.0918	0.1836	
24	-0.0698	0.1862	
25	-0.0471	0.1882	
26	-0.0236	0.1888	
27	0.0000	0.1888	
28	0.0236	0.1888	
29	0.0471	0.1882	
30	0.0698	0.1862	
31	0.0918	0.1836	
32	0.1087	0.1739	
33	0.1214	0.1619	
34	0.1291	0.1476	
35	0.2291	0.2291	
36	0.2461	0.2461	
37	0.2715	0.2715	
38	0.2995	0.2995	
39	0.3304	0.3304	
40	0.3645	0.3645	
41	0.4021	0.4021	
42	0.4436	0.4436	
43	0.4894	0.4894	
44	0.5398	0.5398	

45	0.5955	0.5955
46	0.6570	0.6570
47	0.7247	0.7247
48	0.7995	0.7995
49	0.8820	0.8820
50	0.9729	0.9729
51	1.0733	1.0733
52	1.1840	1.1840
53	1.3062	1.3062
54	1.4409	1.4409
55	1.5895	1.5895
56	1.7535	1.7535
57	1.9344	1.9344
58	2.1339	2.1339
59	2.3540	2.3541
60	2.5969	2.5969
61	2.8648	2.8648
62	3.1603	3.1603
63	3.4863	3.4863
64	3.8459	3.8459
65	4.2426	4.2426
66	-0.2291	0.2291
67	-0.2461	0.2461
68	-0.2715	0.2715
69	-0.2995	0.2995
70	-0.3304	0.3304
71	-0.3645	0.3645
72	-0.4021	0.4021
73	-0.4436	0.4436
74	-0.4894	0.4894
75	-0.5398	0.5398
76	-0.5955	0.5955
77	-0.6570	0.6570
78	-0.7247	0.7247
79	-0.7995	0.7995
80	-0.8820	0.8820
81	-0.9729	0.9729
82	-1.0733	1.0733

83	-1.1840	1.1840
84	-1.3062	1.3062
85	-1.4409	1.4409
86	-1.5895	1.5895
87	-1.7535	1.7535
88	-1.9344	1.9344
89	-2.1339	2.1339
90	-2.3541	2.3541
91	-2.5969	2.5969
92	-2.8648	2.8648
93	-3.1603	3.1603
94	-3.4863	3.4863
95	-3.8459	3.8459
96	-4.2426	4.2426

*

*

TIMEFUNCTION 1

0 0.0

1 1.0

11 106.0

*

MAT 1 PLASTIC E=2.0E5 NU=0.3 DEN=7.8 YIELD=519.615 ET=0.0

EGROUP 1 TWODSOLID SUBTYPE=STRAIN DISPL=SMALL MATERIAL=1,
FORMULATION=1

*

* Mesh generation

*

GSURFACE 2 20 18 19 NODES=9

GSURFACE 20 21 17 18 NODES=9

GSURFACE 21 22 16 17 NODES=9

GSURFACE 22 23 15 16 NODES=9

GSURFACE 23 24 14 15 NODES=9

GSURFACE 24 25 13 14 NODES=9

GSURFACE 25 26 12 13 NODES=9

GSURFACE 26 27 11 12 NODES=9

GSURFACE 27 28 10 11 NODES=9

GSURFACE 28 29 9 10 NODES=9

GSURFACE 29 30 8 9 NODES=9

GSURFACE 30 31 7 8 NODES=9
GSURFACE 31 32 6 7 NODES=9
GSURFACE 32 33 5 6 NODES=9
GSURFACE 33 34 4 5 NODES=9
GSURFACE 34 1 3 4 NODES=9
GSURFACE 19 3 35 66 EL1=16 NODES=9
GSURFACE 66 35 36 67 EL1=16 NODES=9
GSURFACE 67 36 37 68 EL1=16 NODES=9
GSURFACE 68 37 38 69 EL1=16 NODES=9
GSURFACE 69 38 39 70 EL1=16 NODES=9
GSURFACE 70 39 40 71 EL1=16 NODES=9
GSURFACE 71 40 41 72 EL1=16 NODES=9
GSURFACE 72 41 42 73 EL1=16 NODES=9
GSURFACE 73 42 43 74 EL1=16 NODES=9
GSURFACE 74 43 44 75 EL1=16 NODES=9
GSURFACE 75 44 45 76 EL1=16 NODES=9
GSURFACE 76 45 46 77 EL1=16 NODES=9
GSURFACE 77 46 47 78 EL1=16 NODES=9
GSURFACE 78 47 48 79 EL1=16 NODES=9
GSURFACE 79 48 49 80 EL1=16 NODES=9
GSURFACE 80 49 50 81 EL1=16 NODES=9
GSURFACE 81 50 51 82 EL1=16 NODES=9
GSURFACE 82 51 52 83 EL1=16 NODES=9
GSURFACE 83 52 53 84 EL1=16 NODES=9
GSURFACE 84 53 54 85 EL1=16 NODES=9
GSURFACE 85 54 55 86 EL1=16 NODES=9
GSURFACE 86 55 56 87 EL1=16 NODES=9
GSURFACE 87 56 57 88 EL1=16 NODES=9
GSURFACE 88 57 58 89 EL1=16 NODES=9
GSURFACE 89 58 59 90 EL1=16 NODES=9
GSURFACE 90 59 60 91 EL1=16 NODES=9
GSURFACE 91 60 61 92 EL1=16 NODES=9
GSURFACE 92 61 62 93 EL1=16 NODES=9
GSURFACE 93 62 63 94 EL1=16 NODES=9
GSURFACE 94 63 64 95 EL1=16 NODES=9
GSURFACE 95 64 65 96 EL1=16 NODES=9

*

LIST COORDINATES

*

LINE COMBINED N1=1 N2=65 ,
 3 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 ,
 56 57 58 59 60 61 62 63 64

LINE COMBINED N1=2 N2=96 ,
 19 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82,
 83 84 85 86 87 88 89 90 91 92 93 94 95

LIST LINE N1=1 N2=65

LIST LINE N1=2 N2=96

*

*

** Fixing the nodes for rigid boundaries along the base plate ***

FIXBOUNDARIES DIR=23 TYPE=LINES

2 96

*** PRESCRIBED DISPLACEMENT IN THE Z-DIRECTION FOR EACH NODE

LOADS DISPLACEMENTS TYPE=NODES

1	3	0.00080870
3	3	0.00080477
35	3	0.00080396
36	3	0.00080351
37	3	0.00080257
38	3	0.00080154
39	3	0.00080039
40	3	0.00079913
41	3	0.00079774
42	3	0.00079621
43	3	0.00079451
44	3	0.00079265
45	3	0.00079059
46	3	0.00078831
47	3	0.00078580
48	3	0.00078304
49	3	0.00077999
50	3	0.00077662
51	3	0.00077291
52	3	0.00076881
53	3	0.00076429
54	3	0.00075931

55	3	0.00075381
56	3	0.00074774
57	3	0.00074105
58	3	0.00073366
59	3	0.00072552
60	3	0.00071654
61	3	0.00070662
62	3	0.00069569
63	3	0.00068363
64	3	0.00067032
65	3	0.00065564
160	3	0.00080673
194	3	0.00080446
258	3	0.00080383
322	3	0.00080304
386	3	0.00080206
450	3	0.00080097
514	3	0.00079976
578	3	0.00079844
642	3	0.00079697
706	3	0.00079536
770	3	0.00079358
834	3	0.00079162
898	3	0.00078945
962	3	0.00078706
1026	3	0.00078442
1090	3	0.00078151
1154	3	0.00077830
1218	3	0.00077477
1282	3	0.00077086
1346	3	0.00076655
1410	3	0.00076180
1474	3	0.00075656
1538	3	0.00075077
1602	3	0.00074439
1666	3	0.00073736
1730	3	0.00072959
1794	3	0.00072103

1858	3	0.00071158
1922	3	0.00070116
1986	3	0.00068966
2050	3	0.00067697
2114	3	0.00065564

*

*

*** PRESCRIBED DISPLACEMENT IN THE Y-DIRECTION FOR EACH NODE
LOADS DISPLACEMENTS TYPE=NODES

1	2	0.00023782
3	2	0.00024174
35	2	0.00024255
36	2	0.00024300
37	2	0.00024394
38	2	0.00024498
39	2	0.00024612
40	2	0.00024738
41	2	0.00024877
42	2	0.00025031
43	2	0.00025200
44	2	0.00025387
45	2	0.00025593
46	2	0.00025820
47	2	0.00026071
48	2	0.00026348
49	2	0.00026653
50	2	0.00026989
51	2	0.00027361
52	2	0.00027770
53	2	0.00028222
54	2	0.00028721
55	2	0.00029271
56	2	0.00029877
57	2	0.00030547
58	2	0.00031285
59	2	0.00032100
60	2	0.00032998
61	2	0.00033989

62	2	0.00035083
63	2	0.00036289
64	2	0.00037619
65	2	0.00039087
160	2	0.00023978
194	2	0.00024206
258	2	0.00024269
322	2	0.00024347
386	2	0.00024446
450	2	0.00024555
514	2	0.00024675
578	2	0.00024808
642	2	0.00024954
706	2	0.00025116
770	2	0.00025294
834	2	0.00025490
898	2	0.00025707
962	2	0.00025946
1026	2	0.00026209
1090	2	0.00026500
1154	2	0.00026821
1218	2	0.00027175
1282	2	0.00027566
1346	2	0.00027996
1410	2	0.00028472
1474	2	0.00028996
1538	2	0.00029574
1602	2	0.00030212
1666	2	0.00030916
1730	2	0.00031692
1794	2	0.00032549
1858	2	0.00033494
1922	2	0.00034536
1986	2	0.00035686
2050	2	0.00036954
2114	2	0.00039087

*

*LIST LOADS DISPLACEMENTS

*

LIST ENODES FIRST=272 LAST=272

*

*

FRAME HEADING=NONE

MESH BCODE=ALL MARGIN=YES

EVECTOR VAR=PDISP OUTPUT=ALL

*

BZONE CORNER ZMAX=0.4

BZONE SUDUT ZMIN=0.3

*

*FRAME

*MESH CORNER EL=1

*FRAME

*MESH CORNER NODES=11

*FRAME

*MESH SUDUT NODES=11

*

ADINA

END

```
***** A D I N A - P L O T INPUT FILE *****
***** Program: Fillet Weld Study on Lazy-L *****
**      Predominant Weld Leg Shear Case
**      BY: JULIANA ATMADJA
**
FILEUNITS LIST=8 LOG=7
FCONTROL HEADING=UPPER ORIGIN=UPPERLEFT
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
DATABASE CREATE FORMATTED=YES MEMORY=1000
*NINFO VAR=YES
*EINFO VAR=YES
*****
* POSTSCRIPT OUTPUT HEADER FILE
*****
FILEUNITS LIST=8
CONTROL PLOTUNIT=PERCENT HEIGHT=0.8
FCONTROL SIZE=ISO ISO=-4.5 XSF=10 YSF=5
WORKSTATION SYS=12 COLORS=RGB BACKGROUND=WHITE
COLORS ORI=INVERSE EL=INVERSE BC=INVERSE XYA=INVERSE
XYL=INVERSE
COLORS DEF=INVERSE VE=INVERSE ST=INVERSE
** HEADING OPTION
FCONTROL HEADING=UPPER
*****
PLOTAREA 1 5.0 95.0 5.0 85.0
*
*FRAME HEADING=NONE
*MESH ORI=2 DE=1 MARGIN=YES
*
*
BTABLE STRESS UPPER=CONSTANT V=ABSOLUTE
  0.0 INVERSE
  75.0 BLUE
 350.0 CYAN
 470.0 GREEN
 500.0 BLUE_MAGENTA
 502.0 YELLOW
 510.0 MAGENTA
```

550.0 ORANGE

599.0 RED

*

BZONE CORNER ZMAX=0.3

BZONE INT ZMIN=2.6 ZMAX=3.2 YMIN=-2.0 YMAX=-1.3

BZONE ACROSS ZMIN=2.6 ZMAX=3.2

BZONE TOP YMIN=-1.0 ZMIN=2.8

BZONE TOP1 YMIN=-1.0 ZMIN=3.6

BZONE MIDDLE ZMIN=1.8 ZMAX=2.6

BZONE MISESHOLE YMIN=-0.11 YMAX=-0.06 ZMAX=0.22

BZONE NORMAL YMIN=-0.05

*

*

*BZONE TENGAH1 ZMIN=0.2 ZMAX=0.8 YMIN=0.0

BZONE TENGAH1 ZMIN=0.5 ZMAX=0.8 YMIN=0.0

BZONE TENGAH2 ZMIN=0.7 ZMAX=1.2 YMIN=0.0

BZONE TENGAH3 ZMIN=1.1 ZMAX=2.0 YMIN=0.0

BZONE ATAS ZMIN=1.8 YMIN=-0.1

BZONE STRESSES ZMIN=0.5 ZMAX=1.9

*

*

*FRAME

*MESH MISESHOLE ORI=1 DE=0 EL=1

*FRAME

*MESH MISESHOLE ORI=1 DE=0 EL=1

*CONTROL PLOTUNIT=PERCENT HEIGHT=0.5

*FRAME

*MESH TENGAH2 ORI=1 DE=0 NODES=11

*TEXT XP=20 YP=90 STRING='TENGAH2'

*

*

*FRAME

*MESH INT ORI=1 DE=0

*EVECTOR VAR=STRESS POINTS=YES

*TEXT XP=20 YP=85 STRING='INTEGRATION POINTS'

*

*FRAME

*MESH ACROSS ORI=1 DE=0 EL=1

```
*EVECTOR ACROSS VAR=STRESS POSITIVE=7 NEGATIVE=4 OUTPUT=ALL
*
*CONTROL PLOTUNITS=PERCENT HEIGHT=0.3
*
*FRAME
*MESH NORMAL ORI=1 DE=0 EL=1
*
*FRAME
*MESH NORMAL ORI=1 DE=0
*EVECTOR NORMAL VAR=STRESS POSITIVE=3 NEGATIVE=4 OUTPUT=ALL
*
*FRAME
*MESH TOP ORI=1 DE=0
*EVECTOR ZONE=TOP VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
*FRAME
*MESH ORI=1 DE=0 MARGIN=YES
*EVECTOR VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
FRAME HEADING=NONE
MESH ORI=1 DE=0 MARGIN=YES
*BAND VAR=PRESSURE TYPE=LINES MAXLABEL=YES COLORMAX=11
EVECTOR VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
*FRAME
*MESH ORI=1 DE=0 MARGIN=YES LINES=1
*BAND VAR=PRESSURE TYPE=LINES COLORMAX=11
*
RESULTANT NORM-MEAN '(-1*PRESSURE)/600'
*
*FRAME
*MESH ORI=1 DE=0 MARGIN=YES LINES=1
*BAND VAR=NORM-MEAN TYPE=LINES COLORMAX=11
*
*FRAME HEADING=NONE
*MESH TOP ORI=1 DE=0 MARGIN=YES
*BAND ZONE=TOP VAR=NORM-MEAN TYPE=LINES COLORMAX=7 MAX-
```

```
LAB=YES
**FRAME
*MESH TOP ORI=1 DE=0 MARGIN=YES
*BAND ZONE=TOP VAR=PRESSURE TYPE=LINES COLORMAX=11 MAX-
LAB=YES
*FRAME
*MESH TOP ORI=1 DE=0 MARGIN=YES
*BAND ZONE=TOP VAR=PRESSURE TYPE=LINES COLORMAX=7 MAX-
LAB=YES
*FRAME
*MESH TOP ORI=1 DE=0 MARGIN=YES
*BAND ZONE=TOP VAR=PRESSURE MAXLAB=YES COLORMAX=7
*EVECTOR VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*TEXT=NO
*
*FRAME
*MESH TOP ORI=1 DE=0 MARGIN=YES
*BAND ZONE=TOP VAR=PRESSURE MAXLAB=YES COLORMAX=7
*EVECTOR ZONE=TOP VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
TEXT=NO
*FRAME HEADING=NONE
*MESH TOP1 ORI=1 DE=0 MARGIN=YES
*EVECTOR ZONE=TOP1 VAR=PLASTIC_STRAIN POSITIVE=3 NEGATIVE=4
*
END
```

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

Single-Hull Tanker Stranding

From the single-hull tanker stranding study, it has been concluded that:

1. The study of the 2-D single hull oil tanker stranding shows that some combination of plate and fillet welds size in oil tankers set by the classification societies such as the ABS and NK, allow deformation on the welds during grounding or accidents.
2. Localization and curvature of the bottom plate near the hard-point support under combined bending and tension were observed in the analysis. Further work was carried on to study the behavior of the plate, including the significance of bending in the maximum load and elongation of the plate.

Plate under Combined Bending and Tension at Hard-Point Support

The study of a plate under combined bending and tension near the bulkhead reinforcement (hard-point support) leads to conclusions:

3. The maximum load of a plate under combined bending and tension at hard-point support is only 2.5% less than the maximum load of a plate under pure tension.
4. The combined bending and tension on a plate reduces the elongation of a plate at the maximum load by 40%.
5. The strain near the hard-point support is about 82% higher than that of pure tension. The high value of strain indicates that necking and fracture are potential problems in a plate near hard-point support.

Finite Element Analysis of Fillet Welds for Lazy-L Test

The study of single fillet weld Lazy-L test using finite element method gives results as follows:

6. Single arc sliding fields calculated by the upper bound theorem give good first approximations of the limit moment, mean normal stress, and radius of sliding for single fillet weld both in predominant weld leg shear and predominant opening bending.
7. The finite element analysis for predominant weld leg shear gives less bending moments than that of the least upper bound calculations.
8. The study of the effects of friction on the interface of the base plate and the stiffener web and on the support point showed that frictions do not effect the radius and the magnitude of the support load significantly. This means that frictions do not change the limit load significantly and the frictionless assumption is valid.
9. The finite element studies of single fillet welds give previously unknown slip line fields for both predominant opening bending and predominant leg shear of single fillet weld.

10. For double fillet welds joint, NK Classification society dimensions on max. weld size cause yielding first in the stiffener or web even with $k_f/k_w = 1$. The values are presented in Table 4.3 in Chapter 4 of this thesis.
11. The least upper bound calculations on double fillet welds showed that for small fillets, cracking might occur on the compression side of bending where the mean normal stress across the crack tip is of the order of the shear yield strength, k .

5.2 Recommendations

1. The fixed end boundary condition for the hard-point study is not realistic because the longitudinal and transverse bulkhead give some flexibility or compliance. A study of some compliance provided by the existence of the bulkhead is needed.
2. Use isotropic strain hardening material for the study of plate under combined bending and tension and compare the results with the kinematic strain hardening material results.
3. A finite element analysis on the web folding of double fillet welds is needed to obtain the actual slip-line field and a more accurate limit moment. The finite element study is also needed to verify the least upper bound calculations and the previous work on the Lazy-L test studied by Brooks [Brooks, 1995].
4. In this thesis the material used for the finite element study of the Lazy-L test was idealized. In real structure, the weld material is strain hardened. A finite element study of the Lazy-L test using strained hardened material is recommended
5. Inhomogeneity is part of the real weld material. The study of the fillet weld presented in this thesis has not taken this aspect into considerations. A study using finite element method on inhomogeneous weld material properties will be useful for

fillet weld designers.

6. To make the weld stronger, Wilcox (1995) suggested a fillet weld with deep penetration. A series of experiments studying the strength of the fillet weld with deep penetration under tension loading was studied by Wilcox in 1995. A study of fillet weld with deep penetration using finite element analysis is needed to be compared with the experimental results. This study will help ship designers in designing oil spill resistant tankers.